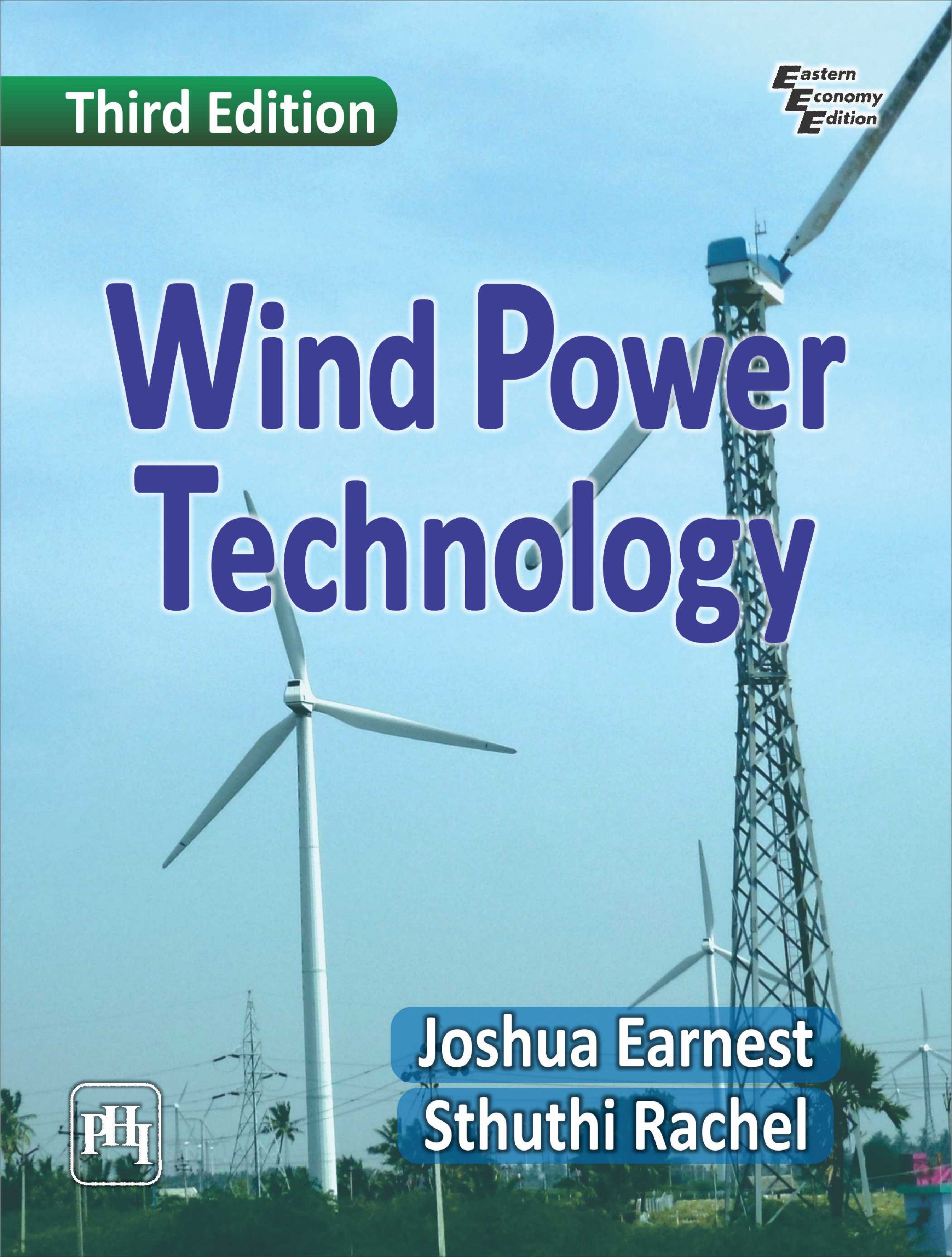
Third Edition

Eastern Economy Edition

Wind Power Technology

Joshua Earnest
Sthuthi Rachel



PHI

Wind Power Technology

THIRD EDITION

JOSHUA EARNEST
Dean
Planning and Monitoring
Professor of Electrical Engineering
National Institute of Technical Teachers' Training & Research
(*Under Ministry of Human Resource Development, Government of India*)
Shamla Hills, Bhopal, Madhya Pradesh

STHUTHI RACHEL
Assistant Professor
Department of Electronics Engineering
Ramrao Adik Institute of Technology
D.Y. Patil University, Nerul
Navi-Mumbai

PHI Learning Private Limited
Delhi-110092
2019

WIND POWER TECHNOLOGY, Third Edition
Joshua Earnest and Sthuthi Rachel

Disclaimer
Every effort has been made to give the correct information and details obtained from various sources believed to be reliable. However, any inadvertent error or discrepancy, which may have crept in, if brought to the author's notice is most welcome. This shall be taken into cognisance in future editions. However, the publisher and the author are supplying the information but are not attempting to render engineering or other professional services and thereby will not be responsible for any errors, omissions, damages or losses caused to anyone due to the use of information from this book. If such services are required, the assistance of an appropriate professional should be sought.

ISBN-978-93-88028-49-3 (Print Book)
ISBN-978-93-88028-50-9 (e-Book)

Third Printing (Third Edition) . . . . July, 2019

Published by Asoke K. Ghosh, PHI Learning Private Limited, Rimjhim House, 111, Patparganj Industrial Estate, Delhi-110092 and Printed by Mudrak, D-61, Sector 63, Noida, U.P.-201301.

To

GOD

Who is Omniscient, Omnipresent and Omnipotent

and

Bindhu Joshua
Koshy Earnest
Mariamma Thomas
Late John A. Earnest
Late Achamma Earnest
Late Saramma Earnest
Late M.T. Thomas

Preface

HE let loose the East wind from the heavens and by HIS power made the South wind blow
—Psalms 78:26 (Bible)

The enthusiastic response to the earlier editions motivated us to bring forth the new edition with improved and significant changes. The speciality of this edition is that apart from the significant updation of the 1st chapter of this book, a new Chapter 15 has been added which will be of great interest as it deals with the Electronics in Renewable Energy Systems. We are thankful to all those who encouraged us by giving tremendous responses about the book. At the same time, the readers' feedback and suggestions have been incorporated in several chapters and at the same time retaining the systematic flow of contents, visuals and pagination of the 1st edition for the readers' convenience. However, the readers can also note all the other significant improvements made in the book while reading through the book. One of the key features of this book is the lucidity of the diagrams and images, which have been carefully chosen in order to develop a clear understanding of the various concepts of wind power technology.

Today, wind energy is the world's fastest growing source of renewable energy. To abate the global climate change, commercialisation of the renewable energy technologies and wind power in particular, are growing quite fast across the world. More and more windy areas are being discovered and every year, grid connected wind power is growing in leaps and bounds and India is one such happening place, where the world is watching. Among the renewable energy sources, the cost of producing one kilowatt hour (kWh) of electrical energy from the wind power is the cheapest. It is competing almost at par with the other fossil fuel power plants. All this has become possible because of the recent advancements in electrical, mechanical, power electronics, digital electronics, materials and other branches of engineering, which are used in renewable energy technologies.

Although the earlier jointly authored book *Wind Power Plants and Project Development* along with Tore Wizelius was written to cater to industrial need, it was also well received by the academia and training organisations, as such information was not available in other Indian books. Therefore, it dawned on the author that there was a niche for an additional book on "wind" to fulfil the needs of the Indian universities. It is in this backdrop that this book *Wind Power Technology* got evolved and now revised to the third edition. Along with the former, this book has been proved as a good additional resource material to satisfy the needs of various curricula of different universities and also for those who are interested in developing a deeper understanding of modern wind power plants.

With the race hotting up, China overtook the USA to occupy the top slot with the largest capacity of installed wind power plants in the world, a position long held by the USA for the last several decades. India is also not far behind and is in the fourth position. In this changed industrial scenario of renewable energy, a number of universities across India have revised their curricula to give a greater focus to wind power and renewable energy courses and also to include exclusive wind power courses in various short and long term engineering and training programmes.

As a result of research and development, the capacities of the large wind turbines are continuously increasing, the largest one today being the 7.58 MW Enercon wind turbine, they behave almost similar to the conventional power plants and therefore, the term wind power plant (WPP) is more relevant. Since the modern WPP integrates the technologies from various branches of engineering, all the chapters of this book focus on the various technological principles of these branches that govern the functioning of a typical modern wind turbine. The concepts and principles have been written in such a manner that most of the students of the various branches of engineering would be able to acquire the requisite knowledge to understand the broad-based technology of the wind turbine.

A unique feature of this book is that along with every figure title, a brief explanation that follows helps the reader to understand without referring to the relevant paragraphs again and again. Another salient feature is that the learning outcome expected to be developed in the student is provided on the title page of every chapter, thereby helping the reader to focus better on how to learn. Moreover, worked-out examples are given at relevant places and exercises are given at the end of the chapters to cement the learning further.

To address some specific curricular needs, Chapter 1 of this book begins by explaining the basic working principles of the various types of electricity generating renewable energy technologies and the tremendous potential that they have in India including the significance of wind power. Chapter 2 discusses the wind characteristics that are necessary to be understood in the context of electricity generating WPPs.

The WPP being a classic example of a mechatronic machine, Chapter 3 describes the functions of various components of this state-of-the-art electricity producing WPP. Chapter 4 explains the working principles on the basis of which the WPPs are designed to convert most efficiently the wind energy into useful electrical energy.

For safety and to maximise electricity production, Chapter 5 elaborates the various strategies that can be adapted to aerodynamically control the WPP. Apart

from the aerodynamic control, there are electrical and electronic control strategies for additional control of the WPP that are explained in Chapter 6.

WPPs are broadly classified as constant speed and variable speed WPPs. With considerable amount of research and development being undertaken across the world, state-of-the-art wind power technologies are adapted for these different categories of WPPs and explained lucidly using relevant visuals and diagrams in Chapter 7 and Chapter 8.

Chapter 9 discusses about the electrical power quality produced by the different types of WPPs, while Chapter 10 explains how the different issues are resolved to integrate this green power into the electrical grid network supported by worked-out examples and some software simulations as well.

The rest of the chapters will also be of special interest to the students. Chapter 11 on *Wind Resource Assessment Technologies* describes the different types of wind related sensors necessary to determine the wind potential at a particular site. Chapter 12 discusses some of the major *Design Considerations of WPPs* supported by some worked-out examples as well.

All those enthusiasts of small wind turbines will be very happy to read Chapter 13. It explains in detail the essentials related to various types of small wind turbine technologies hardly found in a single book. *Wind Project Life Cycle* a concept in the curricula of some Indian universities is discussed in Chapter 14.

Chapter 15 on *Electronics in Renewable Energy Systems* is a new chapter in this edition and will help all students interested in the electronics related to this area.

Finally, to solve the energy crisis, the authors wish that this book may serve to advance in the greater use of renewable energy and wind power technology in particular.

Best wishes for a smooth sailing through this book.

Joshua Earnest
Sthuthi Rachel

Acknowledgements

First and foremost, the authors would like to thank Jesus GOD and LORD, who empowered them and taught them wind power technology, and spurred them to write this, much needed book for the university students, a unique book of its kind.

The first author thanks to one of his mentors and friend Tore Wizelius, the 'Guru of Swedish Wind Power' and co-author of his first book *Wind Power Plants and Project Development* for the encouragement to write this book to cater to the needs of the university system and for some unique ideas that are reflected in different sections of this book.

The authors are grateful to all those wind power plant manufacturers, individuals and other websites who have extended their cooperation directly or indirectly in permitting them to use the pictures duly acknowledged under each visual and thus, help in the cause of spreading the knowledge of this green and clean energy. The authors also thank the National Renewable Energy Laboratory (NREL) and DOE—Subcontract Report NREL/SR-500-35524, entitled *Northern Power Systems WindPACT Drive Train Alternative Design Study Report; Period of Performance: April 12, 2001 to January 31, 2005,* by G. Bywaters, V. John, J. Lynch, P. Mattila, G. Norton, J. Stowell, M. Salata, O. Labath, A. Chertok, and D. Hablanian for use of their pictures.

The first author extends his thanks to the feedback of his students spread over different continents of the globe who have attended his wind power training programmes over the past several years, whom he taught in the face-to-face sessions, conference rooms during the wind farm visits and also in the e-classroom of the distance mode training programmes offered by National Institute of Technical Teachers' Training and Research (NITTTR) Bhopal.

Here, the authors would like to admit that the concepts, ideas and discussions contained in this book are also the result of the interactions with various wind power plant manufacturers, their brochures, Websites, wind farm developers and

authors of wind related books. They are also thankful to the authors of various journal papers, research reports, conference proceedings, and monographs which they have referred to extensively and duly acknowledged them in the bibliography.

The first author is also grateful to Thomas Ackerman, author of *Wind Electric Systems* and founder, Energynautics GmbH, Germany as well as to his close friend Sven Ruin, CEO of Teroc, Sweden, who has given him valuable feedback regarding the earlier wind power book. He also owes his sincere thanks to his friend Henk Polinder of Delft University, The Netherlands, whose numerous papers, articles and discussions have considerably educated him about wind power. His thanks also go to his close friends Lars Hallen, Founder & Chairman, LIFE Academy, Sweden and Bo Gillgren for their encouragement. Special thanks are due to his friends of the Union of Evangelical students of India, whose encouragement and prayers spurred him on in this endeavour. He would also like to thank his colleagues Ms. Susan S. Mathew, A.S. Walkey, Shashikant Gupta, N.P. Patidar and other friends and well-wishers who have directly or indirectly supported him in this book writing project. He also grateful to Aditya Patil, PRDC, Bangalore, and Dr. Vinod Kumar of Maharana Pratap Univesity, Udaipur, Rajasthan for their valuable academic inputs.

The authors would also like to thank Dr. C. Thangaraj, Director of National Institute of Technical Teachers' Training Institute, Bhopal, India, for his constant support to academics, writing and publishing.

The authors appreciate the work of Ms. Shivani Garg, Ms. Babita Mishra, Ms. Lakshmi, Mr. Suman Kumar and Mr. Ajai Kumar Lal Das of PHI Learning for their meticulous work in meeting the publishing deadline.

Last, but most important, the authors thank to the unstinting support of Mrs. Bindhu Joshua, who has greatly sacrificed many of her precious hours and encouraged them in completing this book during these long years. They would like to express their deep gratitude to her from the bottom of their hearts.

Joshua Earnest
Sthuthi Rachel

Contents

List of Symbols/Notations

Symbols/ Units	***Main use of the Symbols in this Book***	***Other Uses/Comments***
α	Angle of attack	—
β	Blade pitch angle	—
γ	Kinematic viscosity of fluid	—
δ	Load angle (angle between the rotating magnetic field of electrical machine)	Yaw angle of a WPP
λ	Tip speed ratio	—
σ	Solidity	Standard deviations (SD)
θ	Angle between voltage and current	—
φ	Flux density and power factor (cos φ)	Inflow angle (fabrication angle)
ω	Angular velocity (rad/s)	—
ψ	Flux	Could be stator/rotor flux
ρ	Density of air (kg/m^3)	—
ρ_a	Area density (kg/m^2)	—
η	Efficiency	—
η_g	Efficiency of gearbox	—
η_e	Efficiency of electrical generator	—
A	Swept area of WPP rotor (m^2)	—
a	Ampere–current	—
B	Flux density	—
c	Shape parameter of Weibull probability function	—
C	Capacitance (F)	—
C_D	Drag coefficient	Dimensionless number

Symbols/ Units	***Main use of Symbols in this Book***	***Other Uses/Comments***
C_L	Lift coefficient	Dimensionless number
C_M	Pitching moment	Dimensionless number
C_p	Power coefficient or aerodynamic efficiency	Dimensionless number
C_T	Torque coefficient	Dimensionless number
D	Diameter of wind turbine rotor	Diameter of electrical generator
Dg	Air gap diameter	—
E_A	Generate voltage	—
E	Lift-to-drag ratio	—
E_{year}	Energy content of the wind during a year	—
f	Frequency	—
f_s	Shear stress (Pa or N/m^2)	—
f_d	Tangential force	—
F_{circ}	Circumferential or driving force applied in the plane of rotation and helps the rotor to rotate and produce the useful power	—
F_d	Drag force	—
F_L	Lift force	—
F_{res}	Resultant force	—
F_{torque}	Torque producing force	—
F_{thrust}	Useless force, gets applied perpendicular to the plane of rotation which tries to bend the WPP tower	—
g	Gravity	—
G	Giga (10^9)	Shear modulus
H	Hub height or height of obstacle	—
I	Polar mass moment of inertia	—
J	Polar area moment of inertia	—
k_T	Torsional spring constant	—
K	kelvin (absolute temperature measurement)	—
L	Lift of the wind turbine blade	Inductance of a winding or coil
l	litre	
l_s	Axial length of generator stator	—
I	Current	—
I_F	Fault current	—
J	Polar moment of inertia of the wind turbine rotor	—
k	Shape parameter of Weibull probability function	kilo (10^3)
M	Mega (10^6)	—
m	Metre	Mass or milli (10^{-3})
mb	Milibar (ambient pressure measurement)	—
m/s	Metre per second	—

Symbols/ Units	*Main use of Symbols in this Book*	*Other Uses/Comments*
μ	Micro (10^{-6})	—
n	Number of wind turbine rotor blades	—
N	Revolutions per minute	—
Nm (N)	newton meter (unit of force in SI units)	—
N_s	Synchronous speed of generator	—
P	Active power (kW)	—
p	Number of poles of an electrical generator	Air pressure
p.u.	Per unit	—
P_e	Electrical power delivered by the generator	—
P_{kin}	Kinetic power in wind or energy/second (W or J/s)	—
P_m	Mechanical power produced by the wind turbine rotor	—
Q	Reactive power kVAr	—
R	Radius of rotor	Resistance
R_A	Armature resistance	—
R_k	Reactance of grid	—
R_e	Reynolds number	—
s	Second	Slip of induction generator
S_s	Speed of sound	
S_{sc}	Short circuit power	—
T	Torque	Time (s); period of rotation of rotor; tera (10^{12}), and tesla
T_{aero}	Aerodynamic torque of wind turbine rotor shaft	—
T_{gen}	Torque of electrical generator rotor shaft	—
U	Potential energy of wind turbine shaft	—
V	volt	—
V_G	Generating voltage	—
V_S	Transmission (or sending end) voltage	—
v	Wind velocity (m/s)	—
v_d	Downstream wind velocity after energy is extracted and passing through the blades of the rotor	—
v_h	Number of hourly wind speed values during the month	—
v_{mean}	Mean wind speed	—
v_o	Undisturbed wind velocity before impinging on wind turbine rotor	—
v_{tip}	Wind velocity at blade tip	—
W	watt	—
X	Reactance	—
X_k	Reactance of grid	—
X_s	Synchronous reactance	—
Z	Impedance	—

Acronyms and Abbreviations

AC	Alternating Current
AD	Accelerated Depreciation
ADC	Analogue to Digital Converter
AEP	Annual Energy Production
AF-PMSG	Axial Flux Permanent Magnet Synchronous Generator
agl	Above ground level
ANSI	American National Standards Institute
ASC	Active-Stall Control
AWEA	American Wind Energy Association
BDIG	Brushless Doubly-fed Induction Generators
BJT	Bipolar Junction Transistor
BWEA	British Wind Energy Association
CCT	Critical fault Clearing Time
CDM	Clean Development Mechanism
CEA	Central Electricity Authority
CER	Certified Emission reduction Receipt
CFD	Computational Fluid Dynamics
CFRP	Carbon Fibre Reinforced Polyester
CHB	Cascaded H-Bridge
CMS	Condition Monitoring System
CoE	Cost of Energy
CRGO	Cold Rolled Grain Oriented
CSI	Current Source Inverter
CSP	Concentrating Solar Power
CTU	Central Transmission Utility
dB	Decibel (measure of sound levels)
DAC	Digital to Analog Converter

DC	Direct Current
DDT	Dichloro-Diphenyl-Trichloroethane (pesticide)
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DisCom	Distribution Company
DMPPT	Decentralised maximum power point tracker
DNES	Department of Non-conventional Energy Sources
DNO	Distribution Network Operator
DST	Department of Science and Technology
DVR	Dynamic Voltage Restorer
EIA	Environment Impact Assessment
EMI	Electro Magnetic Interference
EPF	Energy Pattern Factor
EU	European Union
EWEA	European Wind Energy Association
FACTS	Flexible AC Transmission System
FRT	Fault-Ride-Through (similar to LVRT)
GBI	Generation-Based Incentive
GEDA	Gujarat (and Goa) Energy Development Agency
GIS	Geographical Information Systems
GMT	Greenwich Mean Time
GPRS	General Packet Radio Service (used by GSM mobile phones)
GR	Gearbox Ratio
GRP or GFRP	Glass-fibre Reinforced Plastic
GSC	Grid-Side Converter
GTO	Gate Turn-On Thyristor
GWh	Gigawatt hours
HF	High Frequency
Hg	Mercury
HWRT	High Wind Ride Through
Hz	hertz [i.e., electric power frequency (in cycles per second)]
IC	Integrated Chips
IEA	International Energy Agency
IEA 2003	Indian Electricity Act 2003
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
IG	Induction Generator
IGBT	Insulated Gate Bipolar Transistor
IGCT	Integrated Gate Commutated Thyristor
IREDA	Indian Renewable Energy Development Agency
JNNSM	Jawaharlal Nehru National Solar Mission
kVA	kilovolt ampere
kVArH	kilovolt ampere reactive hours
kW	kilowatt
kWh	kilowatt hours

LAN	Local Area Network
LIDAR	LIght Detection And Ranging
LV	Low Voltage
LVRT	Low Voltage Ride Through
MCS	Micro-generation Certification Scheme
MNRE	Ministry of New Renewable Energy
MOSFET	Metal Oxide Field Effect Transistor
MPPT	Maximum Power Point Tracking
msl	Mean sea level
MV	Medium Voltage
MW	Megawatt
MWh	Megawatt hour
NACA	National Advisory Committee for Aeronautics
Nd-Fe-B	Neodymium-iron-boron
NFYP	National Five Year Plan
NIWE	National Institute of Wind Energy, Chennai, India
NPC	Neutral Point Clamped
NPS	Negative Phase Sequence
O&M	Operation and Maintenance
OLTC	On load tap changing (for transformer)
OSIG	Opti-Slip Induction Generator
OTEC	Ocean Thermal Energy Conversion
PC	Personal Computer
PCC	Point of Common Connection (same as POI)
PEC	Power Electronic Converter (Circuits)
PFC	Power Factor Correction
PLC	Power Line Communication
PLC	Programmable Logic Controller
PM	Permanent Magnet(s)
PMSG	Permanent Magnet Synchronous Generator
POI	Point of Interconnection (same as PCC)
PPA	Power Purchase Agreement
PV	Photo Voltaic
PWM	Pulse Width Modulation
R&D	Research and Development
REC	Renewable Energy Certificates
RF-PMSG	Radial flux Permanent Magnet Synchronous Generator
RLDC	Regional Load Despatch Centres
RoCoF	Rate of Change of Frequency
RPM	Revolutions Per Minute
RPO	Renewable Purchase Obligation
RSC	Rotor-Side Converter
SAPS	Stand Alone Power Systems
SCADA	Supervisory Control And Data Acquisition
SCIG	Squirrel Cage Induction Generator

SCR	Silicon Controlled Rectifier
SERC	State Electricity Regulatory Commission
SODAR	SOnic Detection And Ranging
SPV	Solar Photo Voltaics
SR	Spinning Reserve
SSC	Static Series Compensator
STATCOM	STATic (Synchronous) COMpensator
SVC	Static VAr Compensators
SWCC	Small Wind Certification Council
T&D	Transmission and Distribution
TCR	Thyristor Controlled Reactors
TCS	Thyristor Switched Capacitors
TF-PMSG	Transverse Flux Permanent Magnet Synchronous Generators
THM	Top Head Mass
TSO	Transmission System Operator
TSR	Tip Speed Ratio (or Thyristor Switched Reactor)
TWh	Terawatt hours
Type-A	Constant speed WPP
Type-A0	Constant speed WPP with stall regulation
Type-A1	Constant speed WPP with pitch regulation
Type-A2	Constant speed WPP with active-stall regulation
Type-B	Narrow range speed WPP
Type-B0	Narrow range speed WPP with stall regulation
Type-B1	Narrow range speed WPP with pitch regulation
Type-B2	Narrow speed WPP with active-stall regulation
Type-C	Limited range speed WPP
Type-C0	Limited range speed WPP with stall regulation
Type-C1	Limited range speed WPP with pitch regulation
Type-C2	Limited range speed WPP with active-stall regulation
Type-D	Wide range speed WPP
Type-D0	Wide range WPP with stall regulation
Type-D1	Wide range WPP with pitch regulation
Type-D2	Wide range WPP with active-stall regulation
VAr	volt ampere reactive
VSC	Voltage Source Converter
VRLA	Valve Regulated Lead Acid (batteries)
VSI	Voltage Source Inverter
WEC	Wind Energy Converter
WEG	Wind Energy Generator
WFMS	Wind Farm Management System
WPP	Wind Power Plant
WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator

1

Renewable Energy Technologies

...HE makes the wind blow, and the waters flow
—Psalm 147:18

Learning Outcome

'On studying this chapter, you will be able to justify the need and potential of renewable energy technologies and even designing a simple domestic solar PV system'.

CHAPTER HIGHLIGHTS

1.1 *Introduction*
1.2 *Renewable energy sources bridging the energy gap*
1.3 *Small hydel power plants*
1.4 *Geothermal power plants*
1.5 *Solar power plants*
1.6 *Biomass power plants*
1.7 *Ocean energy power plants*
1.8 *Wind power plants*
1.9 *Drivers and bottlenecks for wind power development*
1.10 *Strengths and limitations of wind power*

1.1 INTRODUCTION

Renewable energy can be defined as the energy sources that are natural and continually replenished either at the same rate or faster than the rate at which they are being used up by humans more or less indefinitely such as the sun, wind, rain, tides, biomass and geothermal energy. *Green energy*, *alternative energy* and *sustainable energy* are the other synonyms sometimes used to describe the renewable energy that is converted into either electricity, heat or mechanical power for use in homes or in industries by clean, harmless and non-polluting methods. But it is important to understand the differences between the technologies used by each of the different sources to make the right choice for any particular application.

The crude oil crisis which began in 1971 and the continuously increasing prices for fossil fuels, has adversely affected the economic growth of developing countries. This woke up the world to look for the alternative and sustainable energy solutions. Therefore, energy security calls for using renewable energy resources. With rapid economic growth, the demand for energy is increasing. Energy is by far the largest industry in the world. It is worth about US $ 7 trillion per year while the world's total GDP is about US $ 55 trillion. Thus, the energy industry is worth more than 10% of the entire world's economy. As reported by Renewable Energy World Magazine in their February 2, 2018 Issue, for the first time in history in 2017 in the 28 nation European Union, the power from renewables generated jointly by wind, solar and biomass was an all time high of 20.9% of all power, overtaking the power generated by coal which was down to 20.6%.

Since 1980s, the government of India (and many other governments) has introduced myriad of incentives for the use and promotion of renewable energy sources. This chapter has been written to make the reader aware of the vast potential of renewable energy and it also provides an overview of the various renewable energy technologies. It is expected that this chapter will encourage and motivate the reader to undertake further study and research with the ultimate aim to make the concerned renewable energy technology efficient, reliable techno-economical and commercially viable for the community at large. Table 1.1 shows a comparison of renewable and conventional energy.

Table 1.1 Comparison of Renewable versus Conventional Energy

S.No.	Criteria	Renewable Energy	Conventional Energy
1	Availability	Can be used without any treatment	Needs to be extracted and treated through laborious and environmentally damaging processes
2	Quantity available	Continuously replenish-able resource	Dwindling reserves
3	Transportability	No need to transport, used where it is available	Needs to be transported from the site rendering it environmentally harmful
4	Green house gases (GHG)	Nil	Releases green house gases
5	Energy security	Minimises reliance on dwindling resources such as oil, coal and others	Energy security remains at risk due to more dependence on oil
6	Pollution	Completely pollution-free	Pollution occurs at various levels

1.2 RENEWABLE ENERGY SOURCES BRIDGING THE ENERGY GAP

India is world's 3rd largest producer (3,44,690 MW) and 3rd largest electrical energy consumer as on September 2018. Massively expanding the large scale deployment of both centralised and distributed renewable energy including solar, wind, small hydro, biomass, and geothermal will ease the strain on the present transmission and distribution systems.

As on September 2018 (see Figure 1.1) India is having the 6th largest installed electric generation capacity of 3,44,002 MW. Of this total installed power, the contribution from thermal power plants is 2,22,906 MW (64.80%), large hydroelectric power plants is 45,293 MW (13.17%), nuclear power is 6,780 MW (1.97%) and that from all renewable sources put together is 70,648 MW (20.54%).

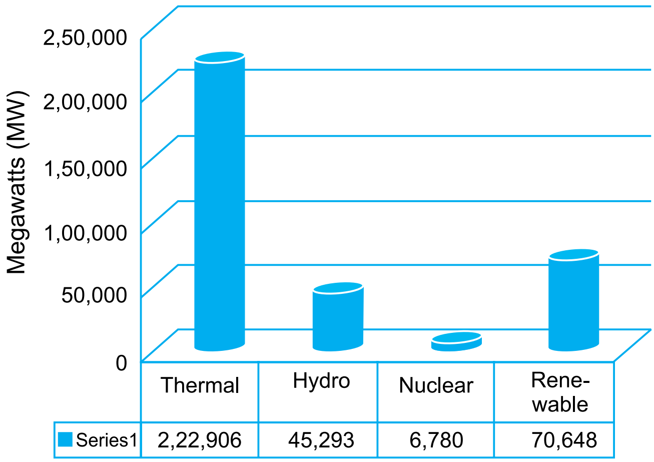


Figure 1.1 Installed Grid Connected Electrical Capacity in India (MW): As on September 2018.

The grid connected renewable energy in India is (see Figure 1.2): 70,648 MW (on September 2018), wind power 34,294 MW (9.9%) small hydro—4,493 MW (1.3%), biomass—8,839 MW (2.6%), Solar PV—23,023 MW (6.7%). India plans to make a massive switch over from coal, oil, natural gas and nuclear power plants to renewable energy power plants, as MNRE has targeted to have an installed capacity of 1,00,000 MW of solar power and 60,000 MW of wind power by the year 2022. The large scale deployment of solar and wind power projects which represent a bright spot on India's economic future needs to be continued even at a quicker pace in order to effect the smooth transition from fossil fuels to renewable energy sources.

In 1982, the foundation stone for harnessing renewable energy was laid in India by the establishment of the Department of Non-Conventional Energy Sources (DNES). In 1992 the DNES was converted into the Ministry of Non-Conventional Energy Sources (MNES) and later in 2006 it was re-christened as Ministry of New and Renewable Energy Sources (MNRE).

In order to fully exploit the indigenous renewable energy sources at its doorstep, the MNRE has been addressing several challenges to remove the barriers that are holding back the development, by formulating suitable policies and setting up demonstration

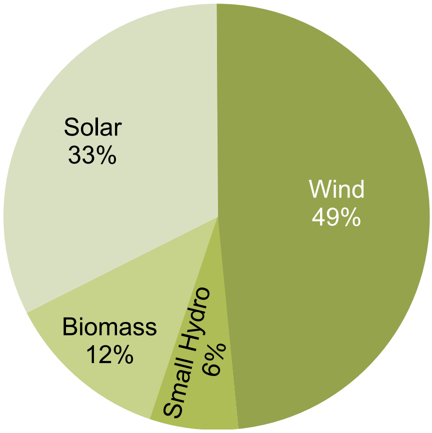


Figure 1.2 Overview of Grid Connected Renewable Energy Capacity in India (MW): As on September 2018.

projects for various types of renewable energy power plants in various parts of India build up investor confidence and to promote research even in the private sector.

Table 1.2 depicts the presently available potential of the grid connected renewable sources in India.

Table 1.2 Potential of Grid Connected Renewable Energy in India

S.No.	Renewable Energy Source	Potential Capacity	Assumed PLF (%)
1	Wind power	1,00,000	25
2	Small hydro power	15,000	45
3	Bagasse power	5,000	60
4	Biomass power	16,881	60
5	Waste-to-power	5,000	60
6	Solar CSP-based power	2,00,000	35
7	Solar PV power	2,00,000	20
8	Geothermal power	10,000	80

The initial policy support for renewable energy began in 1993 when MNES issued guidelines for purchase of power prescribing the power purchase tariff of ₹ 2.25 kWh with annual escalation of 5% for the power generated from renewable energy sources.

The renewable energy initiatives got a shot in the arm with the enactment of Indian Electricity Act 2003 and the State Electricity Regulatory Commissions (SERC), which states that *every utility will have to mandatorily purchase the energy from the renewable energy sector*. In 2011, the trading of renewable energy certificates (REC) started in India in line with the renewable purchase obligations (RPO) by various states of India. Under the National Action Plan for Climate Change (NAPCC), the government has set a goal for 15% of renewable energy (excluding the large hydroelectric power plants) and 15% of wind power by 2020 to promote renewable energy. India has reiterated its commitment by upscaling the renewable energy target to 175 GW capacity by 2022 to provide equitable sustainable development.

Table 1.3 provides an overview of the capital cost for 1 kW of energy and generation cost of 1 kWh of electrical energy from various energy sources.

Table 1.3 Energy Costs from Different Types of Energy Sources

S.No.	Energy Source	Capital Cost of 1 kW (Indian Rupees)	Generation Cost of 1 kWh (Indian Rupees)
1	Natural gas	27,500 to 82,500	2.16 to 3.38
2	Coal	1,04,500 to 3,19,000	1.08 to 2.16
3	Nuclear	2,47,500 to 4,12,500	15.66
4	Geothermal	1,40,400 to 1,89,400	5.4
5	Solar thermal	1,62,000 to 2,70,400	3.24 to 8.1
6	Solar photovoltaic	60,000 to 95,000	3.0
7	Wind	70,200 to 1,35,000	2.43 to 5.4
8	Biomass	Differs with technology	2.43 to 5.4
9	Tidal	Differs with technology	5.4
10	Wave	Differs with technology	6.48

1.3 SMALL HYDEL POWER PLANTS

A small hydroelectric (*hydel*) power plant essentially uses water pressure to drive a turbine, which in turn feeds into a generator that creates electricity. The small hydel power plant potential already identified in India is 15,000 MW, is largely unexploited (see Figure 1.2). Small hydel schemes use small dams or weirs, water storage reservoirs or diversion of the rivers' water flow through tunnels or canals. Many of the hydel plants in India could be seasonal especially in the hilly regions during the rainy season and can be used to power single properties or small villages, depending on the size of the installation.

Microhydro plants typically below 100 kW basically consist of two types: impulse and reaction type. *Flow* is the speed of water passing in each second. The rate of flow is called *flow rate* (Q) measure in litres per second. *Head* (H) is the vertical level difference of water in metres from the source (say settling tank) to the turbine level. The greater is the head, the greater will be the power output. The types of turbine to be chosen depend on the 'flow rate' and the 'head' of the source of water flow that is available. The amount of potential energy available at a site can be determined by multiplying the 'head' (in metres) by the 'flow rate' (litres per second) by 9.81 m^2 (gravity).

The power 'P' available from a hydel power plant is given by:

$$P = \eta G H Q \tag{1.1}$$

where,

η = Efficiency of the hydro turbine (between 80%–95%)
G = Gravitational constant (9.81 m/s^2)
Q = Flow rate of water (in cubic metre per second)
H = Head of water (in metres)

EXAMPLE 1.1

A small stream drops 30 m down the side of a mountain producing a water flow rate of 700 l/min past a fixed point. How much power could a small hydel power plant generate, if the type of water turbine used has a maximum efficiency (η) of 90%?

Solution:

$$P = \eta G H Q$$

where,

η = 90%

G = 9.81 m/s^2

H = 30

Q = 0.01166 m^3/s (i.e. 1000 l is equal to 1 m^3, so 700 l is equal to 0.7 m^3. One minute is equal to 60 s, then flow rate of 0.7 m^3/min is equal to 0.01166 m^3/s)

$$\therefore \quad P = 0.9 \times 9.81 \times 0.01166 \times 30$$

$$P = 3.088 \text{ kW}$$

i.e., equivalent to over 27,054 kWh, i.e., (i.e., 3.088 × 24 × 365) of free hydroelectricity annually.

1.3.1 Types of Impulse Turbines

These 'high head' water turbines rely on the force of the water striking the water wheel impellers. The impulse types are more popular as they are essentially simpler in design and therefore have relatively less maintenance issues as compared with reaction types.

Pelton turbines are essentially small cup shaped buckets arranged around a wheel. In this system, the water is pushed through a gradually narrowing pipe to increase the pressure as it reaches the turbine and strikes the buckets to cause it to move and turn the electric generator connected to it. It operates most efficiently at high head and low flow situations.

The *Turgo impulse* wheel turbine is a more efficient version of the Pelton turbine. Here also the water pressure is increased by the narrowing pipe, but the water jet is angled in such way that it hits more of the cup shaped buckets to create a faster revolution.

1.3.2 Types of Reaction Turbines

The reaction turbines are highly site specific and are scaled down versions of the Francis turbine and Kaplan turbine. The rotations of the turbines depend on the pressure created by the water rather than the speed with which it hits the turbine. The designs of the impellers of these two types of turbines are also different. They are highly efficient compared to the impulse turbines.

The *Francis turbine* is a device that has a spiral casing where the water is directed through vanes on a rotor. It is used in medium head and high flow situations.

The *Kaplan turbine* (also called *Propeller turbine*) acts like the propeller of a boat adjusting to the flow of water.

Continued research and development of these technologies can still be undertaken for commercially profitable business in India.

1.4 GEOTHERMAL POWER PLANTS

Geothermal energy makes the use of the energy stored as heat in the water deep below the earth's surface. Different types of geothermal energy are given below:

- **Direct geothermal energy** wherein the geothermal hot water is available very close to the earth's surface that can be used directly for heating, bathing or washing.
- **Ground source geothermal** wherein the geothermal hot water resource is a little deep, but by boring it can be accessed for heating, bathing or washing.
- **Geothermal power plants** wherein the hot water (having very high temperature) or steam is deep underground, but can be accessed by boring for generating geothermal steam and then, the electricity.

Although not exploited, India's geothermal potential stands at 10,600 MW of power (see Figure 1.3). Ministry of New and Renewable Energy (MNRE) of India has already taken an initiative for implementing the demonstration projects in geothermal

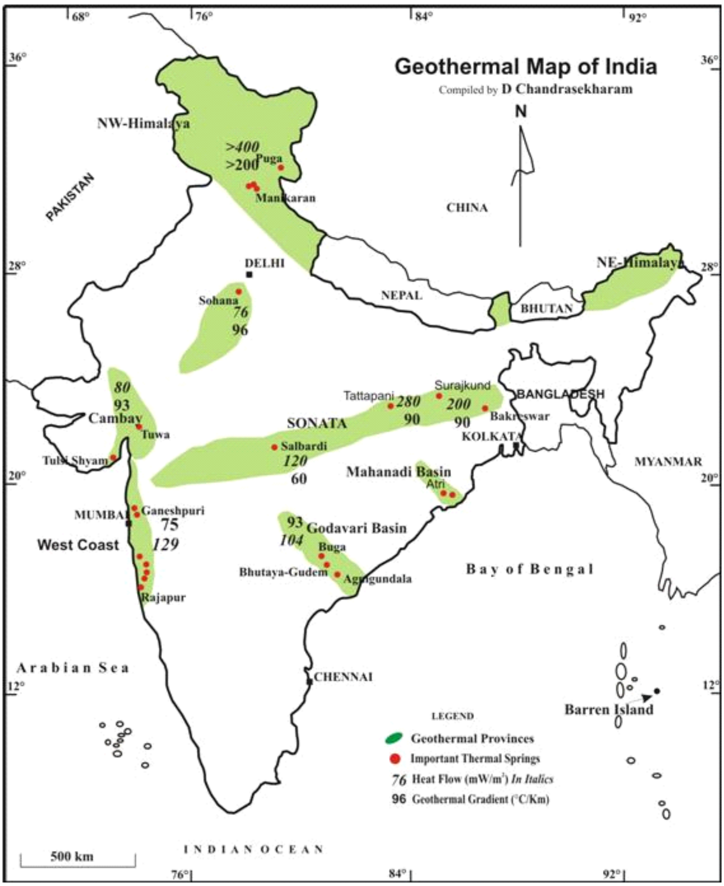


Figure 1.3 Geothermal Map of India (mW/m^2).
Courtesy: www.renewbl.com.

energy. Under this programme, geothermal resource assessment studies will be supported for bringing the data on potential geothermal energy exploitation sites, especially in the states of Jammu and Kashmir, Himachal Pradesh, Uttarakhand, Chhattisgarh and Jharkhand.

1.5 SOLAR POWER PLANTS

Sun is the prime free source of inexhaustible energy available to most of the energy sources. Next to wind power, solar power is the fastest growing renewable energy in the world.

Being a tropical country, India is blessed with lots of sunshine for most of the time in a year. India lies in a sunny tropical belt (of high insolation) of total theoretical potential over 5000 trillion kWh annually (see Figure 1.4). Jawaharlal Nehru National Solar Mission (JNNSM) is an example which is initiated by MNRE to tap this resource.

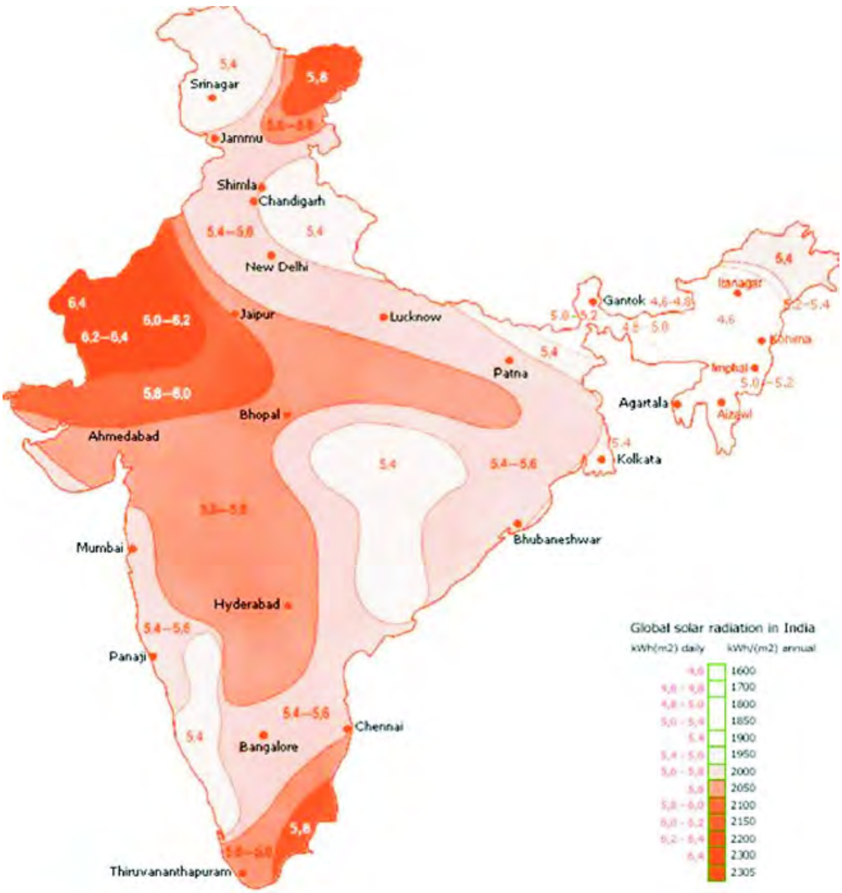


Figure 1.4 Solar Map of India: Annual mean daily global solar radiation in kWh/m^2/day. *Courtesy:* www.renewbl.com

The high costs of solar power have been decreasing significantly with the sharp drop in the prices of solar panels. The current cost of production (after bidding) is around ₹ 3.00 per kWh. This includes operation and maintenance, amortised/depreciated capital costs, loan repayment costs and other expenses such as insurance. With the level of technology advancement that is going ahead, it is expected that the costs of production of solar PV power plants will come down to ₹ 3 per kWh by 2022. Further, with JNNSM and other Generation Based Incentives (GBI) through MNRE, there is a great scope to tap the solar power.

The challenges and constraints for the use of solar power are also there. The per capita land availability is a scarce resource in India. Dedication of land area for exclusive installation of solar panels might have to compete with the other necessities that require land. The amount of land required for utility scale solar power plants (currently, it is approximately 1 km^2 for every 20 MW–60 MW power generated) could pose a strain on India's available land resource.

Although the present high cost of solar PV, high population density (land scarcity) and technology obsolescence are seen as the bottlenecks and barriers, there is still a lot of potential for solar power in India which needs to be tapped.

For producing grid-connected electric power, following two major types of solar energy technologies are commercially viable:

- Concentrated solar power (CSP) technology
- Solar photo voltaic (PV) technology.

The government of India is expected to spend $19 billion on these till 2022. By putting solar CSP and solar PV together, JNNSM attempts to reach an installed capacity of 100 GW by 2022.

1.5.1 CSP Technology

Solar thermal electric energy (STE) generation concentrates the sunlight to create heat in order to run a heat engine which turns a generator to generate electricity. Concentrated solar power (CSP) plants produce electric power by converting the sun's energy into high temperature heat using various mirror configurations. The working fluid in the heat engine that is heated by the concentrated sunlight can be a liquid (water, oil) salts or a gas (air, nitrogen, helium). The amount of power generated by a CSP plant depends on the quality of the reflector design and material and of course, on the amount of direct sunlight impinging on the reflector. The efficiency of a CSP is often between 30% and 40% and is capable of producing considerable amount of kW/MW of power. Today India has only 52.5 MW of CSP projects in operation in different parts of the country.

Heat storage is a far easier and efficient method which makes the solar thermal attractive for large scale energy production as compared to the solar PV which can only work during daylight. Heat can be stored during the day and then converted into electricity at night.

Following are the four commercially accepted CSP technologies for each of which various design technology variations exist:

- Parabolic trough

- Parabolic dish
- Power tower
- Fresnel reflector.

(a) Parabolic Trough

In the parabolic trough system (see Figure 1.5), the sun's energy is concentrated by the parabolically curved, mirrored trough-shaped reflectors. These reflectors direct the solar radiation onto the receivers positioned at the focal point of the reflectors. These receivers are generally of glass tubes containing a fluid (synthetic oil, molten salt or some other) running along the length of the trough.

The focused solar energy heats the fluid flowing through the pipe and this heat energy is used by a special type of boiler to generate steam for running a steam turbine connected to a conventional electrical generator in order to produce electricity fed to the grid. The trough tracks the sun and tilts from east to west so that the direct radiation remains focused on the receiver pipe.

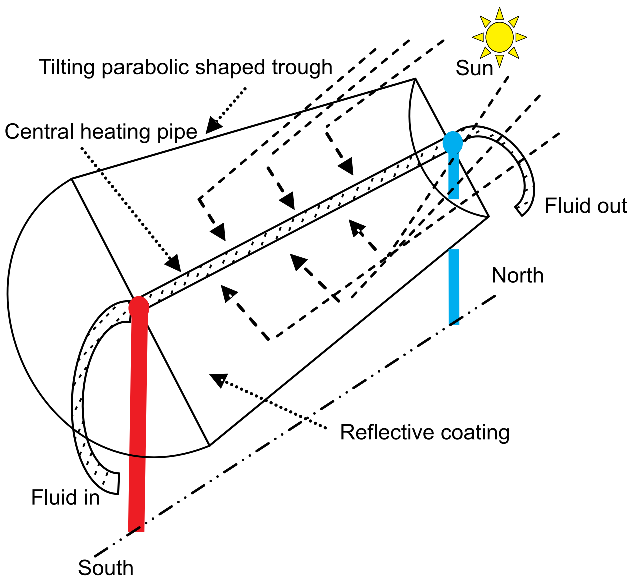


Figure 1.5 Tracking Parabolic Trough System: Parabolic along one axis and linear in the orthogonal axis.

(b) Parabolic Dish

The parabolic dish system consists of a large reflective parabolic dish (similar in shape to satellite television dish, see Figure 1.6). It focuses all the sunlight that strikes on the upper surface of dish onto a single point above the dish where a receiver captures the heat and transforms it into useful electric energy by a heat engine mounted on the receiver moving with the dish structure. This dish has a tracking system so that it follows the sun. Such systems of 6–7 m diameter are available and can yield temperatures upto 3000°C. Such dish systems of 50 kW have peak efficiencies up to 30% as compared to that of the solar PV which is around only 15%.

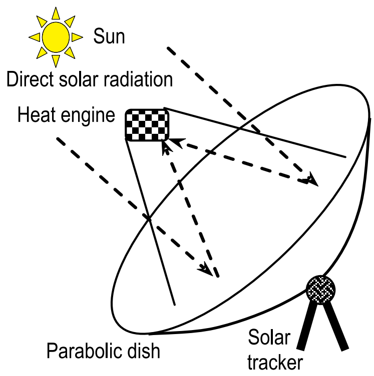


Figure 1.6 **Parabolic Dish:** It focuses the sunlight that strikes on the upper surface of dish onto a single point.

(c) Power Tower

A power tower (see Figure 1.7) consists of central receiver mounted on a tower with several large, sun-tracking flat mirrors called *heliostats* to concentrate sunlight onto it. These heliostats track the sun to concentrate its energy on the receiver as long as the sun shines. A heat transfer fluid is heated in the receiver and then supplied to a special type of boiler to generate steam. The steam is then fed to a steam turbine which is connected to a conventional electric generator to produce electricity fed to the grid network.

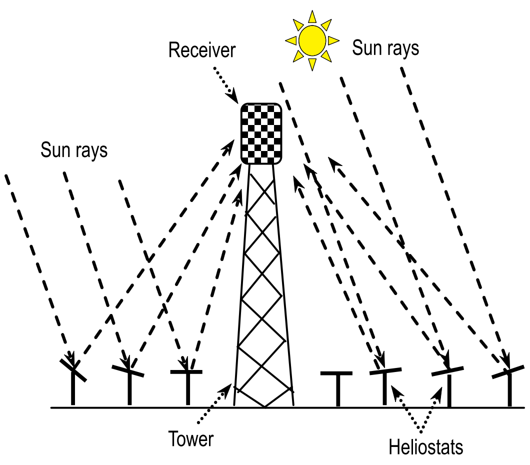


Figure 1.7 **Power Tower:** Heliostats concentrate the sunlight onto the receiver.

(d) Fresnel Reflector

The **fresnel reflector** system (see Figure 1.8) consists of large fields of modular Fresnel reflectors that use a series of long, narrow, shallow flat (or even curved) mirrors to focus the sunlight onto one or more linear receivers positioned above the mirrors as well as onto the stationary receiver present at several metres height.

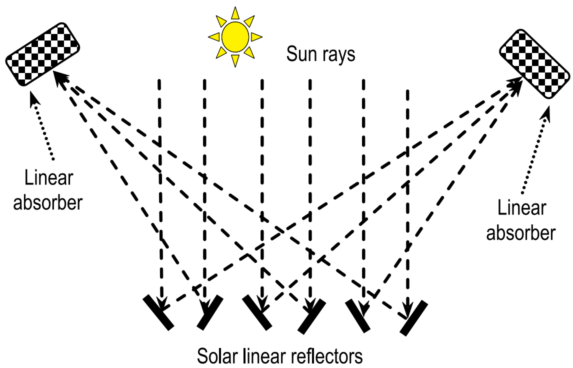


Figure 1.8 **Fresnel Reflector:** Flat mirror strips to concentrate sunlight onto the tubes.

The mirrors (having a width of 0.5 m each) are not completely flat but have a very small curvature which is achieved by mechanical bending. These thin, flat mirror strips concentrate the sunlight onto the tubes through which working fluid is pumped to absorb the heat. Flat mirrors capture more amount of the available sunlight and are much cheaper than the parabolic reflectors. The main advantages of the Fresnel collector system as compared to the trough collectors are as follows:

- Inexpensive planar mirrors and simple tracking system.
- Fixed absorber tube without any need for flexible high pressure joints.
- Due to the planarity of the reflector, wind loads are substantially reduced. So, the reflector width for one absorber tube can easily be three times the width of parabolic troughs.
- Due to direct steam generation, no heat exchanger is necessary.

1.5.2 Solar PV Technology

The government of India is providing considerable incentives for promoting the use of solar photovoltaic (PV) systems (see Figure 1.9) consisting of a sequence of series and parallel connected PV cells. A PV cell (see Figure 1.10) is a wafer made of semiconducting material such as silicon that absorbs the sunlight. The solar cell (PV) systems convert sunlight directly into electricity.

(a) PV System

Due to the irradiance of sunlight, the electrons (negatively charged) are knocked loose from their atoms allowing them to flow through the material to produce a variable direct current (DC) at a fixed open circuit voltage (V_{oc}) of about 0.5 to 0.6 volts at 25°C depending upon the type. This PV cell voltage remains fairly constant (see Figure 1.11) as long as there is a sufficient irradiance of light from dull to bright sunlight. The PV cell converts only a small fraction of the irradiance into electrical energy (less than 20%), the balance is converted into heat, resulting in the heating of the cell.

Figure 1.9 **Solar PV System:** A typical rooftop monocrystalline solar PV system in Madhya Pradesh, India. The title picture of this chapter is an example of a polycrystalline PV system. *Picture by author.*

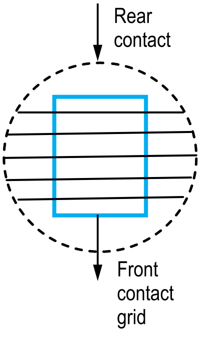


Figure 1.10 **Solar Cell.**

When connected to an external load, the output voltage of the PV cell drops and this is due to the resistance and resulting power losses within the cell structure.

In solar PV parlance, *full sun* can be defined when a solar cell (PV) gives 1000 W/m^2 or 1 kW/m^2 at midday at the equator. Less than full sun will reduce the current output of the cell proportionally. Under the standard conditions of sunlight and temperature with no shading (full sun), the *I–V* (current-voltage) curves (see Figure 1.11) of a solar PV cell are generally given by the manufacturers. There is only one point on the characteristic at which the maximum electrical power is produced.

In practical applications, the *I–V* characteristics keep on changing with changing the insolation and temperature. Hence, an electronic maximum power point tracker (MPPT) need to be introduced between the PV system and the load.

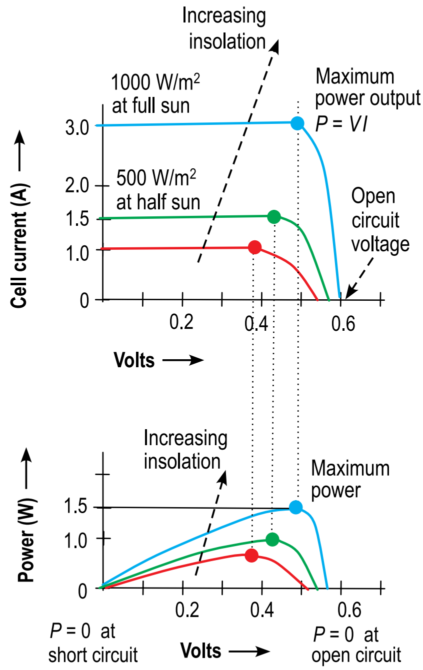


Figure 1.11 **Typical *I-V* and *P-V* Curves of Solar *PV* Cell:** The cell open circuit voltage V_{OC} is almost flat even when the solar insolation increases the power is also reduced to almost half.

However, contrary to the voltage of the PV cells, the output DC current *I*, is directly proportional to the amount or intensity of the sunlight (photon energy) falling on the face of PV cell. Thus, the output current is directly proportional to the cell's surface area, i.e., larger the cell area for the sunlight to impinge, more will be the current produced by it (see Figure 1.12).

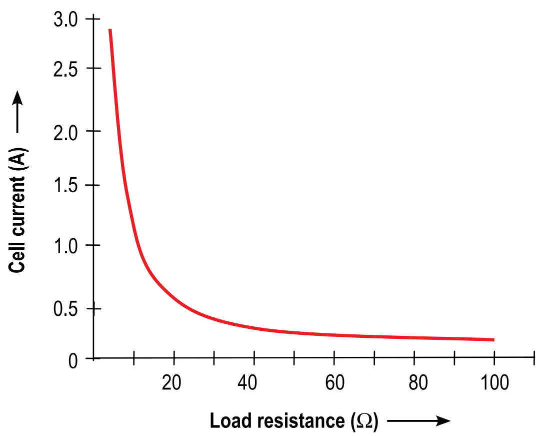


Figure 1.12 **Typical Solar Cell Current Parameters:** The cell current I_L decreases rapidly as the load resistance increases.

The conversion efficiency of a solar cell is the ratio of the electrical output to the incident solar power and this is in the range of 12%–15% for commercially available single solar cells.

A number of series or parallel connected solar cells are put together to make a *module*. Typically, each module holds about 40 cells. The module of solar cells converts the solar energy into usable amount of DC. A number of modules are put together and then mounted on a panel to make an *array* (see Figure 1.13). PV arrays can be used to generate electricity for a single building and even for a power plant when these are present in large numbers.

A typical 12 V solar PV panel consisting of 32 or 36 individual cells connected together in a series arrangement gives about 20.8 V peak output (assuming 0.58 V cell voltage) which is enough to charge a standard 12 V battery. Typically, about 10 modules are mounted in a PV array and are fixed onto the iron fixtures of solar panels so that it can withstand the wind and weight.

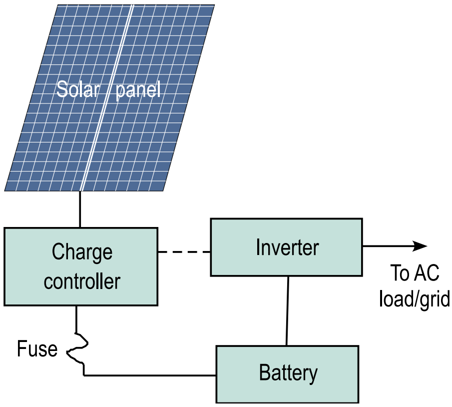


Figure 1.13 PV Array.

Crystalline PV cells are of silicon that is first melted and then crystallised into ingots of pure silicon from which thin slices of silicon wafers are sliced out. Following are the three grades of PV cells in the market:

- A grade PV cells are primarily flawless.
- B grade PV cells are those that contain a visual flaw that does not affect the power. Their price is a little lower than A grade cells.
- C grade PV cells have flaws that affect the power output which is lower quality than A and B grade cells and so the price is also the lowest.

As silicon is a brittle material, the size of the solar cell's area is also limited and the sizes that are generally available are 100 mm diameter or 100 mm (or 125 mm) square single crystalline. There are basically three types of solar cells:

- Amorphous
- Crystalline
  - Monocrystalline silicon
  - Polycrystalline silicon
- Thin film silicon.

Thin film PV is produced by printing or spraying a thin semiconductor layer of PV material on a glass, metal or plastic foil substrate.

Solar PV cells have solar power ratings (in watts):

$$P_m = V_{out} I_m \text{ W} \tag{1.2}$$

where,

P_m = Maximum deliverable solar power or watts
V_{out} = Cell voltage
I_m = Maximum cell current.

If a tracking system is incorporated to the solar PV system, it would track the sun throughout the day from east to west. This solar tracker will help the solar PV panels to have greater amount of full sun time for extracting greater kW from the sun every day.

EXAMPLE 1.2

Calculate the maximum output current of a single 0.55 V silicon photovoltaic cell with a maximum rated power output of 1.85 W at full sun.

Solution:

$$P_m = V I_m \text{ W}$$

$$\therefore \quad I_m = \frac{P_m}{V} = \frac{1.85}{0.55} = 3.63 \text{ A}$$

EXAMPLE 1.3

At full sun, a 0.55 V photovoltaic solar cell produces an output current of 1.79 A. Calculate the maximum power output of the photovoltaic cell in watts.

Solution:

$$P_{max} = V_{out} I_{max} \text{ W}$$

$$\therefore \quad P_{max} = 0.55 \times 1.79 = 0.9845 \text{ W}$$

EXAMPLE 1.4

A solar module has 36 polycrystalline silicon cells arranged in a 9 × 4 matrix. The cell size is 100 mm × 100 mm. Assuming the instant global radiation on the PV system to be 1 kW/m² and the cell efficiency as 13%, calculate how many solar modules will be required to operate a 1/2 HP DC motor of 90% efficiency by a PV system.

Solution:

Solar PV cell areas = $9 \times 4 \times 100 \times 100 \times 10^{-6} = 0.24 \text{ m}^2$

Electric input required by DC motor = $\frac{735}{2} \times 0.9 = 330.75$ W

Solar radiation incident on the panel = 1000 kW/m^2

Cell efficiency = 0.13

Output of solar module = $1000 \times 0.13 \times 0.24$

If M be the number of modules required, then output of the solar array is

$$= 1000 \times 0.13 \times 0.24 \times M = 31.2 \times M \text{ W}$$

If M be the number of modules required, then output of the solar array is the input to the DC motor.

i.e., $$31.2 \times M = 330.75$$

$$\therefore \quad M = \frac{330.75}{31.2} = 10.60 \approx 11$$

Therefore eleven modules are required for the PV array.

(b) Solar Power Inverters

Since the output from a solar PV system is DC, an inverter is invariably needed. An *inverter* is a power electronic device required to convert the low solar DC power into higher AC power of constant frequency and voltage and to make it compatible to be connected to the grid or operate household electrical appliances. The inverters could be stand-alone, grid-tied or battery backup inverters.

A suitable inverter should be selected so that the DC input power rating of the inverter would match the DC power output rating of the solar PV panel or array, which may be based on the maximum load and the maximum surge required. The size of an inverter is measured by its maximum continuous output in watts and this rating must be larger than the total wattage of all of the AC loads connected at the same time.

Generally, the electric home appliances require twice the normal power during the starting time than they require to run. So, this aspect should be considered while sizing the inverter wattage. However, it can also be noted that inverters are capable of delivering three to five times their rated wattage in short term surges and overload conditions.

(c) Batteries for Solar Power

Batteries are essential for any stand-alone or grid-tied solar PV system (see Figure 1.14). They are required for a solar PV system to tide over the cloudy days and the nights. Batteries chemically store electrical energy and the most common varieties are 6 V and 12 V. The useful life of all battery types is measured (rather than units of time) by the number of charge cycles possible; the deeper the batteries are drained each time, the charge cycles will become fewer. Different types of batteries are available. *Primary batteries* are those which can only be discharged and then discarded such as the small alkaline power batteries used in remote controls or cameras.

Deep cycle battery (also called *secondary battery* as they can be continuously charged and discharged) is generally preferred for solar PV systems. It is a lead–acid battery designed to be deeply charged and discharged regularly using most of its capacity. The main requirement for a deep cycle battery is the maximum cycle life, i.e., the number of times in which the battery gets charged and discharged or deep cycled. These batteries could easily last up to five years if the cycles are shallower and even up to ten years or more, i.e., if the state of charge is between 100% and 50% instead of that state which is between 100% and 20%.

Figure 1.14 Solar PV Battery Bank: The battery charged by the solar PV system provides uninterrupted power supply even when sunlight is absent in between.
Picture by author.

Different kinds of batteries are available for solar PV and wind solar hybrid systems. These are:

- Flooded lead–acid (FLA) batteries
  - Liquid vetted
  - Sealed valve regulated lead acid (VRLA)
    - Absorbed glass mat (AGM)
    - Gel cell
- Alkaline batteries
  - Nickel–cadmium
  - Nickel–iron.

Being cost-effective, FLA batteries are commonly used in residential scale PV application. But they require constant monitoring of voltage and topping up the water at regular intervals. Moreover, these batteries release hydrogen under heavy charging, so these batteries must be stored in a well ventilated enclosure. FLAs can last for many years if maintained well.

As *sealed FLAs* do not require topping of water and do not release gases they are becoming popular due to these less maintenance issues. *AGM* and *Gel Cell* are sealed batteries, but these are costly and are more sensitive to overcharging. Sealed batteries tend not to last longer than FLAs.

Alkaline batteries such as nickel–cadmium and nickel–iron also have positive and negative plates in an electrolyte. These plates are made of nickel and cadmium or nickel and iron and the electrolyte is potassium hydroxide. Their merit is that they are not affected by varying temperatures. For this reason, alkaline batteries are

usually recommended only for commercial and industrial applications in locations where extremely cold temperatures (–10°C or less) are anticipated. However, these batteries are often expensive and may have voltage window compatibility issues with certain type of inverters and charge controllers.

Batteries designed for automobiles deliver a sort of high current bursts for cranking the engine, thus frequently get discharged by using only a very small part of their capacity. The structural differences between the two types are in the lead battery plates. Deep cycle battery plates are thicker with higher density active paste material and thicker separators and hence, relatively expensive. These thick battery plates resist corrosion through extended change and discharge cycles.

(d) Charge Controllers

A charge controller (see Figure 1.15) is necessary for a PV system. Generally, a deep cycle lead acid battery can be charged at any rate that does not produce excessive gassing, overcharging or high temperatures. The battery absorbs very high current during the early part of the charge when its state of charge is at its lowest, but there is a limit to the safe current as the battery becomes fully charged. Excessive voltage is produced by the solar cells due to brighter sunlight. This could damage the batteries. Hence, a charge controller is necessary to prevent overcharging of the batteries.

Figure 1.15 Solar PV Charge Controller: The MPPT solar PV charge controller seen here gets the maximum possible power from one or more solar PV panels.
Picture by author.

The PWM charge controllers operate by sending out pulses of charge to uniformly distribute the charges on the plates of battery. These modulate the pulse widths and slopes of the voltage and current levels and also their rate of change.

EXAMPLE 1.5

Determine the ratings of a solar PV system for the electrical lamp and fan load requirements of a typical home.

Solution:

Table 1.4 depicts the electrical fan and lamp load requirements of a typical Indian home which helps in calculating the total daily consumption:

Table 1.4 Electrical Fan and Lamp Load Requirements of a Typical Indian Home

Equipment	Quantity	Rating (W)	Hourly Wh	Daily Hours	Daily Wh
Fan	3	60	180	10	1800
Television	1	100	100	5	500
Fluorescent tube	2	40	80	5	400
Compact fluorescent lamp	6	15	90	4	360
Total			**450**	**–**	**3060**

PV module requirement

Total daily consumption = 3060 Wh

Today's PV module of 1 m^2 produces 125 W to 130 W. Therefore, if a 100 Wp rating (i.e., average power under ideal conditions), 12 V module is selected, then assuming 5 peak sun hours on an average day total number of PV modules required will be:

$$= \frac{3060}{100 \times 5} = 6.12 \approx 6 \text{ modules}$$

Battery requirement

Assuming a 2 day backup for the battery, then

Battery capacity = 3060 × 2 = 6120 Wh

If 100 AH, 12 V battery is the choice, then

$$\text{Total number of batteries required} = \frac{6120}{12 \times 100} = 5.1 \approx 6 \text{ numbers}$$

Inverter requirement

Total hourly load = 450 Wh

So, a 500 VA, 12 V input, 230 V output AC inverter is required.

As per MNRE task force recommendation, for every 1000 W, 1.1 kVA rating inverter is required.

(e) Location of Solar PV Systems and Maintenance Tips

Solar PV requires relatively more land area than wind power and other renewable sources for every kW/MW of power. Therefore, one of the most popular locations for solar PV systems continues to be roof top mounting.

The routine maintenance of the solar PV systems is very simple, but it should be done at regular intervals. The following are some of the tips:

(i) The first major issue of maintenance with the solar PV system is the gathering of dust on the panels shutting off the sun rays from reaching the solar cells. Hence, some provisions need to be in place to keep the solar panels spick and span. One of the best techniques is to have a water sprinkler system. This greatly improves the efficiency of the solar panels.

(ii) Secondly, as suggested by the manufacturer, strictly adhere to the solar PV installation procedure and periodically maintain the battery bank.

(iii) If a supervisory control and data acquisition (SCADA) system is in place, it will greatly help in monitoring the solar PV system for lesser downtime.

A good innovation has been proposed and practised by Gujarat government (India) to install the solar PV systems all over the water canals of the big state, thus saving vast tracts of the land area which could be used for agriculture and other purposes. This has multiple benefits. First and foremost, it has saved the land area. Secondly, it prevents the evaporation of much needed water. Thirdly, it keeps the solar PV panels cooler, thereby increasing the efficiency of the solar cells. Fourthly, the water sprinkler system keeps the inclined solar PV panels always clean and at the same time, the water is saved from wastage as the cleaned water falls back into the flowing canal. In this way, hundreds of kilowatts of solar PV power are being harnessed in Gujarat.

1.6 BIOMASS POWER PLANTS

The materials of plants and animals including their wastes and residues (see Figure 1.16) are called *biomass* which is organic, carbon-based and reacts with oxygen in combustion for natural metabolic process to produce heat. If such heat is more than 400°C, it can be used to produce electricity. But the main challenges of biomass lie in its properties, i.e., low energy density often requiring drying and densification; seasonal availability and problematic storage requiring further pre-treatment. When biomass is used for producing electricity, it is termed as *biomass power*.

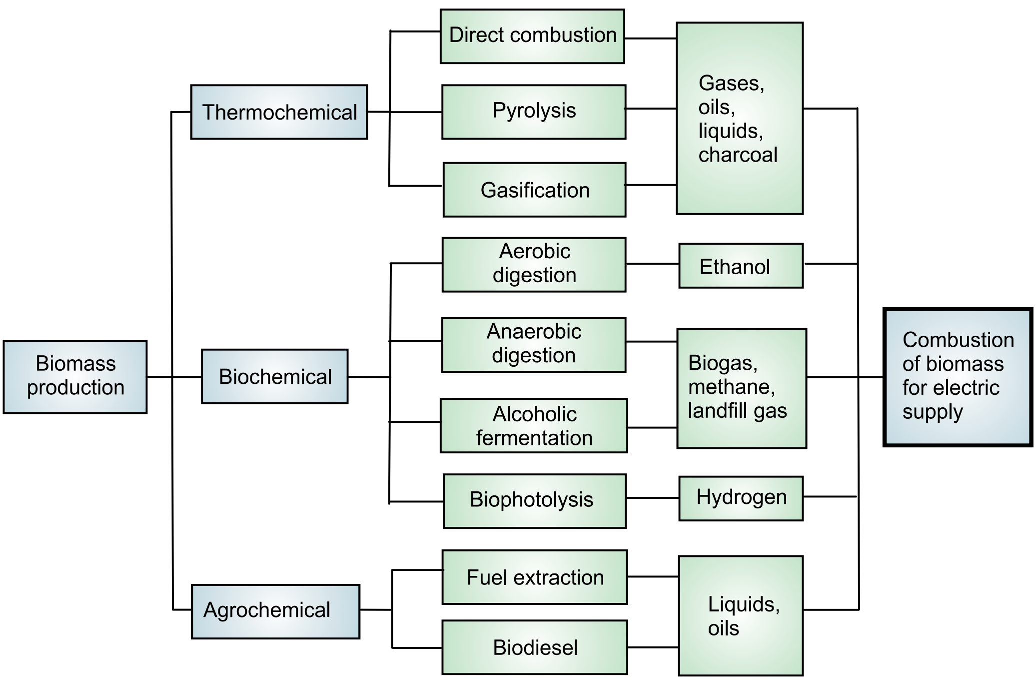


Figure 1.16 Biomass Classification for Electric Power Generation.

Biomass boilers are a low-carbon and renewable energy source which burn biological plant material, predominantly wood, in order to generate heat or both heat and electricity for combined units.

Biomass is available in three basic forms of matter—solid, liquid and gas.

1.6.1 Solid Biomass

Solid biomass in India includes the following:

- Bagasse plant waste and agricultural residues like straw, grasses, seeds, roots, dried plants, nut shells and crop residues like rice husk, etc.
- Municipal solid waste from household rubbish and garbage.
- Animal waste such as dried slurry and manure.
- Wood and its residues such as trees, shrubs, sawdust, pellets, chips and waste wood.

Since these are in solid form, they can be used as it is or compressed in the form of pellets that release their stored energy through combustion and burning to fire boilers in order to produce steam to run the steam turbines that are connected to the electrical generators to produce the electricity.

1.6.2 Liquid Biomass

Liquid biomass includes the following:

- Biodiesel distilled from vegetable oils, Jatropha and animal fats.
- Vegetable oils from sunflower, rape seeds or other vegetable oils.
- Methanol, ethanol and alcohol-based fuels fermented from corn, grain and other plant matter.
- P-Series fuels which blend various solid and liquid matters together to produce a fuel.

Since these are in liquid form, they can be processed to produce a type of fuel. Liquid biomass or biofuel is burnt to derive the heat which produces steam to run the turbines that are connected to the electrical generators so as to produce the electricity.

1.6.3 Biogas

Biogas is any kind of natural forming gas given off by animal faecas, manure, decaying plants or slurry that can be used as a type of fuel. It may include the following:

- Methane from decomposing plants, animals and manure.
- Biogas generated from rotting rubbish in landfills.
- Hydrogen from batteries and fuel cells.
- Synthesis gas blended from carbon monoxide and hydrogen.
- Natural gas from fossil fuels.

India has a vast untapped potential for different sources of biomass (see Tables 1.2 and 1.3) that can be used for electric supply. In India, agro-residue has a potential of generating approximately 18,000 MW of energy while bagasse has a potential of generating about 5000 MW of energy.

The technologies involved to convert these sources into electrical energy are also much different and hence there is a considerable scope for continued research and development in the field of biomass too. There is enough scope for anyone to undertake different researches in the relevant technologies and also improve the efficiencies of the current biomass technologies.

Biomass combustion can be of various types such as:

- Direct combustion power plant
- Cogeneration biomass-based power plant
- Waste to energy power plant
- Biomass-based generator sets
- Biomass co-firing.

The efficiencies of these types are greatly dependent on the feedstock (fuel) and the technologies adapted to use them. But since the fuel is free, they are worth adopting.

1.7 OCEAN ENERGY POWER PLANTS

The oceans cover three-fourth part of the earth and contain a great store of energy. The main big advantage of ocean energy is that it is more predictable and less variable, unlike wind energy or solar energy. There are two broad types of ocean energy—mechanical energy from the tides and waves, and the thermal energy from the sun's heat. Ocean mechanical energy is quite different from ocean thermal energy. This ocean energy can be classified as follows:

- Tidal energy
- Wave energy
- Ocean current energy
- Ocean thermal energy.

All of these types of energy sources can be tapped for generating useful electric energy.

1.7.1 Tidal Energy

The influences of the gravitational forces of the earth, sun and the moon become very strong and cause millions of gallons of water to move or flow towards the shore creating high tides and low tides. The coastal water level fluctuates twice daily at the seashores, alternatively filling and emptying natural basins along the shoreline. This process of ebbing and flowing of the tides happens twice during each period of rotation of the earth with stronger weekly and annual lunar cycles superimposed onto these tides. The various tidal energy technologies exploit this regular renewable energy resource.

The energy available from tidal power plant barrage that can be built to harness the tides is dependent on the potential energy contained in the volume of water which can be represented as follows:

$$E = Mgh \tag{1.3}$$

where,

M = Mass of water
g = Acceleration due to gravity (9.81 m/s^2 at the earth's surface)
h = Height of the tide.

Flowing water carries kinetic energy. Moving water carries much more energy than the moving air used in wind power because water is more denser than air. From a practical perspective, it is evident that even the slow tidal currents may represent an economical energy source such as the very first, La Rance tidal power plant in France. The currents flowing in and out of these basins can be exploited to turn mechanical devices in order to produce electricity.

1.7.2 Wave Energy

Waves are formed by the transfer of energy from the wind to the ocean surface. Wave height is determined by the wind speed (the length of time for which the wind has been blowing), the fetch (distance over which the wind has been blowing), depth and the topography of the sea floor. Wave power devices extract energy directly from surface waves or from pressure fluctuations below the surface. The common measure for wave power levels is the average annual power per metre of the wave crest width parallel to the shoreline. The average wave energy E is given as follows:

$$E = \frac{1}{8} \rho g H_s \tag{1.4}$$

where,

E = Energy averaged over specific time interval
ρ = Sea water density
g = Gravitational constant
H_s = Significant wave height.

Most of the energy within a wave is contained near the surface and it falls off sharply with depth, thereby creating the possibility of a number of technologies that can maximise the energy capture. Depending on the location, the wave energy conversion devices can be classified as follows (see Figure 1.17):

- **Shoreline wave energy devices** that are embedded in the shoreline.
- **Nearshore wave energy devices** that are at about 20 m depth in order to extract the wave power directly from and beyond the breaker zone.
- **Offshore wave energy devices** that are beyond the breaker zone using the high energy densities and higher power wave profiles of the deeper waters.

Some of the technologies used to capture the wave energy can be classified as follows:

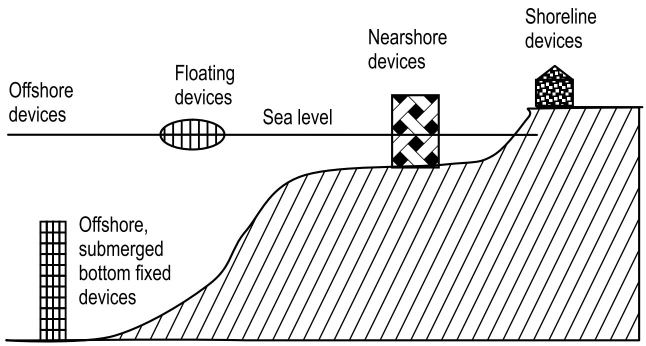


Figure 1.17 Wave Energy Conversion Devices.

- **Oscillating water columns (OWC)** with air turbine
  - Partly submerged fixed type (shoreline), e.g., Pico, LIMPET, Scotland
  - Submerged floating type (offshore), e.g., Mighty Whale, Oceanlinx
- **Point absorbers** are vertical small oscillating bodies with hydraulic motor, hydraulic turbine and linear electric generator either fixed directly to the ocean floor or tethered with a chain that absorb the wave energy from all directions:
  - Partly submerged floating type, e.g., Aquabuoy, Powerbuoy
  - Submerged type, e.g. AWS and Oyster wave energy converters
- **Wave attenuators** are semi-submerged snake-like devices oriented parallel to the direction of the waves to absorb the energy, e.g., Pelamis.
- **Overtopping devices** are either fixed or floating devices that convert the potential energy available in the head of water into mechanical energy to run the Kaplan turbine generator.
  - Fixed type, e.g., Tapchan, SSG plant, Norway
  - Floating type, e.g., Wave Dragon.

1.7.3 Ocean Current Energy

Ocean currents are fast sea currents created by the shape of the seabed when water is forced through narrow channels. These currents are dependent on large thermal movements and run generally from the equator to cooler areas. There are some natural locations where the water flows continuously in one direction only. The similarity between the kinetic energy flux in these ocean currents and the energy available from the wind has prompted the design of the technology resembling to wind turbines (see Figure 1.18). The power can therefore be calculated for water passing through the cross-section of the submerged turbine rotor blades by

$$P = 0.5\, C_p \rho A v^3 \tag{1.5}$$

where,

C_p = Turbine coefficient of performance
P = Power generated (in watts)
ρ = Density of the water (seawater is 1025 kg/m^3)
A = Sweep area of the turbine (in square metre)
v = Velocity of the ocean current flow.

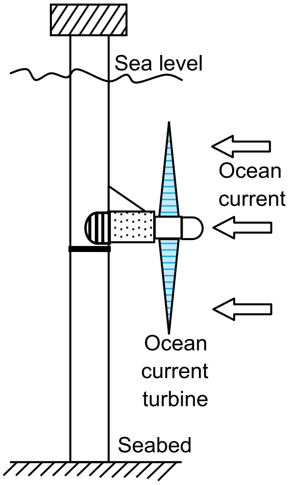


Figure 1.18 Ocean Current Turbine.

Since the density of water is quite high (1000 times more than air) even for a small swept, the submerged ocean current rotor will produce a very large quantity of energy.

1.7.4 Ocean Thermal Energy

Oceans' cover of earth's surface makes them the world's largest solar collectors. The sun's heat warms the surface water a lot more than the deep ocean water and this temperature difference provides exploitation of ocean thermal energy.

Tropical oceans and seas have surface water temperatures between 24°C and 33°C. Below 500 m of sea level, the temperature ranges from 9°C to 5°C. This provides a maximum exploitable temperature difference of 28°C. In practice, the temperature difference is likely to be closer to 20°C providing a theoretical energy conversion efficiency of 6.7%. But since this is freely available, ocean thermal energy conversion (OTEC) technologies (see Figure 1.19) can be researched and deployed to obtain grid compatible electric power.

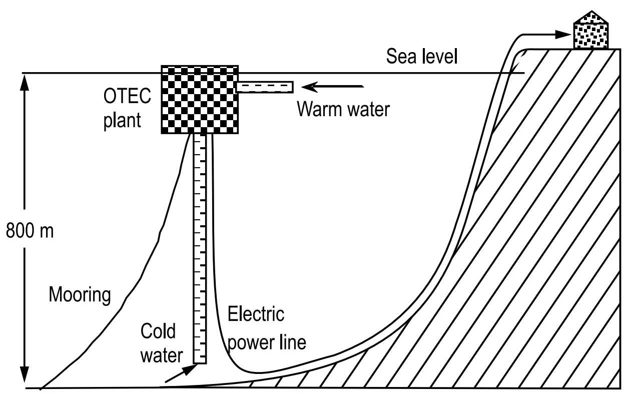


Figure 1.19 OTEC Power Plant.

Small scale OTEC systems and individual system components have been tested successfully off the coast of Hawaii. Basically, three types of OTEC power plants are possible which are as follows:

- **Closed cycle OTEC:** In this strategy, warm surface sea water is pumped through a heat exchanger to vaporise a low boiling point fluid such as ammonia. The expanding gas is run through a turbine and then condensed back into a liquid by cooler seawater pumped through a second heat exchanger.
- **Open cycle OTEC:** In this strategy, warm surface sea water is pumped into a low pressure container where it boils. The expanding steam drives a steam turbine connected to a conventional electric generator and is then condensed back into a liquid through exposure to deep ocean cooler water. In this case, if the steam is isolated from sea water during condensation, freshwater can be a by-product of the energy production process.
- **Hybrid OTEC:** Here, the warm surface sea water is pumped into a vacuum chamber and is then flash evaporated into steam. The steam is then run through a heat exchanger to vaporise a low boiling point fluid within a closed cycle loop.

By a rule of the thumb, in order to generate 1 MW of electricity, an OTEC plant requires 4 m^3/s of warm sea water and 2 m^3/s of cold sea water. This will require a cold water pipe of around 11 m in diameter to supply 100 MW electricity in a plant, the largest size considered to be practical.

1.8 WIND POWER PLANTS

With increasing prices for fossil fuels, wind power has already become one of the cheapest energy sources available. The cost of producing power per kilowatt hour (see Table 1.3) from conventional fossil-based sources has increased over the years, whereas the cost of electric power produced per kilowatt has shown a reduction. As a rule of thumb, the capital cost of 1 MW of wind power project can be around ₹ 6 crores per MW from concept to commissioning. This gives a levelised cost of energy generation in the range of ₹ 2.00/kWh to ₹ 2.50/kWh taking into consideration the fiscal benefits and other incentives extended by the government of India. This explains the current wind rush in India by wind power developers as well as investors.

GWEC has reported that wind farms generate power between 17 and 39 times as much power as they consume as compared to 16 times for nuclear plants and 11 times for coal plants. In just a few decades, the wind power has turned from an alternative energy source to a new fast growing industrial branch worldwide. Today wind power plants (WPPs) produce electric power at competitive costs and contribute a large share of the power in many countries. The cost of electricity from wind has fallen in the past few years with the advancements of technology. Wind energy is competitive with new coal and new nuclear capacity, even before any environmental costs of fossil fuel and nuclear generation are considered.

Almost all WPPs start operating at wind speeds around 3 m/s and produce rated power output between 11 m/s to 15 m/s and continue to do so till the very

high wind speed of 25 m/s (gale force) is achieved as such winds are rare. Although in a year, it typically generates around 15–30% (or more) of the theoretical rated output, the capacity factor is less than the conventional power plants.

As a simple rule of thumb, a typical 1 MW WPP produces 2 GWh/acre on land and 3 GWh/acre offshore. With new WPPs of 80 m–100 m hub heights, these figures would be higher; 2.5 GWh on land and 4 GWh offshore. But as the wind is free, hence, no fuel costs; it is not logical to compare the efficiency of the WPP energy technologies with those fossil-based power plants.

1.8.1 Historical Background

From 5000 BC, the wind energy utilisation can be traced when sail boats were used on the river Nile in Egypt. History says that since 200 BC, wind was used to pump water, grind grain and drive vehicles and ships. In ancient China and Middle East where wind mills were used to convert kinetic energy into mechanical energy.

By the end of 12th century, the first windmills were built on the Mediterranean sea coast in Europe and also in Northern France. Most of these windmills having a horizontal axis were used to grind grain. They soon became one of the most important power sources and kept that position until the end of 19th century.

Another important task for the windmills was to pump water. The wind rotor drove either a blade wheel or a water screw and contributed to reclaim the land for agriculture. Such wind driven pumps made it possible to increase the land area of Netherlands. Windmills were also used to saw timber, stamp rag that was used to make paper and in many other applications. In the industrial area outside Amsterdam, there were 700 windmills in the 19th century that provided mechanical power to the factories. The total power of all the windmills in Europe had reached to its maximum, i.e., 1500 MW, a level that wind power did not reach again until 1988.

During the first half of the 20th century, two new types of wind turbines were invented—the vertical axis Savonius rotor and the Darrieus turbine. A serious effort to develop electricity from wind power started in the beginning of 1970s when the oil crisis pushed several countries to opt for new energy sources.

The Danes were one of the early starters of electricity generation from wind power. In 1892, professor Paul la Cour built the first wind turbine for electric power production with economic support from the government. It produced DC power and used batteries for energy storage. By 1908, 72 wind turbines each of 10 kW–20 kW power were on line and by the end of the second world war, WPPs with a nominal power of 45 kW became common.

Around the same time in USA, many experiments were undertaken in the field of wind power. In Vermont (USA), a gigantic prototype with a rotor diameter of 53 m and a nominal power of 1250 kW was built in 1940s, e.g., Grandpa's Knob. It was on line for 1100 hours and fed power to the grid. The wind rush in early 1980s saw the creation of the largest wind farms in the world in California at Altamont, Tehachapi, and Palm Springs.

About the same time, considerable amount of research work happened in other parts of Europe. In Germany also, a number of designers and manufacturers joined

the fray in the race for grid connected wind power. Enercon, the pioneer of the direct-drive WPP technology, was from Germany.

Later, in 1980s, Sweden experimented with large capacity (e.g., 3 MW) two-bladed WPPs and also with concrete towers. France and Italy also experimented with large capacity (750 kW and 1.5 MW) permanent magnet direct-drive WPPs.

1.8.2 Global Wind Power Growth

The use of wind power to generate electricity gained dominance in mid-1970s following the oil crisis and increased concerns over resource conservation. But at that time, WPPs were of smaller capacities to charge the batteries in remote power systems, residential scale power systems, isolated or island power systems and small utility networks. In 1980s, wind projects really took off the ground, primarily driven by the governmental and industrial initiatives. But with bigger capacity WPPs, in 1990s, there seemed a shift of focus from onshore to offshore development in major wind development countries, especially in Europe as land area became scarce.

After the early small wind turbines of 30 kW, 55 kW capacities from the early 1980s, the capacity of WPPs has been doubling approximately in almost every four years. 600 kW and 750 kW stall controlled WPPs with squirrel cage induction generators continued to be the work horses of the wind industry. The megawatt class WPPs took off the ground in 1998 and since then, there was no looking back. The large commercial WPPs on line today have hub heights ranging from 70 m to 126 m, rotors with a diameters of 70 m to 127 m and a rated power of 2 MW to 7.5 MW. The prototypes of WPPs of 10 MW rating are being testing.

In the beginning of 21st century, the German market grew the fastest. Already by 1994, Germany had overtaken pioneering Denmark with respect to installed wind power capacity. Both German and Danish manufacturers had found new large export markets in USA, India and China.

Now, Asian countries have many WPP factories which manufacture WPPs for their home markets as well as for export.

In terms of installed capacity, the growth has been extremely fast and will continue during the coming decades. In the beginning of September 2018 (see Figure 1.20), India was the 4th largest country with installed wind power of 34,294 MW.

Presently, wind power is the fastest growing renewable energy source in the world. Global Wind Energy Council (GWEC) reports that from 2001, wind power expanded from 23,900 MW installed capacity to reach a new peak of 5,39,581 MW (see Figure 1.21) by January 2018 around the world. There are 29 countries in the world, which have more than 1,000 MW capacity of installed wind power. The wind power industry has created about 11,55,000 jobs in the world by end of 2016 and the number of wind turbines spinning around the world is 3,41,320.

Among the top ten WPP manufacturers of the world shown below, the Indian company Suzlon is in the 10th position. China has also come a long way with many of their manufacturers among the world top ten.

(i) Vestas — Denmark (Headquarter)
(ii) Siemens Gamesa — Spain (Headquarter)

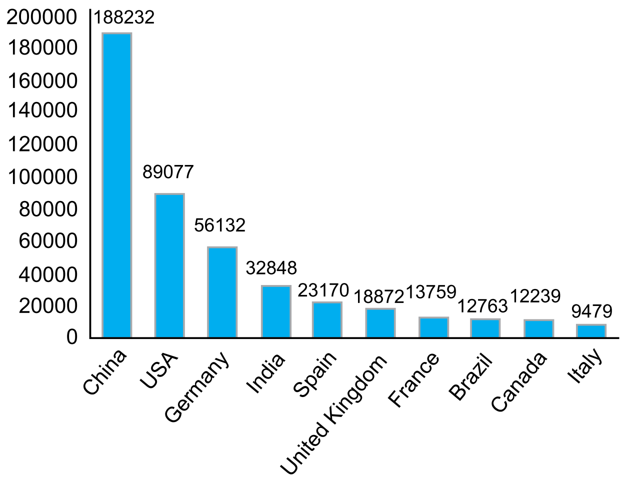


Figure 1.20 **Top Ten WPP Leading Countries (in MW):** Generally, India ranks 5th in the world, as on January 2018.

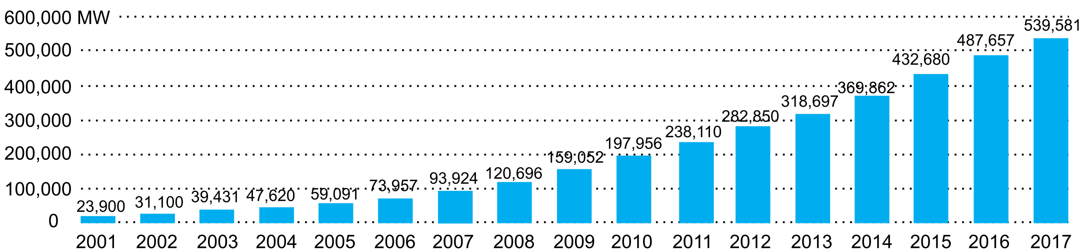


Figure 1.21 **Global Cumulative Installed Wind Capacity 2001 to beginning of 2018**. *Courtesy:* www.gwec.net

(iii) GE Wind	—	USA (Headquarter)
(iv) Goldwind	—	China (Headquarter)
(v) Enercon	—	Germany (Headquarter)
(vi) Nordex	—	Germany (Headquarter)
(vii) Nordex	—	Germany (Headquarter) (owned by USA)
(viii) United Power	—	China (Headquarter)
(ix) Envision	—	China (Headquarter)
(x) Suzlon	—	India (Headquarter)

According to GWEC report, the amount of offshore wind installations in the world has grown rapidly and stands at 18,814 MW (see Figure 1.22). The largest wind turbine in the world today is the Vestas 8 MW turbine with a rotor diameter of 164 m with a swept area of three times a football field. The world's longest wind turbine blade is LM Wind Power's 88.4 m long blade. There continues to be great scope for wind power growth. Hence, there is tremendous demand for wind power technologies within India and abroad (Figure 1.23).

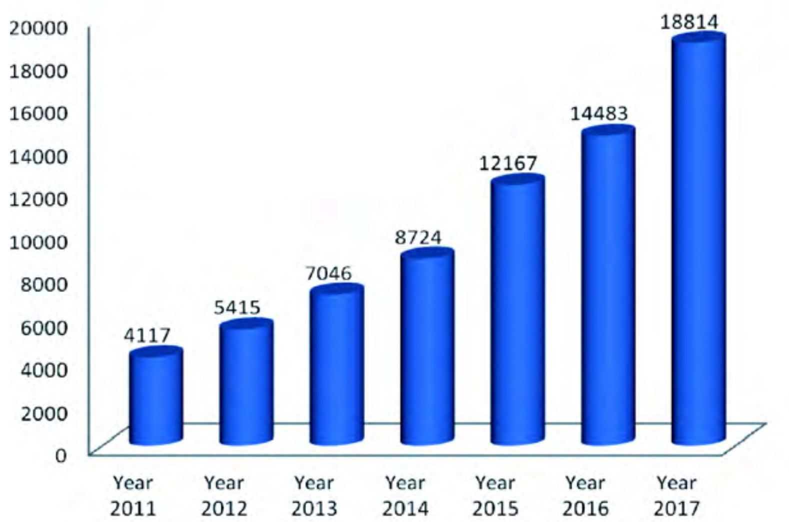


Figure 1.22 **Growth of Global Installed Offshore Wind Power Installations in MW** (2011 to 2017). *Courtesy:* www.gwec.net.

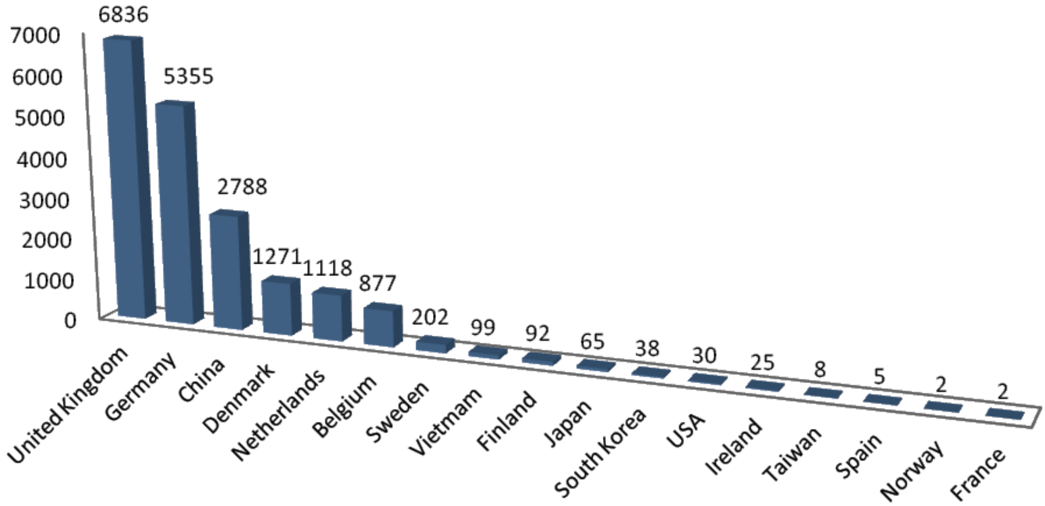


Figure 1.23 **Distribution of Global Offshore Wind Power Installations in MW** (As on February 2018). Courtesy: www.gwec.net

1.8.3 Indian Wind Power Growth

There are good wind resources in India that can be utilised for generating electricity from wind power with windy sites in class I, class II and class III. The best wind resources are not only found in Tamil Nadu in the far south, Gujarat on the Arabian seacoast, but also in the states of Maharashtra, Rajasthan, Karnataka, Andhra Pradesh, Orissa, Madhya Pradesh and Kerala.

Modern WPPs are efficient, reliable and produce power at a reasonable cost. With some 30 years of experience in the field of wind power, India has a mature and cost-competitive wind turbine industry. With the wind resource potential identified and mapped at 1,00,000 MW of wind power in the country and with only about 34,294 MW as on September 2018 tapped so far, India has a enough opportunity to accelerate the pace of wind power development. By increasing the share of wind energy in the power system, the economic growth can be kept on a high level due to the fact that in India, about 98% of the investments in the wind power are by the private sector.

Considering the wind speed at 50 m wind mast height, National Institute of Wind Energy (NIWE) at Chennai has assessed a wind power potential of 49,000 MW. But by the assessment of the private players at 75 to 100 m height, the wind power potential is said to be 1,00,000 MW. However, the Lawrence Berkeley National Laboratory (LBNL) estimates much more wind power potential of India (2,50,000 MW) with the help of satellite and meso-mapping.

The wind power technology starting with 5 kW wind turbines has been about four generations of different types of wind turbines and all of these types are successfully operating in different parts of India, although in other parts of the world many of them have gone into oblivion. Thanks to the expert Indian maintenance crews that have been keeping them in successful operation. Almost all the different technologies can still be seen in Muppandal (see Figure 1.24) lovingly called the *wind country* in Tamil Nadu, South India. This largest cluster of WPPs in India is next to the largest cluster of WPPs at Altamont, Tehachapi and Palm Springs in California, USA. Today, Muppandal spanning several square kilometres in two districts of Tamil Nadu, is one of the permanent exhibition grounds at a single location in the world for a large variety of WPPs attracting not only the wind turbine specialists, but also tourists, researchers and everyone who is interested in them.

Figure 1.24 Muppandal *Wind Country*: This cluster of different types of wind turbines is next only to that in California, USA. Muppandal is a permanent wind turbine exhibition ground attracting not only wind power specialists but also tourists, researchers and others who are interested in watching 'legacy wind turbines' in operation. Now Muppandal goes down into the annals of wind power history of the world.
Picture by author.

The concept of demonstration projects was introduced by the government of India to install and commission WPPs in several windy parts of India so as to build confidence in the investors that wind power technology is commercially viable. It was one of the reasons for the accelerated growth of the wind power sector in India (see Figure 1.25). Further growth of the wind power in various states (see Figure 1.26) is also encouraging as it depends on the favourable various policies adapted by the respective state governments.

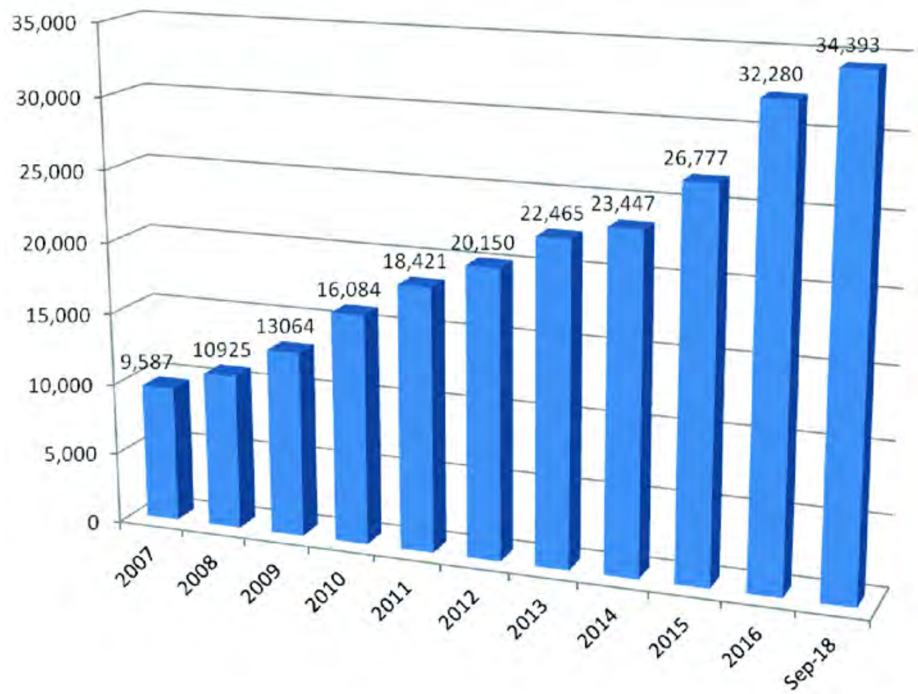


Figure 1.25 Cumulative Installed Growth of Wind Power in India in MW: As on March 2018.

Various types of WPPs are manufactured in India from Type-A to Type-D. Currently, there are 18 large WPP companies manufacturing 46 models of capacities ranging from 250 kW to 2.5 MW. The manufacturing capacity of Indian industry is 10,000 MW to 12,000 MW per annum. At the present pace by 2020, the Indian installed capacity could be 89,000 MW of wind power and 1,91,000 MW by 2030. This would create 179,000 green collar jobs in manufacturing, project development, installation, operation, maintenance, consulting, etc. In the wind sector alone by 2020 and there can be a saving of 131 million tons of CO_2 from being spread into the atmosphere every year.

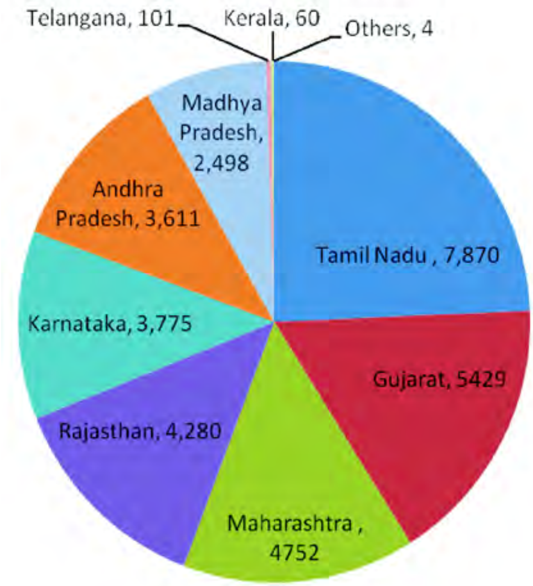


Figure 1.26 Cumulative State Level Power Installations in India (MW): As on March 2018.

1.9 DRIVERS AND BOTTLENECKS FOR WIND POWER DEVELOPMENT

It is quite interesting to note that almost 98% investment in the wind power sector in India has been from the private sector. Two of the key drivers for this growth have been the government policies, i.e., accelerated depreciation (AD) and generation-based incentive (GBI). The concept of AD which is a tax deferral and not a subsidy has played a major role in internal fund accrual that is used as equity of 30% and the balance is borrowed from the banks. GBI has been announced for 4000 MW of ₹ 0.50/kWh produced with a minimum limit of 62.5 lakhs/MW. This promotes better operation and maintenance of WPPs for increased production of wind power.

Other than the above two major drivers, the following incentives have also played a big role in the advancement of the wind power sector in India:

(i) Loans from Indian Renewable Energy Development Agency (IREDA) for setting up of new wind power projects
(ii) Sales tax concessions/benefits
(iii) Power wheeling and power banking facilities
(iv) Electricity tax exemption
(v) Import duty concession on certain WPP components
(vi) Excise duty exemptions
(vii) Feed-in preferential tariff: Making it obligatory for state electricity utilities to buy renewable electricity at the rates specified by the regulator under the Indian Electricity Act of 2003 section 61(h)
(viii) Ten year income tax holiday for wind power projects.

Since most of the class I windy sites have been exploited, wind project developers are now putting up wind farms in class II and class III sites. But identification of new sites for development, scheduling and forecasting wind power generation are some of the challenges faced by the wind project developers. The other impediments faced by Indian developers are acquisition of private land/government land, obtaining forest clearances, development of infrastructure on complex terrain and implementation of evacuation infrastructure.

1.10 STRENGTHS AND LIMITATIONS OF WIND POWER

Every resource has its strengths as well as limitations. Following are some of the main reasons of advocating wind power generation:

(i) Among all the renewable energy sources, wind power is the most matured technology competing with the conventional energy sources.
(ii) Wind power projects have the fastest payback period.
(iii) A wind power project has least investment in manpower.
(iv) The marketing risks are minimal, as the product is electrical energy.
(v) A permanent shield against everincreasing power prices. The cost per kWh reduces over a period of time contrary to the rising cost for conventional power.
(vi) The cheapest source of electrical energy (on a leveled cost over 20 years). The capital cost ranges between 5 crores/MW to 6 crores/MW depending upon the type of turbine, technology, size and location.
(vii) Least equity participation is required as well as low cost debt is easily available to wind energy projects.
(viii) A real fast track power project with the lowest gestation period and a modular concept. Capacity addition can be in modular form.
(ix) Operation and maintenance cost is very low.
(x) Fuel cost is zero.

Although wind power has the following limitations, the strengths discussed above outweigh them:

(i) The installation of WPPs depends on the availability of winds.
(ii) Wind is varying in nature and hence, cannot be used as a base load as large hydro and thermal power plants.
(iii) WPPs are subject to damage from hurricanes, typhoons and cyclones. However, this phenomenon is quite rare in India. Moreover, modern WPPs are generally built for survival wind speeds around 60 m/s.
(iv) Noise from the WPPs can be annoying to the neighbours in the vicinity. This problem is overcome as the WPPs are situated reasonably at a good distance from human habitation.

SUMMARY

It has been seen that the potential and the successful march of the renewable energy in India has been amazing. It is because of the fact that the renewable energy is a perennial source leading to the formulation of favourable policies by the government of India. The steady march of the Indian wind power sector, the fastest growing renewable energy source in the world, has placed India on fifth position of the world wind power map. India is committed to continue this accelerated development still further.

EXERCISES

1.1 Name the state which has major share of geothermal power in India.

1.2 Compare the major features of the two major solar power technologies suitable for grid connection.

1.3 Distinguish the features of the parabolic and dish type solar power plant.

1.4 Compare the features of the power tower and Fresnel reflector system solar power plants.

1.5 Explain the equivalent circuit of a solar cell.

1.6 Describe the differences of the two types of charge controllers in a solar PV system.

1.7 Differentiate between deep cycle and normal battery systems.

1.8 Design a solar PV system for electrical lamp and fan load requirements to be used by a cluster of 20 households in a village.

1.9 Describe three maintenance tips for the efficient and effective functioning of a solar PV system.

1.10 Name at least seven biomass energy sources that can be used for electric power generation.

1.11 Compare the major features of the three types of biomass cofiring methods.

1.12 Distinguish the working of four major ocean energy technologies.

1.13 Explain the wave energy equation.

1.14 Differentiate the working of five types of wave energy technologies.

1.15 Explain the tidal energy equation.

1.16 Explain the marine current power equation.

1.17 Justify the temperature difference required for the OTEC technology.

1.18 Compare the features of the open and closed cycle OTEC technology.

1.19 Highlight at least eight incentives that have advanced the growth of wind power in India.

1.20 Compare the advantages of wind power over other energy sources.

2

The Wind Resource

Then a great and powerful wind tore the mountains apart and shattered the rocks. before the LORD.
—I Kings 19:11

Learning Outcome

On studying this chapter, you will able to justify the wind characteristics required for electricity generation, using wind power plants.

CHAPTER HIGHLIGHTS

2.1 INTRODUCTION

Wind is the air in motion. The wind which is freely available has considerable power to move trees (see Figure 2.1) and turn wind turbine rotors to produce electricity. Energy from the sun heats up the atmosphere and the earth unevenly. The sun heats up the earth's surface and hence, the air close to it rises up.

The air is set in motion by the differences in temperature and air pressure due to solar radiation on the earth's surface. The everchanging temperatures due to the sun create more or less regular patterns for the movement of air on the face of the earth. Since air has mass (the weight of air is a little more than one kilogram per cubic metre), the wind contains kinetic energy. Wind power plants (WPPs) utilise this energy in the wind to produce electrical energy.

Figure 2.1 Power of the Wind: Bent branches of trees.

Air is a mixture of gas, solid and liquid particles. Cold air contains more air particles than warm air. Cold air is, therefore, heavier and sinks down through the atmosphere creating high pressure areas. Warm air rises through the atmosphere creating low pressure areas. This rising air, then, draws in cooler air from the surrounding as the air naturally flows from high pressure area to low pressure area and this movement is known as the *wind*. A modern wind power plant (WPP) produces electricity 70%–85% of the time on an average every year but it generates different outputs depending on the wind speed.

The earth is divided by longitudes and latitudes. Longitudes circle the earth and pass through the north and south poles, whereas latitudes circle parallel to the equator (see Figure 2.2). During a year when the earth circles around the sun once, it moves (seen from a position on earth) from the southern to the northern tropical circle and then back again. If a longitude is followed, then the solar radiation is perpendicular to the equator (at the spring and autumn solstice). As one moves further in the northern hemisphere, the angle between the sun and the surface of

the earth declines so that the same amount of radiation gets spread over an ever larger area. Hence, the sun heats the surface much more at the equator than at the Arctic circle. The earth's axis is also inclined relative to the plane where the earth moves around the sun. This is the reason for different seasons.

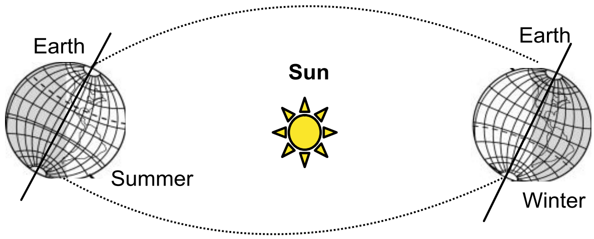


Figure 2.2 **Changing Seasons:** The position of the earth in relation to the sun. In May, to the left, is summer in India and in January, to the right, is winter. Since the axis of the earth has an inclination, the northern hemisphere gets more sunshine in the summer than in the winter.

Several other factors also influence changes in earth's temperature. Oceans cover a large part of the earth and water has quite different properties for storing heat than that of the solid ground surface. Ocean currents as well as the winds transport heat between different latitudes and even out the differences in temperature.

Weather is the instantaneous state of the atmosphere at a particular location or region. It is the totality of atmospheric conditions, i.e., the temperature, atmospheric pressure, wind speed, humidity, cloudiness, rain, sunshine and visibility at a particular place and time.

Wind climate is a wider concept. It is the sum of the weather at a place over the years. Since the average conditions of the weather changes from year to year, climate is described in terms of a specific period of time, a run of years, a particular decade or some decades. The *wind climate* of a location can, therefore, be defined as the variability of the wind speed calculated statistically over a full year. The wind climate is the long term pattern of the wind in a specific site, region or country. Different places on the earth have different wind climates. The *meso climate* is the climate of a country or a region and the *macro climate* is the large-scale climate patterns on the earth, continents or parts of continents. The *local wind climate* is the climate within a limited area that may be a coastal zone, a forest or a field. It is the most important for a wind power developer to have a good information about the local wind climate.

In India, the wind climate is characterised by the *monsoons* which lasts for several months. It experiences two seasonal winds—the *southwest monsoon* (June to September) and the *northeast monsoon* (October to December). The northeast monsoon (commonly called as the *winter monsoon*) mostly benefits Tamil Nadu. The predominant southwest monsoon (commonly called as the *summer monsoon*) blows from sea to land ensuring sufficient wind speeds to the southern and western regions of the country. Almost 65% to 90% of the annual wind power yield is from these winds during these months for India.

2.2 TYPES OF WIND

The earth is continuously rotating and the topography of the earth's surface upto an altitude of 100 m affects the flow of air in various ways. When viewed from the ground, the wind movement in the northern hemisphere is deflected to the right while in the southern hemisphere, it is deflected to the left. This apparent bending force (see Figure 2.3) is known as the *Coriolis force* [named after the French mathematician Gustave Gaspard Coriolis (1792–1843)].

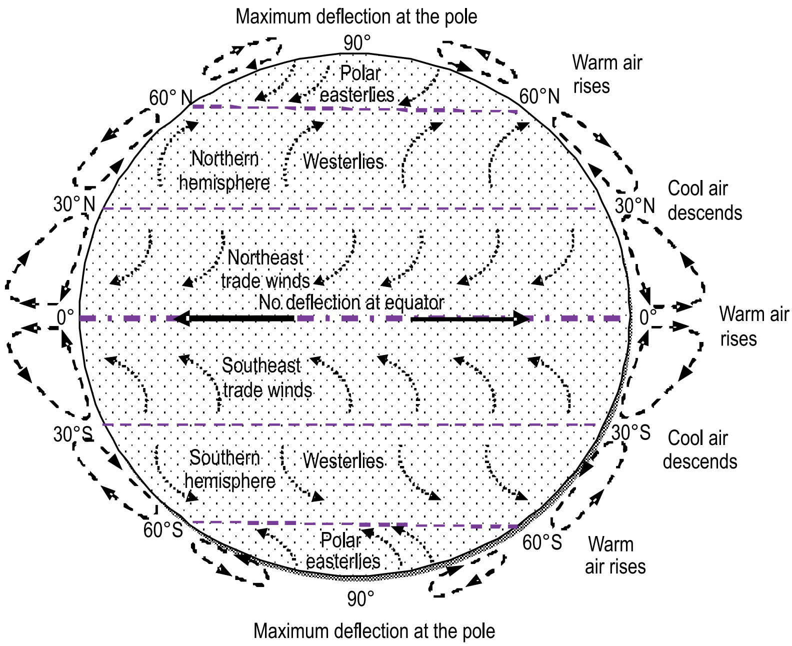


Figure 2.3 Effect of Coriolis Force: Caused due to the earth's rotation.

The equator receives the most direct rays of sun. Here, the air gets heated up and then rises leaving behind low pressure areas. The cool air sinks and moves back to the equator and the rest of the air flows toward the poles.

Around 30° latitude in both hemispheres, the Coriolis force prevents the air from moving much farther. At this latitude, there is a high pressure area, as the air begins sinking down again. The Coriolis force is zero at the equator.

The air movements toward the equator are called *trade winds* that are characterised as warm, steady breezes that blow almost continuously. The trade winds, i.e., westerlies and easterlies flow around the world and cause many of the earth's weather patterns. The westerlies (named from the direction from which they originate) are steady winds that generally blow between 30° and 60° latitude in both the northern and southern hemispheres. These are the winds that are good for wind power generation. The easterlies are the low latitude trade winds near the equator and poles that blow from east to west. These are the trade winds that

are steady throughout the year and hence, the variation in the wind speeds in this region is quite less and strong enough for wind power generation.

Gravity pulls the air towards the earth's surface. Close to the earth, the wind is influenced by friction against the surface. With increasing height from the surface of the earth, this friction gradually decreases and at a specific height, it is negligible. The *geostrophic wind* (see Figure 2.4) is a special case, in which the rising air reaches a condition of balance of two forces (pressure gradient force and Coriolis force) such that the wind flow becomes parallel to an isobar. This undisturbed wind is called the *global wind* or *geostrophic wind*.

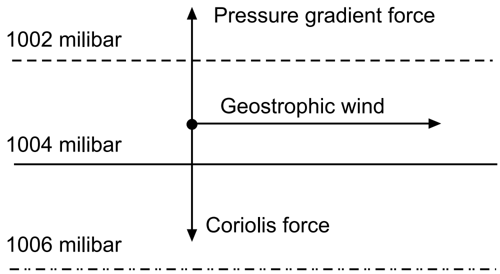


Figure 2.4 Geostrophic Wind: This is due to the balance between the Coriolis force and pressure gradient force.

The geostrophic wind is generally found at an altitude of 1000 m above the ground level and are not very much influenced by the surface of the earth. The distance from the ground to the geostrophic wind varies and depends on the weather conditions and surface roughness. High friction increases the height of the geostrophic wind.

In winters, a strong high pressure dominates Asia and there is an outward flow of air reversing the air flow of summer monsoon. It brings dry and clear weather for several months. The winter monsoon starts in October and goes on until March. Also, the land mass in India cools off quickly in winters but the ocean retains the heat longer creating a high pressure and producing a breeze from land to ocean. The sea temperatures cool very much less rapidly and the winds then move from land to sea.

The earth's surface is marked with trees, buildings, lakes, seas, hills and valleys, all of which also influence the wind's direction and speed, e.g. where warm land and cool sea meet, the difference in temperature creates thermal effects which causes *local sea breezes*. If global winds are weak, then local winds such as land and sea breezes predominate. Night temperature is warmer in cloudy weather than during a starlit night. During day time, the clouds shelter the earth's surface from direct sunlight and reduce heating of the ground. Whereas, in night time, the clouds reflect back the heat radiation towards earth to keep it warm.

2.3 WIND PROFILING

The wind speed varies every second due to the turbulence caused by the land topography, thermals and weather. The final force acting on the wind is the friction due to the earth's surface. The wind in the lowest 1000 m is affected by the friction

of the earth's surface. This force acts as a drag on the atmosphere and the wind speed becomes zero at the earth's surface. This does not mean that the air doesn't move but it means that the sum of their movements in different directions adds up to become zero.

For wind power extraction, winds up to 150 m to 200 m above ground (or sea) are of interest. WPPs are becoming taller and taller but they will always stay within the so called friction layer of the atmosphere. *Wind shear* is the increase in wind speed at greater heights above the ground. For most of the open spaces, wind speed increases to 12% each time the height is doubled. Within these heights, the wind is always influenced by local conditions; the terrain at the actual site in an area with approximately 20 km radius around the site. Variation in land use around a WPP site also affects the wind flow at the WPP site.

Variations or roughness (or undulations) on the earth's surface lead to changes in surface friction of the wind speed, thus changing the wind profile. Over the earth's surface with many obstacles like coconut groves, buildings and other structures, the wind speed gets retarded. The relation between wind speed and height is called the *wind profile* or *wind gradient*. Variations in the earth surface can also lead to vertical temperature gradients, which also affect the wind profile. As a general rule, wind speed increases with height (see Figure 2.5). The wind speed increases more rapidly with height in the areas with high roughness than over a smooth terrain.

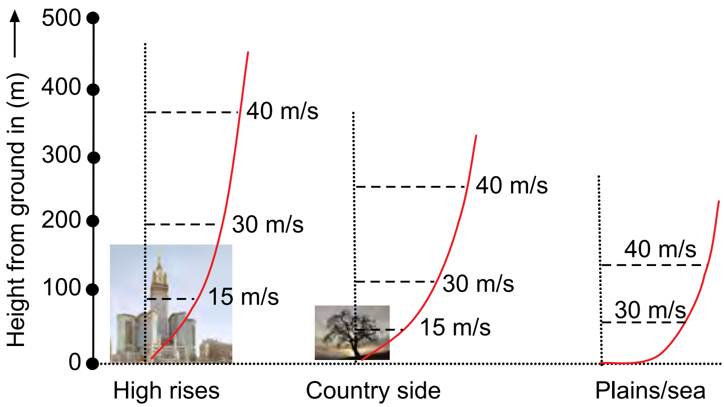


Figure 2.5 Wind Gradient: More the roughness, more will be the bend in the wind profile, affecting the hub height of the wind turbine.

Roughness refers to the terrain and density of vegetation on the landscape. The terrain is classified into different *roughness classes* (see Table 2.1). The roughness classes defined in the European Wind Atlas is on the basis of the roughness length in metres which is the height above the ground level, the value where the wind speed is theoretically zero. Sometimes, the expression *roughness length* is also used. This length has nothing to do with the length of the grass or the height of buildings. In fact, it is a mathematical factor used in the algorithms for calculations of how the terrain influences the wind speed. As a rule of the thumb, a WPP operating with wind speeds of 6.7 m/s at 70 m hub height could generate 20%–25% more if the hub is placed at 100 m instead of 50 m above ground level.

Table 2.1 Roughness Classes and Roughness Lengths

Roughness Class	Roughness Length (m)	Energy Index (%)	Terrain, Obstacles and Buildings
0	0.0002	100	Open water, sea, lakes
0.5	0.0024	70	Completely open terrain such as airport runways
1	0.03	50	Sparse vegetation with no hedges, scattered buildings, soft rounded hills within 0 km to 3 km
1.5	0.05	45	Sparse vegetation with about 7 m–8 m tall hedges within a distance of 1200 m, few buildings
2	0.1	38	Sparse vegetation with about 7m–8m metre tall hedges within a distance of 500 m, few buildings
2.5	0.2	30	Sparse vegetation with about 7 m–8 m tall hedges within a distance of 250 m, few buildings
3	0.35	26	Some villages and small towns with 8 m high hedges, forests less than 250 m and very rough terrain
3.5	0.85	17	Large cities or high thick forest
4	1.65	12	Very large cities or very high thick forest

The force of friction acts in the direction opposite to the wind movement. This change of wind speed and wind direction is called *wind shear* which is defined as the change in horizontal wind speed with the change in height. The wind blows more strongly higher above the ground than closer to it because of the friction of the earth's surface. The *wind shear exponent* (or *power law index*) α is to be determined for each site, as its magnitude is influenced by the site specific characteristics. It is given by:

$$\alpha = \frac{\log_{10}\left(\frac{v_2}{v_1}\right)}{\log_{10}\left(\frac{h_2}{h_1}\right)} \tag{2.1}$$

where,

α = Wind shear exponent or power law index
v_2 = Wind speed at height h_2
v_1 = Wind speed at height h_1

A power law model used for height projection of long term wind is given by

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \tag{2.2}$$

The value of α depends on the roughness of the terrain given as follows:

α = 0.1 for roughness class 0 (still water or plain sand)
α = 0.15 for roughness class 1 (open plain)
α = 0.2 for roughness class 2 (countryside with farms)
α = 0.3 for roughness class 3 (villages and low forest)

EXAMPLE 2.1

At a particular site, the wind speed is 6.1 m/s at 60 m height above ground level (agl) and at 80 m height, the wind speed is 6.5 m/s. Determine the power law index and extrapolate the wind speed at 100 m height at that particular site.

Solution:

Using Eq. (2.1),

i.e.,
$$\alpha = \frac{\log_{10}\left(\frac{v_2}{v_1}\right)}{\log_{10}\left(\frac{h_2}{h_1}\right)} = \alpha = \frac{\log_{10}6.5 - \log_{10}6.1}{\log_{10}80 - \log_{10}60} = 0.221$$

When h_2 becomes 100, then corresponding v_2 will be:

Using Eq. (2.2),

i.e.,
$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha}$$

$\therefore$
$$\frac{v_2}{6.1} = \left(\frac{100}{60}\right)^{0.221}$$

$$v_2 = 6.83 \text{ m/s}$$

So, the wind speed v_2 at 100 m height will be 6.83 m/s.

2.4 TURBULENCE

When the air moves parallel to the ground, it is called *laminar* wind flow which is best suited for generating steady electrical power. When this laminar flow is disturbed, it is termed as *turbulence*. Natural turbulence is caused by obstacles/obstructions, topography, surface roughness and thermal effects. When the wind hits an obstacle, whirls or waves are formed and the flow becomes non-laminar. It moves in different directions around the prevailing wind direction in waves and eddies and thus, the wind is said to be *turbulent*. The turbulence in the air is a feature of the flow and not of the fluid. These are rapid disturbances in the wind speed having a direction towards the vertical component. This parameter is important as it decreases the power output and causes erratic and extreme loadings on the WPP components causing damage and even failure. The orography (height contours of the earth's surface) compresses the air or creates turbulence. When wind flows around buildings and other structures in the landscape, it slows down or becomes turbulent. A WPP should be placed in a location where the influence of obstacles is minimised.

Turbulence Intensity (TI) is a measure of the strength of the turbulence of the wind compared to its underlying average speed. This can be calculated by the

standard deviation (SD) 'σ' of the wind speed variations about the mean wind speed divided by the mean wind speed, using ten minutes or one hour averaging periods.

$$TI = \frac{\sigma}{\bar{v}} \tag{2.3}$$

where,

σ = Standard deviation (SD) of the wind speed

$\bar{v}$ = Mean wind speed.

If TI is less than 0.1, it indicates low level turbulence.

If it is from 0.1 to 0.25, it represents moderate level. If TI is greater than 0.25, it is said to be a high level.

EXAMPLE 2.2

Calculate the turbulence intensity for the mean wind speed of 6.5 m/s with a standard deviation of 2.96 m/s.

Solution:

Using Eq. (2.3)

i.e.,
$$TI = \frac{\sigma}{\bar{v}}$$

$$TI = \frac{2.98}{6.5} = 0.46$$

This means that the wind flow has a high level of turbulence.

Temperature differences in the air can also create turbulence and reduce the wind speed. If the air close to the ground is warmer than the air on higher levels and the temperature decreases rapidly with height, warm air will rise upwards. The horizontal wind will then meet air that moves in the vertical direction and this creates turbulence. When the wind passes through the rotor of a wind turbine, a very strong turbulence is created. This whirling wind on the leeside of the rotor is called *wind wake* and influences the wind speed up to a distance of 10 rotor diameters or more.

2.5 HILL AND TUNNEL EFFECT

Slopes and hills can also have an impact on the wind speed. When the wind passes over an even hill, the air flow is compressed on the side facing the hill and when it spills over to the other side after the top of the hill, it expands again in the low pressure area. This is in accordance to Bernoulli's principle, wherein reduction in static pressure is associated with increase in kinetic pressure and hence, an increase in wind speeds paving the way for good WPP sites. As the wind passes over moderate hills and ridges, it speeds up. This form of terrain can create a so called *hill effect* so that the wind speed increases up to a certain height above the ground level.

When a valley is softly (without much undulations) embedded between two mountain passes, a natural *tunnel effect* (see Figure 2.6) is created and higher wind speeds are obtained than in the surrounding areas (e.g. *Aralvaimozhy Pass*, *Tenkasi Pass* in south India).

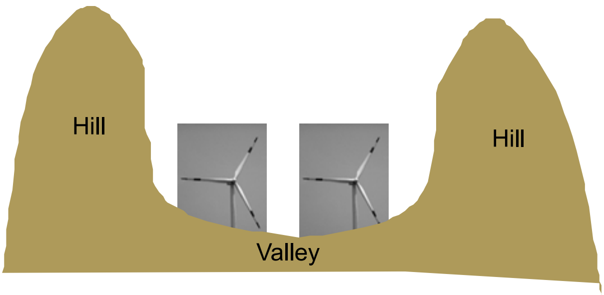


Figure 2.6 Wind speeds up due to Tunnel Effect.

2.6 ENERGY IN THE WIND

Law of conservation of energy states that—Energy can neither be created nor destroyed, it can only be converted from one form to another. When converting (or extracting) the kinetic energy of the wind, the wind turbine rotor has an effect on the wind, as the moving air has to be slowed down, i.e., on the downwind side of the rotor, the air moves more slowly than the upwind side. But if all kinetic energy in the wind has to be converted, the entire moving air has to be retarded completely. This is, however, not a feasible option because if a rotor retards the wind fully, the air flow will stop completely and some of the wind that was heading for the rotor disc diverts around the slower moving air and misses the blades entirely.

In such a case, the wind starts to slow down even before it reaches the rotor blades, thereby reducing the wind speed through the disc [an imaginary circle (see in Figure 2.7) formed by the blade tips, called the *swept area A*]. This proves that, there is always only an optimum amount of power that can be extracted from a

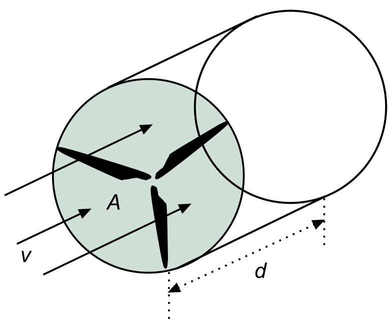


Figure 2.7 Power in the Wind: Wind of velocity v blowing through a disc area (wind turbine rotor) is considered as the swept area A for a distance d. Since moving air is not a solid mass but a fluid, therefore, $m = \rho A d$.

given disc diameter. Therefore, in order to harness the wind energy, the wind turbine rotor must allow some amount of wind to pass through its blades to move on behind the rotor. An ideal wind turbine would slow down the wind by 2/3 of its original speed (maximum being the 59% which is called the *Betz's limit*) on the leeside of the rotor. In practice, only 40% to 50% is achieved by current designs.

The fundamental law of mechanics states that energy can be extracted only from a flow system. Hence, only by allowing the wind to flow from a high speed region to a low speed region, energy can be extracted from a WPP. Therefore, a WPP extracts the wind energy from the vertical area subtended by the rotor span (see Figure 2.7), i.e., when disc of air of mass m flowing at a speed v has kinetic energy E, then this mechanical energy is converted to electrical power, i.e., energy produced per unit time is:

$$P = \frac{\text{Work}}{\text{Time}} = \frac{\text{Kinetic energy } (E)}{t} \tag{2.4}$$

Kinetic energy E contained in wind $P_{\text{kin}} = 1/2\ mv^2$
when,

v = Wind speed (metre per second)
ρ = Density of air (rho) which is 1.225 kg/m^3 at 15°C at sea level
$m = \rho Ad$ (Density $\rho \times$ Area $A \times$ Distance d)
= (kg/m^3) × (m^2) × (m) = kg.

The air density also affects the power produced. The air density varies as a function of pressure and temperature in compliance with perfect gas law. Since pressure and temperature vary according to the altitude of the installation site, their combination affects the air density which can be derived from the simplified relation (valid up to 6000 m altitude) given below:

$$\rho = \rho_0 - 1.194 \times 10^{-4} \times H \tag{2.5}$$

where,

ρ_0 = Standard density (1.225) at sea level
H = Height of the installation site above sea level (m).

But when a volume of air passes through an area A per unit time, d becomes 1, then,

$$m = \rho\ A$$

However, when mass flow rate of air through A is with velocity v, then

$$m = \rho\ A\ v \tag{2.6}$$

Therefore, total power contained in the wind flowing through the swept area A will be:

$$P_{\text{total}} = 1/2\ (\text{Mass flow rate})\ v^2$$
$$= 1/2(\rho\ A\ v)\ v^2$$
$$P_{\text{total}} = 1/2(\rho\ A\ v^3) \tag{2.7}$$

Unit of P = (kg/m^3).(m^2).(m^3/s^3) = kg m/s^2 m/s = N m/s = Watt

This indicates that the power in the wind is proportional to the cube of the wind speed. Therefore, micrositing of WPPs in various terrains is quite crucial, as the slightest increase in wind speed from one location to the next location (which is not very uncommon in windy regions) greatly enhance the economic performance for the same WPP. The following examples will help to develop a better understanding of the need for micrositing.

EXAMPLE 2.3

Calculate the total wind power in an area where the average wind speed is 6 m/s, using a WPP with a 60 m rotor diameter. Assume air temperature is 25°C with a density of 1.225 kg/m³.

Solution:

$$P_{\text{total}} = 1/2\ \rho A v^3$$
$$= 1/2\ \rho(\pi R^2)v^3$$
$$= 1/2 \times 1.225(\pi 30^2)\ 6^3\ \text{W}$$
$$= \frac{1/2 \times 1.225(\pi 30^2)6^3}{1000}\ \text{kW}$$
$$= 373.88\ \text{kW or } 374\ \text{kW}$$

EXAMPLE 2.4

In Example 2.3, if the wind speed v = 4 m/s and 8 m/s, determine the difference in the power output from the wind turbine.

Solution:

$$P_{\text{total}} = 1/2\ \rho A v^3 = 1/2(1.225 \times 3.14 \times (30)^2 \times 4^3) \approx 110\ \text{kW}$$

For wind speed v = 8 m/s, using Eq. (2.7),

$$P_{\text{total}} = 1/2(1.225 \times 8^3) = 0.625 \times 3.14 \times (30)^2 \times 8^3 = 886\ \text{kW}$$

It is seen here that when the wind speed doubles, the power increases by eightfold, i.e., 886/110 = 8.05. But doubling the swept area only doubles the power. Doubling the rotor diameter produces a four-fold increase in energy output. The rotor torque which is closely related to the gearbox cost, will increase by a factor of eight.

Table 2.2 shows the large variability of wind power from around 0.01 kW in a light breeze rising to 41 kW/m² in a hurricane blowing at 40 m/s influences the WPP design. It is essential to spill away power and even shut down a WPP when the wind speed exceeds about 25 m/s, as it would damage the typical WPP if operated under such conditions.

Table 2.2 Power Density and Wind Speed

Wind Speed	m/s	2.5	5.0	7.5	10	15	20	30	40
	km/h	9	18	27	36	54	72	108	144
Power Density	kW/m²	0.01	0.08	0.27	0.64	2.20	5.10	17	41

EXAMPLE 2.5

In Example 2.3, even by slightly, increasing the wind speed from 6 m/s to 7 m/s gives a large increase in power. For this 1 m/s speed increase, calculate the percentage increase in energy content from the same wind power plant at the same site.

Solution:

For $v = 6$ m/s; $P = 0.625 \times 6^3 = 135$ W
for $v = 7$ m/s; $P = 0.625 \times 7^3 = 214$ W

Energy content in the wind for the speed of 6 m/s = 135 × 8760/1000 = 1182 kWh/m^2 in a year (of 8760 hours)

Energy content in the wind for 7 m/s = 214 × 8760/1000 = 1875 kWh/m^2 in a year, i.e., about 59% increase which is quite substantial.

2.7 ENERGY PRODUCTION

The amount of energy produced by a WPP, depends on the wind conditions at the site where it is to be installed. To calculate how much energy a WPP will produce at a specific site, it is necessary to know the wind speed frequency distribution at the hub height at that location. If the wind speed v is measured at a site during one year and the wind speeds are sampled on regular intervals, it is easy to calculate the mean wind speed v_{mean} for that site by adding all the measured values (Σv) for the wind speed and then dividing the sum by n number of observations.

$$v_{mean} = \frac{\Sigma v}{n} \tag{2.8}$$

It is not only the mean wind speed at the site that matters, the frequency distribution is equally important. Based on the wind data collected, the average ten-minute interval wind speed distribution throughout the year is generated as annual histogram in percentage time using vertical bars (see Figure 2.8). The histogram of the percentage duration of different wind speeds is generated as recorded by the anemometers. A narrow distribution means that the wind is quite consistent at the location under consideration. A wide distribution means that the wind varies greatly.

The mean wind speed is not sufficient to calculate the energy output potential of a WPP. This argument can be justified by the following two cases at a particular site for a typical WPP with a rotor diameter of 60 m.

Case 1

At a particular site, twelve days of continuous wind speed at 6 m/s (mean speed 6 m/s) are considered.

$$P_{total} = 1/2\ \rho A v^3$$

$$= 1/2\ \rho \pi \frac{D^2}{4} 6^3$$

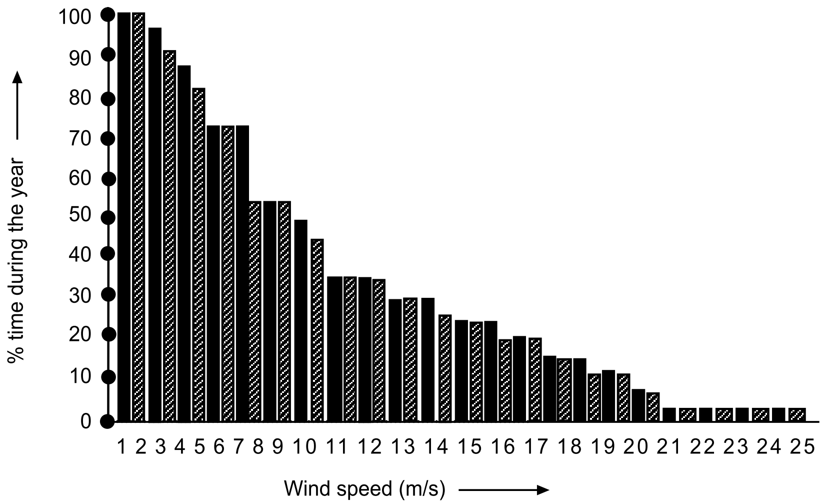


Figure 2.8 Annual Histogram of Wind Speed Duration.

$$= 0.5 \times 1.225 \times 3.14 \times \frac{60^2}{4} \times 216 \approx 374 \text{ kW}$$

$$\text{Energy} = P_{\text{total}}\, t = 374 \times 12 \times 24 \approx 107 \text{ MWh.}$$

Case 2

Twelve days are considered out of which six days are of continuous wind speed at 12 m/s and 6 days are without wind (mean speed 6 m/s).

$$P_{\text{total}} = 1/2\ \rho A v^3$$

$$= 1/2\, \rho\, \pi\, \frac{D^2}{4}\ (12)^3$$

$$= 0.5 \times 1.225 \times 3.14 \times \frac{60^2}{4} \times 1728 \approx 29910 \text{ kW}$$

$$\text{Energy} = P_{\text{total}}\, t = 29910 \times 6 \times 24 \approx 4305 \text{ MWh.}$$

Thus, it can be seen that at the mean wind speed of 6 m/s, the same WPP produces almost 40 times more electric power in six days of case 2 than in twelve days of case 1.

The power from the WPP can still be lowered due to external effects that are as follows:

- **Pressure variation due to altitude:** At sea level, the standard density is assumed as 1.225 at 15°C but in reality as the altitude rises, the density decreases by almost 1% for every 100 m rise in altitude.
- **Temperature variation due to altitude:** When the temperature at the installation site increases, the density decreases by about 3% for every 10°C rise.

- **Due to wake effect:** The aerodynamic interference due to spacing of the WPPs, also affects the performance.
- **Icing and dirt accumulation on blades:** These phenomena also reduce the aerodynamic efficiency of the blades.

However, in a lower wind speed region, a smaller rated wind turbine can produce more energy than a larger roted wind turbine as, it takes lesser wind speed to spin the turbine at full capacity almost all the time.

2.7.1 Weibull and Rayleigh Distribution

There are several methods to describe the wind speed frequency curve. The two most common are the *Weibull* and *Rayleigh* distribution. Weibull is somewhat more versatile, but Rayleigh is somewhat simpler to use.

The statistical probability distribution called *Weibull distribution curve* is named after the Swedish scientist W. Weibull. The Weibull distribution curve (see Figure 2.9) was originally created to describe fatigue loads in mechanical engineering. It is necessary to know all the different wind speeds that occur along with their durations.

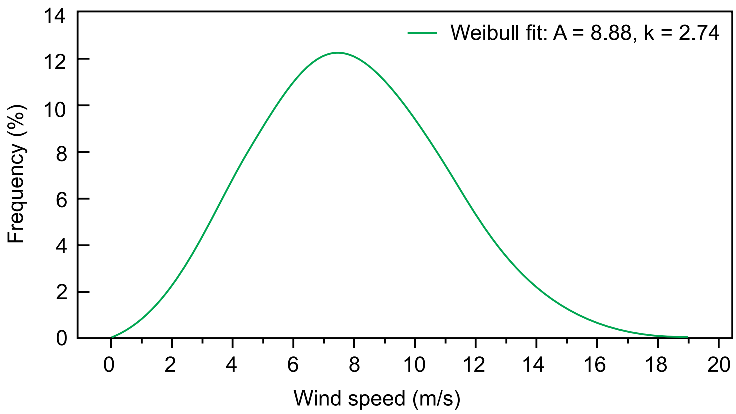


Figure 2.9 Weibull Distribution Curve: A frequency distribution of wind speeds can look like this. The most common wind speeds are 5 m/s–6 m/s. During ~ 950 hours a year, 11% of the time, the wind speed is 6 m/s. The Weibull distribution is defined by two parameters—scale parameter *A* = 8.88 and shape parameter *k* = 2.74 (the so-called Rayleigh distribution).

Weibull distribution curve is a mathematical approximation that describes the number of hours per year that the wind blows at different speed frequencies and provides an anemological description of the site. A typical distribution of wind speed is called the *Rayleigh distribution* (special case of Weibull distribution), which means that there is a little probability of absolutely no wind. This distribution is classified by two parameters to simplify energy estimation methods, as follows:

- Scale parameter, '*A*'.
- Shape parameter, *k*.

The scale parameter *A* (expressed in m/s) is univocally linked to the average speed. The dimensional shape factor *k* modifies the distribution symmetry (values very near to 1 represent very asymmetrical distributions). There are several methods for determining the Weibull parameters *A* and *k* such as:

- Least squares fit method
- Method of moments
- Maximum likelihood method
- Percentile estimator's method.

2.7.2 Wind Rose

A *wind rose* is a pie chart generated from the analysis of the wind resource assessment and it is a helpful tool to determine the wind direction and distribution. After measuring wind data for at least one year, the mean annual wind speed can be calculated. Wind speed and wind direction statistics are visualised in a wind rose pie chart (see Figure 2.10), showing the statistical re-partition of wind speed per direction. To ensure the most effective use of a WPP, it should be exposed to the most energetic wind.

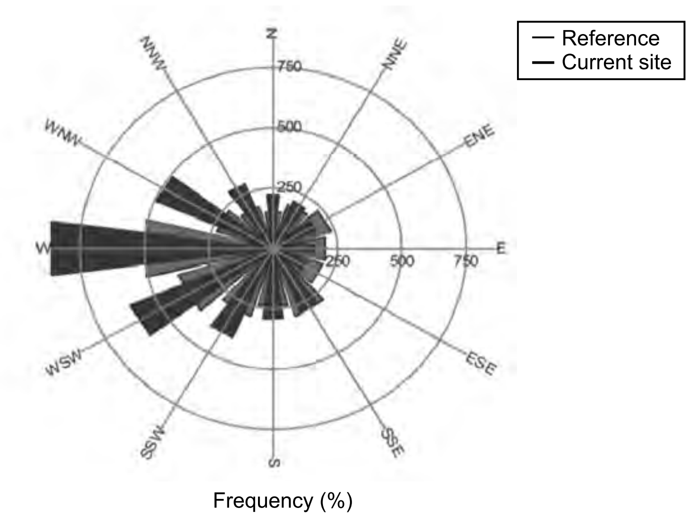


Figure 2.10 Typical Wind Rose. This pie chart is a software output and depicts the wind rose for a particular site. It shows how much energy in different wind directions can contribute.

The wind rose pie chart is a method of graphically presenting the wind direction and wind speed logged at a particular site, at short intervals over a period of time, e.g. one week, one month, or may be longer. The main directions such as north N, NNE, NE, etc. could be sub-divided into 32 directions. North corresponds to 0° or 360° angle measurement, east to 90°, south to 180° and west to 270°. Each concentric circle represents a different frequency, emanating from zero at the center to the increasing frequencies at the outer circles. The length of each spoke around the circle is related to the frequency of the wind that blows from a particular direction

per unit time. To create a wind rose, average wind direction and wind speed values are required.

2.7.3 Wind Power Density

The *wind power density* (WPD) in W/m^2 is the actual indication of the wind energy potential than only the wind speed at any particular site (see Figure 2.10). Its value is a combination of the effects of wind speeds, wind speed distribution and the air density. It is defined as the wind power available per unit area swept by the wind turbine blades. The monthly mean wind power density (in watts per square metre) is given below:

$$\text{WPD} = \frac{1/2\ \rho\ \Sigma_{i=1}^{N}\ v_h^3}{N} \tag{2.9}$$

where,

v_h = Number of hourly wind speed values during the month
ρ = Air density in kg/m^3
N = Total number of hours in a month.

Air is a mixture of gas, solid and liquid particles. Cold air contains more air particles than warm air. Air density decreases as the altitude increases and a power density correction factor needs to be applied in calculations (see Table 2.3). It is evident that the wind is much more sensitive to velocity rather than to air density.

Table 2.3 Air Density with Altitude

Altitude above Mean Sea Level (m)	0	760	1520	2290	3050
Power Density Correction Factor	1.00	0.91	0.83	0.76	0.69

EXAMPLE 2.6

Calculate the wind power density (WPD) for a given air density of 1.163 and $\Sigma_{i=1}^{N} v_h^3$ *= 1604002 m^3/s^3 for the month of October for a ten-minute interval.*

Solution:

$$\text{WPD} = \frac{1/2\ \rho \Sigma_{i=1}^{N}\ v_h^3}{N}$$

$$\text{WPD} = \frac{0.5 \times 1.163 \times 1604002}{4464} = 208.94\ \text{W/m}^2$$

2.8 ENERGY AND POWER

It is important to distinguish the concepts energy and power. *Energy* is the *power* times *time*, i.e., energy is the power multiplied by the time during the period when the power is used.

$$\text{Energy} = \text{Work } W = \text{Power } P \times \text{Time } t$$

The energy is expressed in kilowatt hours (kWh) or joules (J) or British Thermal Units (BTU). A WPP, that gives 1000 kW power during one hour produces 1000 kWh. If the WPP, during a year, gives 300 kW as average power, it produces 300 kW × 8,760 hours = 26,28,000 kWh per year.

Power $P = E/t$, i.e., energy per unit time in watts or kilowatts (1 W = 1 J/s)

Also,
$$\text{Power } P = \text{Torque } T \times \text{Radius of the rotor } R \tag{2.10}$$

Energy content and *wind power density* are, in fact, two different ways to express the same thing. If the power density is known, the energy content is easy to calculate. For this, the power density (W/m^2) is multiplied with the number of hours in a year (365 days × 24 hours = 8760 hours) and divided by 1000 to get the energy content in kWh/m^2.

The energy content of the wind is shown as *isolines* (kWh/m^2 in a year) that connect the points of the same energy content on a map. Isolines for wind energy are named as *isovents* and the maps that contain isovents are called *isovent maps*.

Some wind resource maps just show the average wind speed. Modern wind resource maps give information about the power density or energy content in different areas by isolines or by colours which give much better information than the maps that are just showing the average wind speeds.

To calculate the wind power density and energy content of the wind at a particular site, it is not sufficient to know only the mean wind speed. The power in the wind depends not only on the wind speed but also on the air density. It varies with the air pressure and temperature. For the same wind speed, the wind will contain more power in winters when the temperature is –10°C than the summers when it is +20°C. Data on the wind speeds are sorted into a bin-diagram with wind speed on x-axis and the duration (in hours or percent) on y-axis. The power density of the wind at two different sites with exactly the same mean wind speed can differ considerably.

A WPP is designed to maximise the annual production of electrical energy (kWh) which can be theoretically expressed and assessed by using Weibull distribution as regards the wind speed at the installation site and the power curve of the WPP as a function of the wind instantaneous velocity. Hence, the annual production can be expressed as:

$$E = 8760 \int_0^\infty P(v)\, f(v)\, dv \tag{2.11}$$

where,

8,760 = Number of hours per year

$P(v)$ = Power output (kW) of the wind turbine at a wind velocity v (m/s) deduced from the power curve given by the manufacturer

$f(v)$ = Weibull statistical distribution function of occurrence frequency of wind speeds at the installation site (s/m).

The total potential energy output of a wind farm is obtained by adding the production of every single WPP that are installed.

2.9 ENERGY PATTERN FACTOR

To select the most appropriate WPP for a particular location, it is necessary to estimate the wind resource at that location for which the energy pattern factor (EPF) defined as:

$$\text{EPF} = \frac{\text{Actual power density for a month (a period)}}{\text{Mean power density for the monthly mean speed}}$$

$$\text{EPF} = \frac{1/2\ \rho\ \Sigma \dfrac{v_h^3}{N_m}}{1/2\ \rho\ v_m^3} \tag{2.12}$$

where,

v_h = Number of hourly wind speed values during the month
v_m = Monthly average wind speed
ρ = Air density at that location
N = Total number of hours in the month [24 × 31 (or 30) days]

i.e.,
$$\text{EPF} = \frac{\Sigma_{h=1}^{N} v_h^3}{N v_m^3} \tag{2.13}$$

The value of the cube factor depends on the frequency distribution of the wind. In southern India, with seasonal winds, the cube factor is 1.8. In San Gorgonio pass, California, with local winds, it is 2.4 and in Puerto Rico, with trade winds, the cube factor is 1.4. The range of the EPF consists of a value of 6 for polar regions, 2.7 for continental and irregular regions, 1.57 to 1.92 for coastal regions and 1.22 to 1.36 for trade winds. For general calculation purposes, it is appropriate to use a value between 1.50 and 2.50.

EXAMPLE 2.7

Calculate the EPF for a given mean wind of 5.5 m/s for the month of October for a ten-minute interval and $\Sigma_{h=1}^{N} v_h^3 = 1604002\ m^3/s^3$.

Solution:

Using the formula,
$$\text{EPF} = \frac{\Sigma_{h=1}^{N} v_h^3}{N v_m^3}$$

$$\text{EPF} = \frac{1604002}{4464 \times (5.5)^3} = 2.16$$

To calculate the energy content of the wind during one year, the cubes of the wind speeds are multiplied by the frequency, the products are added up and the sum is entered into a formula.

In Example 2.5, it has been seen that at a site where the mean wind speed is 6 m/s, the wind power is 135 W and the energy content is 1182 kWh/m^2. But

unfortunately this assumption is false, since the power of the wind is proportional to the cube of the wind speed. Then, cube of the sum of the wind speeds, i.e., $(v_1 + v_2 + v_3 + \ldots + v_n)^3$ is not the same as the sum of the cubes of the wind speeds, i.e., $(v_1^3 + v_2^3 + v_3^3 + \ldots + v_n^3)$.

EXAMPLE 2.8

If the wind speed at a site is 4 m/s for half of the year and 8 m/s for the rest of the year, calculate the energy content.

Solution:

$$v_{\text{mean}} = \frac{4}{2} + \frac{8}{2} = 6 \text{ m/s}$$

However, the power density will be

$$P = \frac{1}{2}\rho v^3$$

$$= \frac{1}{2}(4^3 + 8^3)$$

$$= \frac{1}{2} \times 1.225 \times (64 + 512) = 288 \text{ W/m}^2$$

$$\text{Energy content} = \frac{288 \times 8760}{1000} = 1576 \text{ kWh/m}^2 \text{ in a year}$$

A *velocity duration curve* also helps in comparing the energy potential at a windy site. It is defined as a graph with a wind speed on y-axis and the number of hours in the year on x-axis (see Figure 2.11).

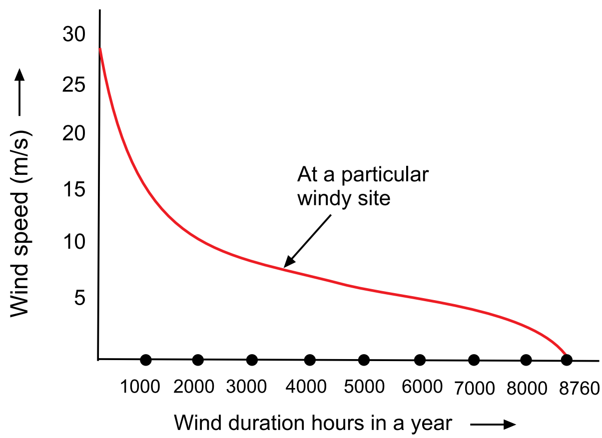


Figure 2.11 Velocity Duration Curve: Sample velocity curve for a particular location.

The nature of the curve gives an idea of the nature of the wind regime at that location. The flatter the curve, the more constant are the wind speeds. More steeper

the curve, more irregular are the wind speeds. For a given WPP swept area, by cubing the ordinates of the velocity duration curve proportional to the available wind power, the *power duration curve* can be obtained. Since the area under the curve is proportional to the annual energy available, the difference between the energy potential of different sites become visually evident.

From the power duration curve, the *machine productivity curve* for a particular WPP at a given location may be constructed. It can be seen that the losses in energy production with the use of an actual WPP can be identified for the location being considered. An example for a 2 MW (see Figure 2.12) WPP is used for a better understanding.

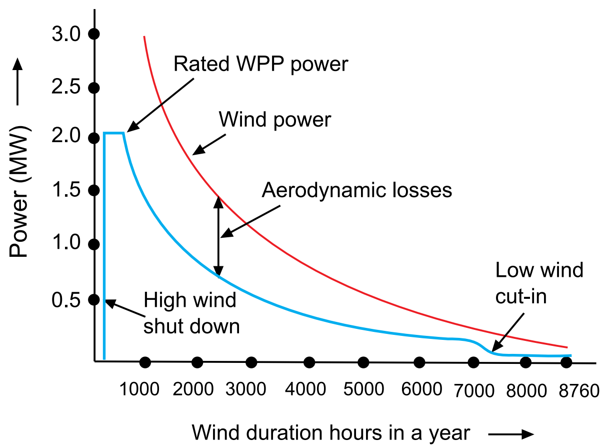


Figure 2.12 Machine Productivity Curve for a 2 MW Wind Power Plant.

There is an increased interest in offshore WPPs, not only due to paucity of the land available but also due to the fact that when a WPP can produce about 1000 MWh–2500 MWh/MW, the same WPP when installed offshore in the sea, can produce 3000 MWh–3500 MWh/MW. But this also implies quite high investments. The efficiency of the use of WPP at a specific site is often assessed based on the ratio between the total annual power output in kilowatt hour and rated power of the WPP in kilowatt.

2.10 SITING

Accurate siting of WPPs at the most appropriate spot is cardinal for maximising the return of investments in wind power projects. The slightest increase in wind speed results in substantial increase in the power output. Wind resource maps (see Figure 2.13) give an initial idea of the probable wind project sites.

In many countries, meteorological institutes have converted the wind data (available over 5–10 year period) from a large number of wind measuring masts into the wind resource maps. These could be used as an initial database. Normally, the standard height

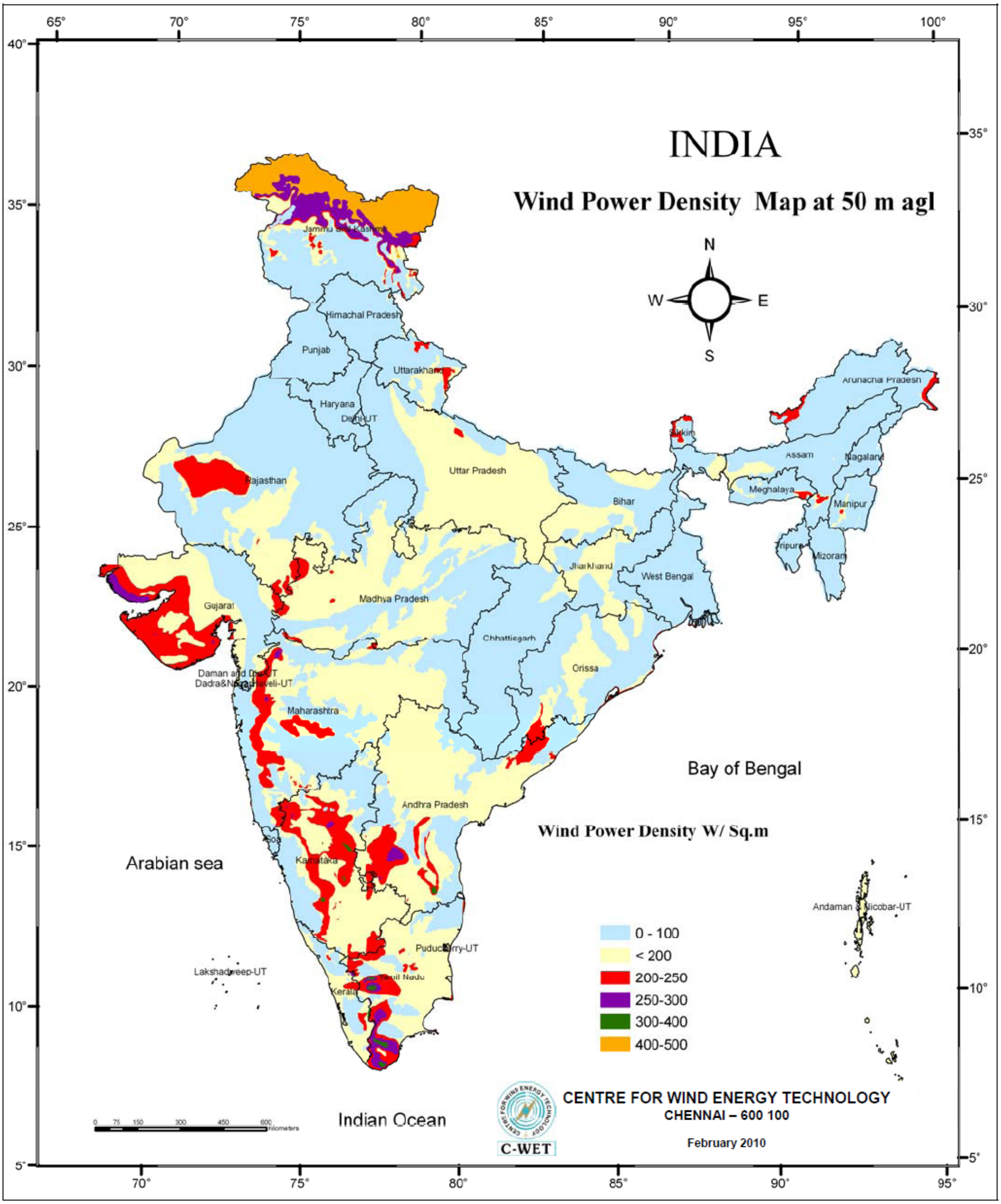


Figure 2.13 **Wind Map of India:** It shows the regions where the wind resources are available. However, for siting the exact location of the WPPs, the detailed wind resource directories are to be referred to that are available at NIWE, Chennai, India.
Courtesy: www.niwe.nic.in

for meteorological masts and measurements made by the meteorological institutes is 10 m agl but now, the general height is taken as 50 m.

In India, the National Institute of Wind Energy (NIWE) at Chennai has made regional surveys and wind resource maps at more than 97 different sites that are suitable for wind power development at 30 m and 50 m heights and the reports are available with them. On a special request, NIWE does wind measurements at greater heights at particular locations. Since the wind speed increases with the height above the ground level, the height in the resource map is always specified. The relevant height for calculations is the hub height which depends on the size of WPP.

Since the power produced by a WPP is directly proportional to the cube of the wind speed, the power production success of any wind power project is all about the exact estimation of the various environmental factors and location of the windy site. Hence, the wind resource assessment and selection of the right site is highly critical for a cost-effective wind power generation. Even a small deviation in the wind resource measurement results can lead to big miscalculations and build up the risk of an uneconomical wind power project.

SUMMARY

First and foremost, a wind power project investor is interested to find out how much energy a wind power project will yield during the 20 years technical lifetime of a WPP. Therefore, knowledge about the wind resource at a particular site is of utmost importance which has been discussed thus far. One megawatt hour of electricity produced by coal emits about a ton of CO_2, one megawatt hour of electricity produced by gas emits about half a ton of CO_2, whereas wind-powered electricity emits no CO_2 at all. For every kilowatt hour of wind energy that is used, approximately 696 g of CO_2 is saved. Wind energy has the lowest life cycle emissions as compared to all other energy production technologies. To get a good production and viable economic returns, the WPPs have to be sited in an area where the wind contains maximum energy. To arrive at an informed conclusion, it is necessary to have a fairly good understanding about the salient features of the wind and its characteristics which have been deliberated in this chapter.

EXERCISES

2.1 Differentiate the terms weather and climate.

2.2 Explain the phenomenon of creation of winds.

2.3 Describe the Coriolis force.

2.4 Distinguish between the concepts of pressure gradient force and geostrophic wind.

2.5 Differentiate the relation between wind profile and surface roughness.

2.6 A WPP generates 3 MW at the rated speed of 8 m/s at atmospheric pressure and 25°C temperature. Determine the change in output power of the WPP if it is operated at an altitude of 1000 m above the sea level at 8°C and the wind speed is 10 m/s and pressure is 0.8 atm.

2.7 Differentiate between the tropical winds, monsoon and polar winds.

2.8 Explain the concept of local winds.

2.9 Give reason for doubling of power output when the swept area of WPP is doubled.

2.10 When the wind speed doubles, the power increases eight times. Explain.

2.11 Explain the concept of air turbulence.

2.12 Calculate the turbulence intensity for the mean wind speed of 8.5 m/s with a standard deviation of 2.94 m/s.

2.13 Describe the impact of slopes and hills on the wind.

2.14 Describe Weibull distribution and its significance.

2.15 Explain how Weibull distribution will change when the shape parameter k is fixed and the scale parameter is increased.

2.16 Describe the effect of obstacles and orography on the wind speed and discuss the implications for turbine siting.

2.17 Describe the local impacts that should be considered in the planning of sites for wind power plants.

2.18 Calculate the energy pattern factor for a given mean wind of 6.5 m/s for the month of August.

2.19 Calculate the total wind power in an area where the average wind speed is 7 m/s using a WPP with a 450 m rotor diameter. Assume air temperature is 25°C with a density of 1.225 kg/m^3.

3

The Wind Power Plant

Who has gathered up the wind in the hollow of HIS hands?
—Proverbs 30:4

Learning Outcome

On studying this chapter, you will able to distinguish the functions of various components of a typical large horizontal axis wind power plant.

CHAPTER HIGHLIGHTS

3.1 INTRODUCTION

Nowadays, the wind turbines have power ratings ranging from a mere 300 W to a stupendous 7.5 MW capacity. Each large WPP functions as a mini (or micro) power station continuously far in excess of the designed technical life time of 20 years as an automatically controlled conventional electrical generator with low maintenance. Hence, the term wind power plant (WPP) is profusely used in this book. The development of the microprocessor has played a crucial role in enabling the cost-effective wind power technology.

By virtue of the market forces, the divide between the small wind turbines and the large WPPs has widened so much that the large WPP manufacturing sector has marched much way ahead. Not only the ratings of the small wind turbines are low, but also the technologies are by and large much different, hence they stand quite apart from the large WPPs.

Based on the type of axis adapted, today, there are two broad families of wind turbines in the world—horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). Although VAWTs have some merits, yet because of their serious limitations, large capacity VAWT market did not survive. The large Darrieus type VAWT (see Figure 3.1) with egg-beater shaped rotors suffered from a number of serious technical problems such as metal fatigue related failures of the curved rotor blades and others which caused the large VAWTs to disappear from the mainstream commercial market, although the small VAWTs and their variations (discussed later in this book) prevail in the market.

Figure 3.1 Darrieus Type Lift VAWT.

Among the HAWTs, there are upwind and downwind wind turbines. The *downwind wind turbines* (see Figure 3.2) have their rotors placed on the leeside of the tower. They have a theoretical advantage that they may be built without a yaw

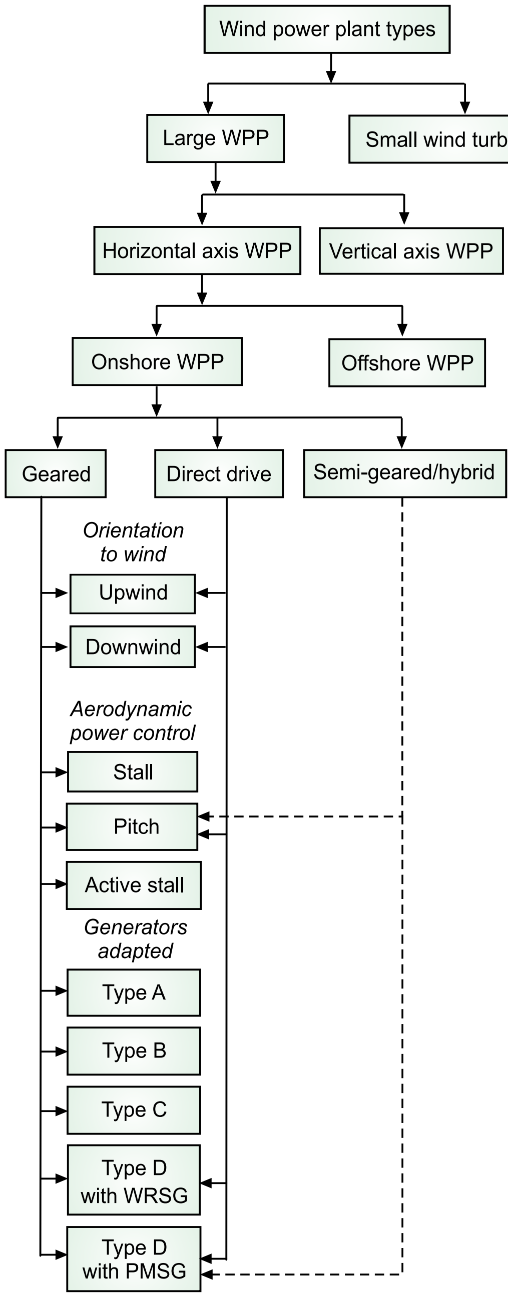


Figure 3.2 Wind Power Plant Classifications.

mechanism, i.e., the rotor and nacelle follow the wind passively so that the wind hits the tower first before they reach the blades. But large wind turbines need cables to take the current away from the generator to the tower bottom. So, untwisting

the cables carrying several hundred amperes of current becomes a problem when the downwind turbine has been yawing passively in the same direction for a long period of time. Therefore, downwind machines of large capacity are few, although several downwind small wind turbines can be found.

When a wind of sufficient speed flows over the modern wind turbine rotor blades, the following sequences of events occur.

(i) No sooner is the cut-in wind speed detected by the anemometer (see Figure 3.4) which may be around 3 m/s and the exact direction of the blowing wind sensed by the digital wind vane (see Figure 3.4), the nacelle is turned (or yawed) to face the wind direction and the rotation of the wind turbine rotor is initiated. Based on the various inputs received from the sensors to the microcomputer, the electronic controller automatically performs the aerodynamic, electric and various controls for the healthy working of the WPP.

(ii) The wind flowing over the wind turbine rotor blades produces a torque on the main shaft connected to the gearbox and/or electric generator.

(iii) If it is a geared wind turbine, the rotation per minute of the slow speed main shaft is increased by a step-up gearbox to match the rotation per minute of the high speed electrical generator. The high speed shaft from the rear of the gearbox connects to the rotor of an induction generator (or synchronous generator) to produce electric power.

(iv) For a direct-drive or semi-geared/hybrid wind turbine, the slow speed main shaft directly turns the rotor of a synchronous generator to produce electric power.

(v) The electric power (produced at 690 V AC under the control of an electronic controller) goes through the circuit breakers in the substation to be stepped up to an intermediate voltage by the electrical transformer.

(vi) The electric power from the transformer is then delivered to the windfarm electric substation by cable or overhead conductors where it is again stepped up to the electric grid voltage level for onward transmission.

The entire operation is fully unmanned and it is automatically controlled by the master electronic controller (see Figure 3.3) to feed power to the electric grid.

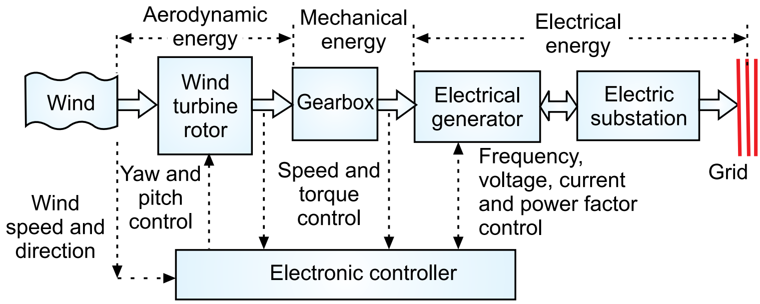


Figure 3.3 Wind Energy Conversion in Wind Power Plant: The wind turbine rotor rotates at slow speed which is stepped up to high speed by the gearbox. The high speed shaft turns the electrical generator to produce electric power which is fed to the electric substation and transmitted through the electric grid to the place of use.

3.2 WIND TURBINE CLASSES

Most large wind turbines are certified to IEC standards. In accordance with IEC-61400, wind turbine class is also one of the factors which determine the suitability of a WPP for the normal wind conditions at a particular site. They are mainly defined by the average annual wind speed (measured at the turbine's hub height), speed of extreme gusts that could occur over 50 years and the amount of turbulence present at the wind site, as given in Table 3.1. Class I, II, and III specify the wind speeds for a specific turbine product. Manufacturers who are certifying WPPs, design them based on one of these classes.

Class I wind turbines are designed to operate in the harshest climates. Class II wind turbines are designed for the medium resource sites and Class III turbines are designed for low wind resource sites. Typically, Class II and III wind turbines have a larger turbine rotor (longer blades) to capture more of the wind energy in lower wind speeds.

Table 3.1 Wind Turbine Classes

Wind class	Type of wind	Wind speed (m/s)	Type of turbulence	Turbulence (%)	Extreme 50 year gust (m/s)
I a	High wind	10.0	Higher turbulence	18	70
I b	High wind	10.0	Lower turbulence	16	70
II a	Medium wind	8.5	Higher turbulence	18	59.5
II b	Medium wind	8.5	Lower turbulence	16	59.5
III a	Low wind	7.5	Higher turbulence	18	52.5
III b	Low wind	7.5	Lower turbulence	16	52.5

The traditional turbulence definition indicates the variation in intensity of the wind speed around a mean value and is based on the simple ratio of the wind speed standard deviation to the mean wind speed. IEC has also developed standards for many other parameters such as power performance, noise and electrical characteristics.

3.3 ROTOR

Today's typical large WPP can have almost 8000 components. Hence, the auxiliary industries manufacturing these parts are doing a great business. Irrespective of different types, every WPP has the following major components (see Figure 3.4):

- Rotor
- Nacelle
- Tower
- Electric substation
- Foundation.

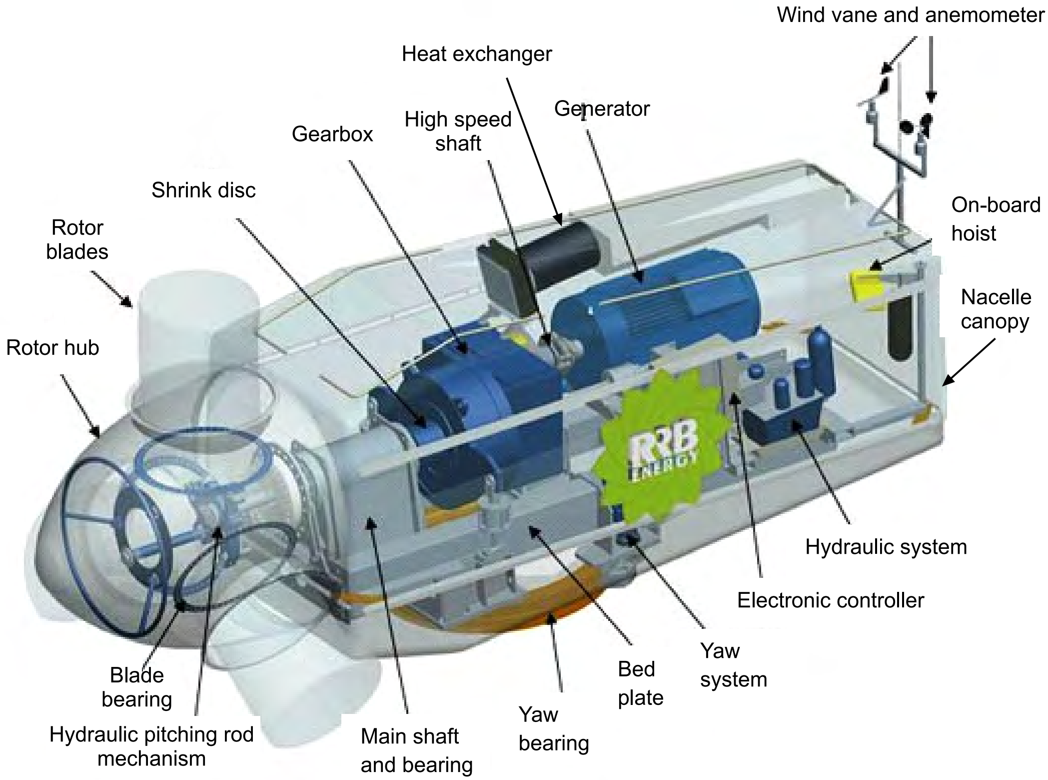


Figure 3.4 Nacelle and Rotor of Three-bladed Geared WPP.
Courtesy: www.rrbenergy.com

A wind turbine rotor (see Figure 3.4) consists of a hub with aerodynamically shaped two or three blades attached to the nacelle. The hub also holds the tip brake control (in case of stall controlled wind turbine) or pitching system for aerodynamic control of the wind turbine. It is made of either welded steel, cast steel or spheroidal graphite iron castings which have better acoustic damping than the normal steel.

Since the main function of the blades (see Figure 3.5) is to harness the maximum energy from the wind, utmost care is taken in its design and manufacture. The blades can be designed for stall control, pitch control or active-stall regulation which means that the aerofoil design as well as the braking arrangements will be different in each case.

To render them light and tough enough, the rotor blades are hollow and made of light weight glass fibre reinforced plastic (GRP) or the more modern material of carbon fibre reinforced plastic (CRP) painted with light colours. The most dangerous enemy of the wind turbine blades is the lightning strike against which an effective protection system is put in place for every blade. The weight of the rotor is carried

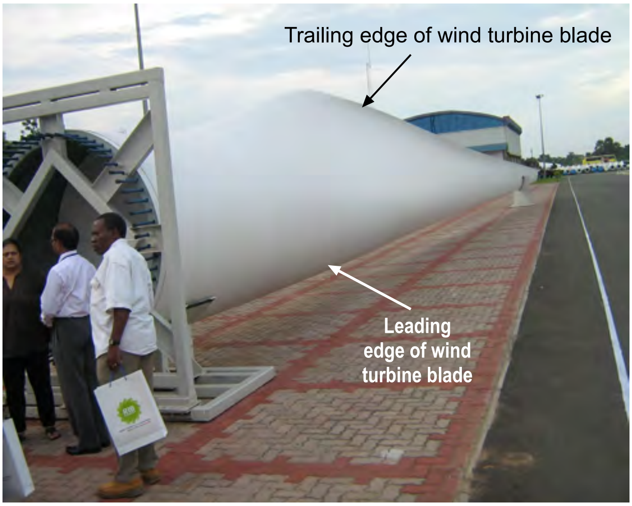


Figure 3.5 **Large Wind Turbine Rotor Blade:** This 600 kW blade is ready to be despatched to the wind farm for installation. The people near the blade depict the sheer size.
Picture by author.

by the nacelle bearings which are so designed that these are also able to absorb all aerodynamic forces, especially the rotor thrust. The longest blade today is the Siemens 6 MW 75 m long blade and its swept area is about 2½ times the football field.

3.4 NACELLE

The function of the nacelle (see Figure 3.4) is to hold together all the components of the WPP. Under normal operating conditions, the nacelle of an upwind WPP always faces the upstream wind direction. The nacelle cover (also called *canopy*) is the outer covering to protect all the parts inside the nacelle from the sun and rain. It is made of GRP or thin steel.

(a) Main Shaft

In the geared WPP, the major function of the main shaft (see Figure 3.6), also referred as the slow speed shaft, is to optimally transfer the torque from wind turbine rotor to the gearbox and/or electrical generator. It is relatively long and supported by roller bearings and/or shrink discs on both the ends. The main shaft of forged steel is generally centre-bored to reduce its weight and at the same time, to allow the hydraulic/electric power circuits and pitch system components to pass through for the blade pitching systems situated in the hub.

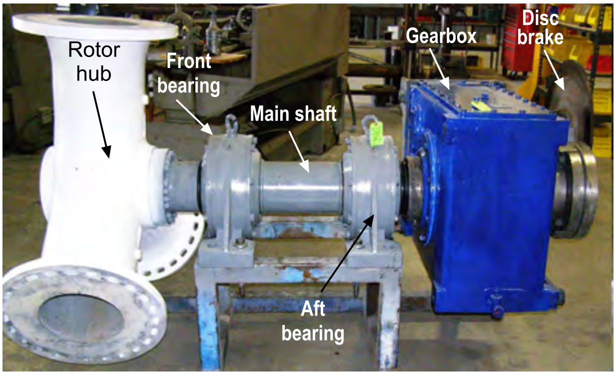


Figure 3.6 **Main Shaft:** Main shaft and drive train of a 110 kW geared WPP. *Picture by author.*

(b) Gearbox

Note: *Variable speed WPP using a direct-drive generator does not require a gearbox.*

The large WPPs run at a low speed in the range of 10 RPM to 20 RPM depending on the rotor diameter. Hence, many WPPs mounted with high speed generators require a gearbox to step up the speed to match the electric generator speed. The gearbox (see Figure 3.6) used in geared large wind turbines is one of the singlemost, heaviest and expensive components. Installed in between the wind turbine rotor and the electrical generator, the gearbox converts the slow speed rotation of the wind turbine rotor on one side to high speed shaft on the other side to match the high speed of electrical generator shaft. If the synchronous speed of the electrical generator is 1500 RPM and if the rated WPP rotor speed (for the most probable wind speed at a particular windy site) is taken as 30 RPM, then a gearbox ratio of approximately 50:1 will be necessary. Following types of gearboxes have been used in WPPs:

- Parallel axis gearbox using spur and helical gears
- Planetary or epicyclic gearbox
- Combination of the above two types
- Hydrodynamic gearbox.

The planetary gearbox consists of the sun gear, planet gears and the ring gear. The planet gears are mounted on the rotating planet carrier.

A typical three-stage planetary gearbox has two planetary stages and one helical stage and is generally used in a typical large geared WPP. Two-stage planetary gearbox is typically used in hybrid (semi-geared) WPP (discussed later). Due to the wind turbulence, the gearbox suffers tremendous stress and even a small defect in any one interlinked component can bring the WPP to a complete halt, rendering it the most high maintenance oriented part. Planetary gearboxes have higher power densities than the parallel axis gears offering a multitude of gearing options and a large change in RPM within a small volume. The limitation of planetary gearbox is the need for highly complex designs and the general inaccessibility of important parts and high loads on the shaft bearings. Cooling of the gearbox is done by the gearbox oil which is again cooled by a heat exchanger (see Figure 3.4).

(c) Couplings

The basic function of the coupling is to transmit the torque. To couple the shafts, gearboxes, generators and other parts, different types of couplings are used by the WPP manufacturers:

- Flange couplings
- Shrink fit couplings
- Fluid couplings.

(d) High Speed Shaft

The high speed shaft is only applicable to the geared WPPs and not to the direct-drive WPPs. The high speed shaft (see Figures 3.4 and 3.7) connects the rear of the gearbox to the electrial generator shaft.

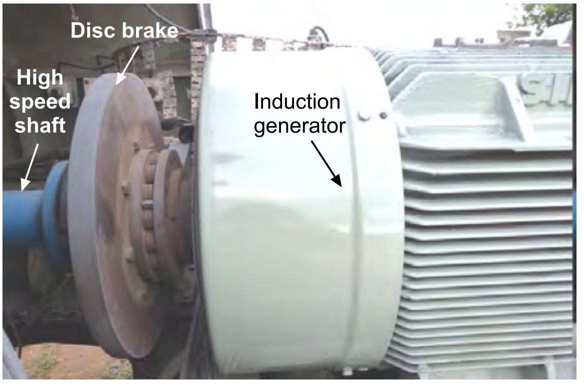


Figure 3.7 Disc Brake: The disc brake is generally mounted on the high speed shaft. *Picture by author.*

(e) Disc Brake

Although, the primary braking of large wind turbines is always aerodynamic (discussed further in this book), most of the wind turbines additionally have a disc brake (see Figure 3.7) that is activated to fully stop the wind turbine rotor after it has been slowed down to around 1 RPM by the primary aerodynamic braking. The disc brake is a friction device of hardened alloy mounted with a brake calliper, brake pads, spring loaded activator and hydraulic circuits. It is generally mounted on the high speed shaft nearer to the gearbox. Depending on the sensor inputs, the signals from the electronic controller activate the brake callipers to apply the brake pads on to the disc to completely halt the rotation of the wind turbine, usually at the time of maintenance. If in any case, the aerodynamic brake fails, the disc brake is also designed to stop the wind turbine with full torque as well.

(f) Hydraulic System

To operate the disc brakes (or tip brakes of stall wind turbines or blade pitching, if hydraulically operated) and other functions, a hydraulic system is mounted generally

on the mainframe of the nacelle (see Figure 3.4). The hydraulic system consists of an oil sump, electric motor, closed loop hydraulic circuits, relevant sensors and all these are controlled by the electronic controller.

(g) Electric Generator

The electric generator is the last link in the geared WPP power train, that is, the main shaft, gearbox, couplings and high speed shaft. Unlike other components of the drive train, the mechanical stress is relatively low on the generator. It is rotated by the high speed shaft (or directly by the main shaft in the case of direct-drive wind turbines) to convert the mechanical energy into electrical energy. Depending on the design and control strategy adopted, different WPP manufacturers use different types of electrical generators. It could be a squirrel cage induction generator (see Figure 3.4), wound rotor induction generator, doubly fed induction generator, wound rotor synchronous generator or permanent magnet synchronous generator.

(h) Cooling Systems

Considerable amount of heat is generated continuously in a WPP nacelle, mainly from the electrical generators, gearbox, yaw gears and the hydraulic unit. The cooling of the gearbox is done by the lubrication oil inside the gearbox which is again cooled by a heat exchanger (see Figure 3.4). The heat exchanger mounted on the nacelle canopy pushes out the heated air to the outside atmosphere.

The electric generator can be cooled in two ways—either by air or liquid. Lower capacities WPPs usually employ air cooled generators while the higher capacity ones generally adopt liquid systems. The air flow needed for air-cooled ones is produced by a fan located on one end of the generator axis.

(i) Electronic Controller

It is the electronic controller (see Figures 3.3 and 3.4) which is responsible for rendering the WPP to be intelligent and fully unmanned. It regularly analyses the signals from all the WPP sensors, especially the power output several times in a second. Every WPP has two electronic controllers—the *nacelle electronic controller* (see Figure 3.4) mounted on the mainframe of the nacelle and *tower bottom electronic controller*. Both are almost identical, and can monitor and control the entire WPP operations simultaneously and independently. This is done for redundancy, that is, if one of them fails for any reason, the other will still continue to function and keep the WPP operating. Moreover, the maintenance personnel can monitor and control the WPP from the tower bottom itself without climbing to the top of the tower.

(j) Sensors in WPPs

Numerous sensors in every WPP are that which renders it to be fully automatic and unmanned. For a typical multimegawatt WPP, there could be around 500 sensors. From safety point of view, the critical sensors like the wind vane, anemometer and a few others are duplicated for redundancy. So, if one of the sensor fails, the

alternate one continues to function. The signals from all these sensors are fed to the on-board microcomputer in the electronic controller (see Figure 3.4) which is the brain of the WPP. To provide an overall idea, functions of some of major sensors are stated below:

(i) **Wind vane:** Sensing the wind direction is of prime importance as the wind turbine has to be turned (yawed) in a particular direction.
(ii) **Anemometer:** The wind speed is continuously measured by the anemometer to decide various modes of operation of the WPP. This comes in various types, however, the cup type is the most popular, but of late the modern ultrasonic ammeter is also becoming popular.
(iii) **Pitch angle sensor:** This measures the blade pitch angle for pitch-regulated WPPs.
(iv) **Wind turbine rotor speed sensor:** This optical speed sensor keeps track of the rotation per minute of the slow speed shaft.
(v) **Electric generator rotor speed sensor:** This continuously monitors the speed of the electric generator.
(vi) **Sensors for hydraulically activated tip brakes:** This is for stall regulated WPPs.
(vii) **Pressure drop sensor:** This monitors the pressure in the hydraulic circuits of the hydraulic system.
(viii) **Disc brake pad sensor:** One of the most replaced components during maintenance checks are the brake pads which get worn out due to the frequent operation of the disc brake and its wearing out is monitored by the brake pad sensor.
(ix) **Temperature sensors:** There are temperature sensors in various locations of the WPP nacelle to measure the ambient temperature outside the nacelle, inside nacelle, main bearings, gearbox oil, generator winding, hydraulic fluid, etc. They are even duplicated at crucial places for redundancy.
(x) **Vibration sensors:** These are for the WPP nacelle and the tower structure to avoid their collapse.
(xi) **Oil level sensors:** These sensors are found wherever there are oil filled enclosures such as the gearbox and other components.
(xii) **Electrical parameter measurement sensors:** These are used to measure various parameters such as voltage, current, power, frequency and others.
(xiii) **Automatic shut down sensor:** In the event of grid failure, this is necessary to avoid islanding.

(k) Electric Hoist

Almost all modern large WPPs have an electric service hoist (see Figure 3.8) at the rear end of the nacelle on the mainframe to lift up maintenance related heavy material from the ground level. The hoisting capacity may range between 500 kg to 1 ton or more.

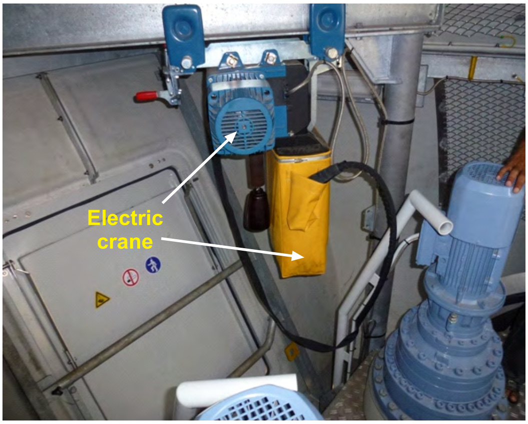


Figure 3.8 **Nacelle Electric Hoist:** The electric hoist is almost a mandatory item in the WPP to lift up mainte-nance related material from the ground level.
Picture by author.

(l) Yaw System

The yaw system (see Figure 3.4) of a WPP consists of the yaw drive and the yaw bearing (or yaw ring) and is located at the bottom of the nacelle mainframe. Depending on the wind direction sensed by the wind vane and the wind speed sensed by the anemometer, the electronic controller commands the yaw drive to turn the nacelle to face the wind. Generally, each WPP (depending on the capacity) contains two or more yaw drives. Yawing speed (yaw rate) is extremely slow to reduce large forces that are detrimental for the stability of the tower.

(m) Nacelle Mainframe (Bedplate)

The nacelle mainframe, also called bed plate, is either a steel-welded structure or a cast material (see Figure 3.4). During operation of the WPP, the nacelle mainframe has to carry the load of all the components safely to keep the WPP effectively functioning. Secondly, it has to transmit the thrust loads safely to the tower foundation.

(n) Electric and Electronic Control Cables

The electric power generated by the electric generator at the top is brought down to the tower bottom by three-phase electric cables that are suspended down from the nacelle bottom (see Figure 3.9). The electronic control cables (generally optical fibre cables) from the nacelle electronic controller are also brought down along with the power cables by clamping them along with the electric cables suspended from the nacelle bottom.

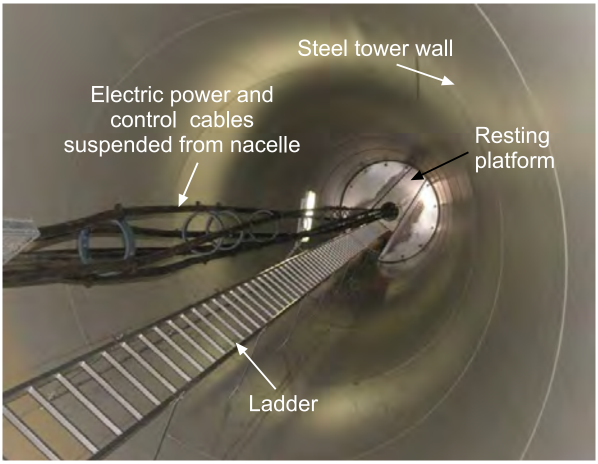


Figure 3.9 **Electric and Electronic Control Cables Inside Tubular Tower:** The electric and control cables are suspended down to the tower bottom. The antitwist sensor ensures that the cable is untwisted after the permissible limit.
Picture by author.

3.5 TOWER

The main function of a tower is to hold the nacelle high above the ground safely so that the rotor blades get a relatively non-turbulent laminar wind flow which is usually available at greater heights. Larger WPPs are usually mounted on tower heights ranging from 50 m to 127 m above the ground level. The tower also ensures that the blades do not touch the ground and also transfers the useless thrust loads effectively to the foundation. Following are the major types of towers that are used by the wind industry:

- Lattice towers (see Figure 3.10) assembled from angle iron members.
- Steel conical tubular towers (see Figure 3.9).
- Guyed towers are generally used for lower capacity WPPs where guy wires (or stay wires) are used to hold the tubular or lattice type tower in vertical position and also to tilt it down for maintenance.
- Concrete tower is built of concrete with steel reinforcements.
- Hybrid tower is partly built of concrete tubular section at lower base and the upper portion of steel tubular sections.

(a) Electric Control Panel

Every WPP has an electric panel at the bottom of the tower. If it is a tubular tower, this will be housed inside the tower bottom (see Figure 3.11). The power and control cables, which are brought down from the nacelle top, are terminated in the electric control panel at the bottom of the tower consisting of power electronic devices, relays, electrical contractors and measuring and recording instruments.

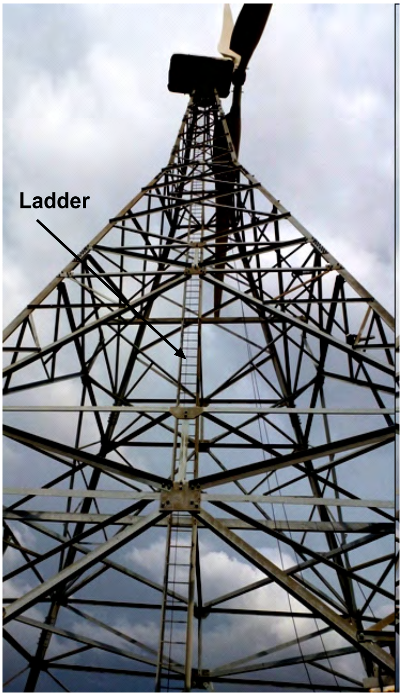


Figure 3.10 Lattice Tower Ladder. *Picture by author.*

Figure 3.11 Tubular Tower Bottom: In a tubular tower, no separate building is required for the electric panel and transformer. *Picture by author.*

(b) Tower Bottom Electronic Controller

The tower bottom electronic controller (see Figure 3.11) is a replica of the nacelle electronic controller and is generally housed adjacent to the electric panel. The microcomputer housed in electronic controllers, continuously stores the enormous amount of data collected from the various sensors, checks the status and controls numerous switches, actuators, hydraulic pumps, valves, and electric motors of the WPP.

Through the electronic modems provided therein, the electronic controllers can also communicate with the owner/operator of the WPP at a distance through wired or wireless supervisory control and data acquisition (SCADA) systems. The SCADA communicates with the WPPs through various communications networks (such as optical fibres) and communication links (like internet or SMS messages) that provide real time data and send alarms/requests for record or maintenance service. Simultaneously, the operator can even remotely control the WPP.

The SCADA system acts as a brain connecting the individual WPPs, substation and the meteorological stations to the central computer. The SCADA helps the owner/operator to see which WPPs are working or which are stopped on his/her computer screens (shown as dotted circle in Figure 3.12). It keeps a record of all the activities on a ten-minute intervals such as energy output, availability and error signals and allows the operator to determine what corrective action, if any, needs to be taken.

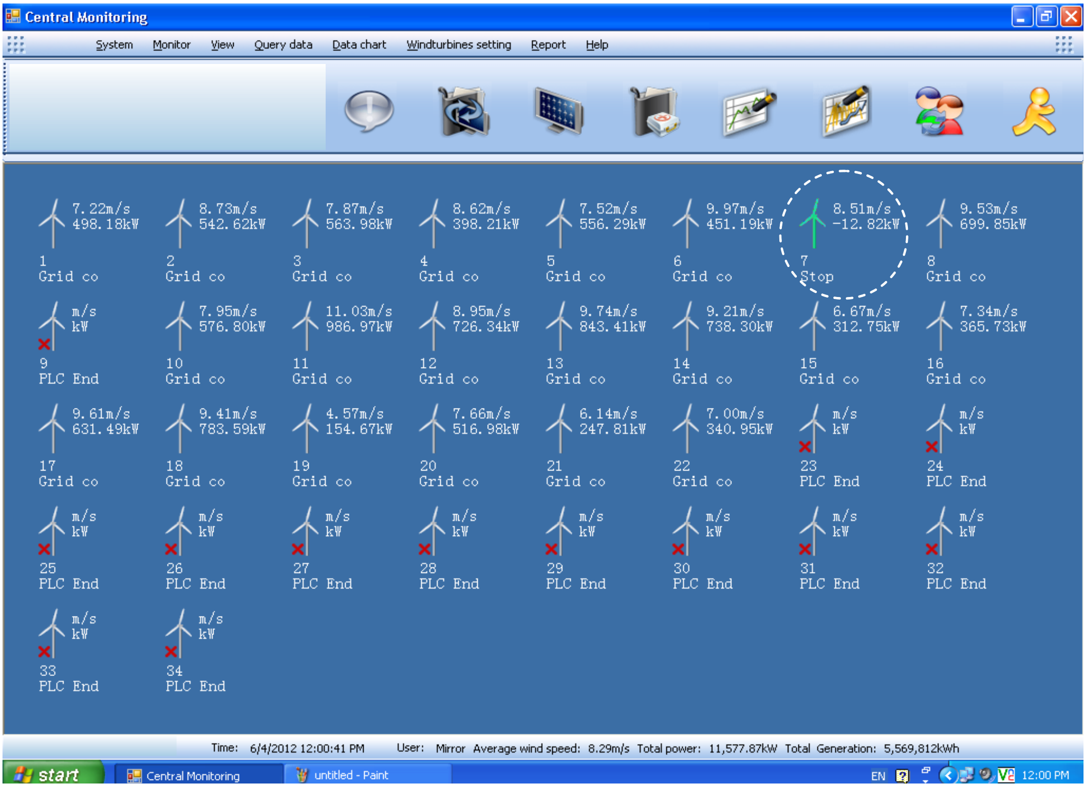


Figure 3.12 **SCADA Screendump of Typical Modern Wind Farm:** The encircled WPP is in stopped condition. *Picture by author.*

(c) Tower Climb Systems

To reach the nacelle for maintenance purposes, the maintenance crew enter the tower door to climb the tower ladder (see Figures 3.9 and 3.10) in every tubular and lattice tower. At regular intervals along the ladder, resting platforms (see Figure 3.9) are provided inside the tower, for the maintenance crew as they climb up for service and maintenance.

As the capacity of WPPs increase the tower height also increases. For certain modern multi-megawatt WPPs, in addition to the ladders, electric lifts (see Figure 3.13) are also provided inside the tubular towers for faster access and efficiency. Today, even the hub height of 135 m for the 7.5 MW Enercon wind turbines is not uncommon.

3.6 ELECTRIC SUBSTATION

Most of the WPPs produce power at 690 V AC. Some larger WPPs such as the direct-drive ones use a higher generator voltage, around 3 kV but this is not high

Figure 3.13 **Service Lift in Tubular Tower:** For tall wind turbines, additional lifts are also provided to take the members of maintenance crew up to the nacelle.
Picture by author.

enough for economical direct interconnection to the grid. Invariably, all WPPs have an electric substation (see Figure 3.14) consisting of a pad-mounted transformer connected to transmission network through a medium voltage collector network. A power transformer is used to interface with the transmission grid.

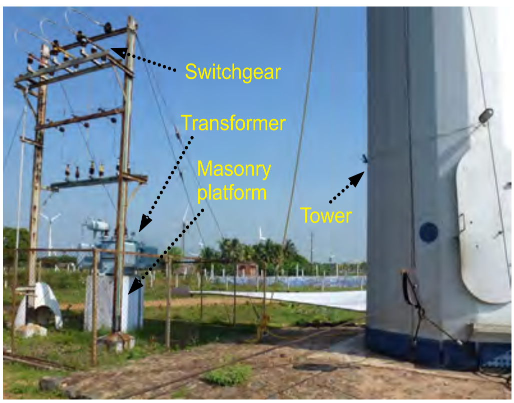


Figure 3.14 **Electric Substation.**
Picture by author.

(a) Transformer

Generally, the power produced by a typical WPP is of 690 V AC and hence, cannot be directly fed to the grid. Therefore, it is necessary to have a transformer (to step up to medium voltage) with protective circuit breakers, protection relays and associated switchgear located at the tower base of each WPP (sometimes, outside the tower base in a switchyard) and is termed as *padmount transformer* (see Figure 3.14). In most of the WPPs, the electric power cables from the nacelle top are dropped down to the electric transformer at the bottom of the tower where the voltage is stepped up to a higher voltage of 11 kV or 33 kV/66 kV. Most of the times in India, whether it is a lattice type or tubular type tower, the transformer is mounted on a raised masonry platform (see Figure 3.14) in a separate fenced enclosure.

In some WPPs of relatively smaller capacity, the electric substation can also be mounted on the outer wall of the tubular tower.

(b) Electric Switchgear

Most of the associated electric switchgear like circuit breakers, isolators, other interconnecting devices and the associated electrical poles are installed inside the fenced enclosure adjacent to the tower (see Figure 3.14). From safety point of view, the entire WPP installation and substation is well earthed.

Fire extinguishers are also provided inside the switch room/switchyard at the bottom of the tower (to be used in case of fire).

3.7 FOUNDATIONS

The foundation of a WPP performs two basic functions. Firstly, it has to bear the dead load weight of the WPP and the tower to keep it upright without any sinkage during the whole technical lifetime of 20 years. Secondly, due to the major cantilever dynamic loads produced as result of the wind thrust and other forces, it has to prevent the wind turbine from tipping over. Whether it is the tubular tower foundation or the lattice tower foundation, the average depth of the foundation approximately ranges from 3.5 m to 4.5 m depending on the soil condition and the capacity of WPP.

SUMMARY

Various components of a typical horizontal axis large capacity WPP are discussed in this chapter. It became evident that the modern WPP is a classic mechatronic machine which involves the coordinated efforts of electrical, mechanical, civil, electronics, instrumentation and computer engineers for designing, manufacturing and operation of wind power plants.

EXERCISES

3.1 Large VAWTs have not become so popular as compared to the large HAWTs. Give reasons.

3.2 Distinguish the features of the three major types of aerodynamic control in large WPPs.

3.3 Justify the reasons for centre-bored main shafts of the geared WPPs.

3.4 Justify the choice of planetary gearbox for large WPPs.

3.5 Distinguish the major features of at least four major types of sensors used in WPPs.

3.6 The high speed shaft is an electric fuse in large WPPs. Comment.

3.7 Describe the methods of reducing the heat produced in the needle by different components of the large WPP.

3.8 Describe the importance of vibration sensors in WPPs.

3.9 Justify the reasons for the slow yaw rate of large WPPs.

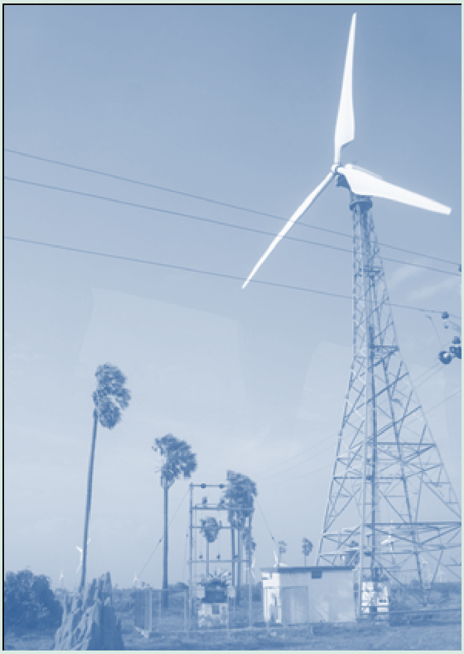
3.10 Distinguish the major features of five types of towers used for WPPs.

3.11 Describe the role of SCADA system in a WPP.

4

Wind Energy Conversion

And the LORD changed the wind to a very strong west wind.
—Exodus 10:19



Learning Outcome

On studying this chapter, you will able to explain how the wind power plants convert the wind energy into electrical energy.

CHAPTER HIGHLIGHTS

4.1 INTRODUCTION

Wind can be very strong and powerful. It can be strong enough to bend (see title page picture) or break-off trees and rip off roofs from buildings. Storms and hurricanes can create natural disasters. This wind power can be turned into useful electric power by wind power plants (WPPs). Therefore, the winds that move above our heads have to be caught and transformed to a usable form of energy. This can be done by the wind turbine rotor which is connected to an electric generator. It was seen earlier that the power of the wind can be very strong since it is proportional to the cube of the wind speed. When the wind speed doubles, the power increases to eight times.

The amount of energy that a wind turbine rotor can convert into electrical energy depends on a number of factors. Other than the wind speed, it depends on various factors on how efficiently and effectively the wind turbine rotor can convert the kinetic power of the wind to useful electrial power as discussed in this chapter.

4.2 ROTATION PRINCIPLE

Bear in mind that air is a fluid and its behaviour is based on the theory of fluid mechanics. Like all gases, air flows and behaves in a similar manner as the water and other liquids do. Even though air and water seem very different substances, they all conform to the same set of mathematical relationships of fluids.

There are two major methods for converting the kinetic energy of the wind into mechanical work. Both strategies depend on slowing down the wind to extract the kinetic energy:

- Drag principle
- Lift principle.

It should be noted that the *lift* and *drag principle* can only exist in the presence of a moving fluid. It doesn't matter if the object is stationary and the fluid is moving or the fluid is stationary and the object is moving through it. The thing that really matters is the relative difference in speeds between the object and the fluid that makes the object (in this case, the wind turbine blades) to move.

4.2.1 Drag Principle

The least efficient principle of rotating the wind turbine rotor is by the drag principle. 'Drag' is the force experienced by an object that is in line with the flow of any fluid such as the air stream. Drag force is developed by obstructing the flowing wind and creating a turbulence. Drag devices are simple wind machines that use flat or curved blades to catch the wind in the enclosed area to turn the rotor. Drag force depends on exposing a flat or curved area on one side of a rotor to the wind while shielding the other—the resulting differential drag force turns the rotor. The parachute is an example that relies on the drag force to slow down

the rate of descent. Savonius wind turbine (see Figure 4.1) is another example which works on the drag principle. The Savonius rotor consists of two or more curved interlocking plates grouped around a central shaft between two end caps. It works on the principle of drag. Such turbines are more popular in the small wind turbine category.

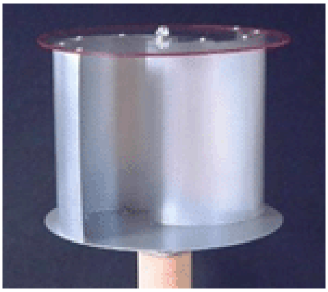


Figure 4.1 Drag Principle: The force of the wind impinges on the concave surfaces on the vertical axis to drag them along to rotate and the electrical generator coupled to it generates power. *Courtesy:* http://cygnus-power.com

The drag force is due to the viscous frictional forces at the aerofoil surface and the unequal pressure on the aerofoil surface facing towards and away from the oncoming flow. In other words, the wind drags the blades along the direction in which it is blowing. Since the blades are fixed to the hub and have only one degree of freedom, it cannot move linearly in the wind's direction. Instead, it is dragged into a rotational movement.

A pure drag force D can be found by calculating the power P captured by a body with surface area A, moving with a velocity v due to the impinging of the wind stream of undisturbed wind velocity v_o.

$$P = D v_r \tag{4.1}$$

where,

v_r = Relative velocity given by $v_o - v$.

Savonius is a less cost-effective WPP, as it consumes considerable amount of material as compared to its size and it is also relatively inefficient. Moreover, it is difficult to protect it from overspeeding during a storm and may fly into pieces.

4.2.2 Lift Principle

The modern electricity producing large WPPs work on the principle of 'lift'. The lift principle is applicable to streamlined objects (see Figure 4.2). Objects designed to minimise the drag forces are called as streamlined because the lines that flow around them follow smooth, stream-like lines such as the shape of a fish, aircraft fuselage and wing sections of aircrafts, helicopters and the wind turbine blade aerofoil.

The forces developed by the lift machines are far greater than those achievable with the drag machines having the same surface area. Typically, lift devices can

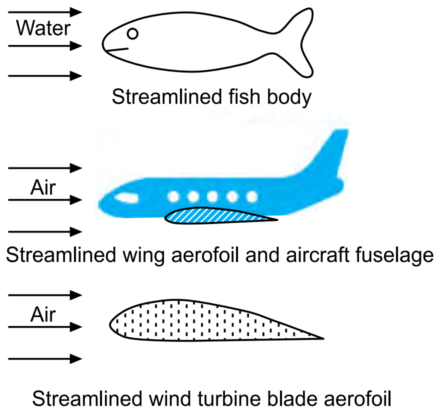


Figure 4.2 Fluid Flow Streamlined Objects.

capture 50 times more power per unit of the projected area than the drag devices. If you stretch your arm out through the window of a car moving at a good speed parallel to the road and change the angle slightly, you will suddenly feel your arm being drawn upwards and backwards. Your arm works like the wings of an airplane at the most appropriate angle as you can feel a strong *lift force* (see Figure 4.3).

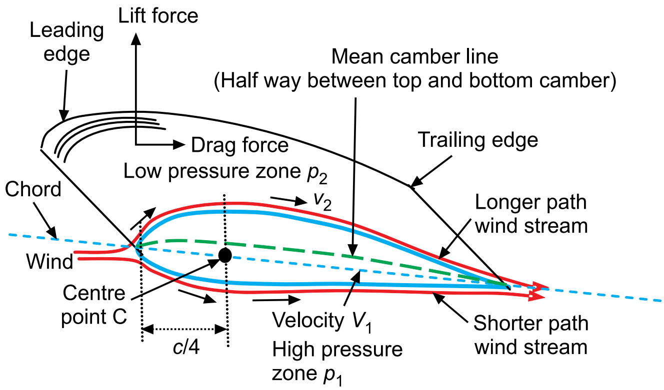


Figure 4.3 Aerofoil Lift Action: When air (i.e., fluid) moves over the aerodynamically designed wind turbine blade, a lift action is created. Application of Bernoulli's theory is one of the theories to explain the lift action. All the forces act on the centre point C inside the blade which is about 1/4 of the chord line.

Although, generation of lift always causes a certain amount of drag to be developed, it is relatively quite small. Hence, all large modern WPPs use the lift principle. Unlike the drag devices, the wind turbine blades are aero-dynamically shaped (see Figure 4.3) and show similarity to the aerofoil wings of aircrafts and the helicopter propellers. When a lift type rotor blade is cut, its cross section shows a streamlined asymmetrical aerofoil shape with the thicker edge known as the *leading edge* facing the direction of the wind and the thinner part on the leeside called the *trailing edge*.

The line that divides the aerofoil into two equal halves joining the leading edge and trailing edge extremities is called the mean *camber* line. The centre line that joins the two extremities of the leading and trailing edges of the aerofoil is called the *chord line c*. The aerofoil has also a *centre point C* which is situated on the chord about 25% from the leading edge of the aerofoil (this distance depends on the shape of the aerofoil). All the forces acting on the aerofoil is concentrated at this point.

The wind turbine blades (analogous to the aircraft wings) also experience the same lift force. The basic difference is that the aircraft wings are fixed to the fuselage that is mounted on the wheels to move in horizontal plane. As, the wind turbine rotor blades are mounted on a hub, the lift action lifts the blades in vertical plane. As it has one and only one degree of freedom, it moves in a circular motion.

Figures 4.4 and 4.5 illustrate the pressure distribution around the blade aerofoil for different angles of attack α. It is evident that the pressure distribution around the blade aerofoil changes with the change in angles of attack.

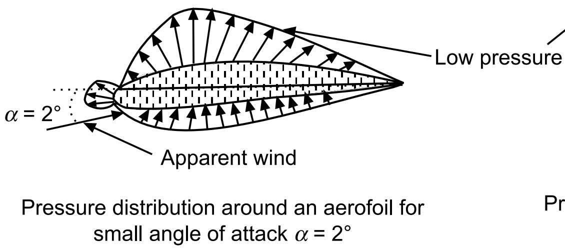


Figure 4.4 Aerofoil Pressure Distribution at α = 2°.

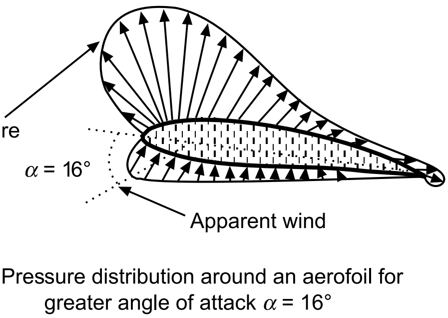


Figure 4.5 Aerofoil Pressure Distribution at α = 16°.

Lift mainly deflects the wind and extracts the kinetic energy with little turbulence. Therefore, it is a more efficient method of extracting the energy from wind than the drag phenomenon.

It is to be noted that the total aerodynamic energy captured by the wind turbine rotor is the sum of electric energy (produced), rotational energy (inertia) and energy losses (heat).

The performance of a WPP also depends on the following wind speed values:

- ***Start-up speed:*** With this wind speed, the rotor just starts to rotate and the electric generator generates a voltage increases when the wind speed rises.
- ***Cut-in speed:*** At this wind speed, the voltage which is high enough for the WPPs to be connected to the grid. It ranges between 2 m/s–4 m/s.
- ***Rated speed:*** It is the wind speed at which the rated power is reached and its range is between 10 m/s–14 m/s.
- ***Cut-off speed:*** It is the wind speed beyond which the rotor is stopped to save the WPP from possible damage. It ranges between 20 m/s–25 m/s.
- ***Survival speed:*** It is the wind speed which the WPP withstands without getting damaged in the worst storm which may occur on the installation site during the design lifetime (50 year recurrence period). It ranges between 55 m/s–65 m/s.

4.3 FORCES ON A ROTOR BLADE

No sooner does the wind vane sense the direction of the wind, the nacelle is turned by a yaw angle δ (delta) to face the wind and the following phenomena occurs:

- Undisturbed wind velocity v_o parallel to the turbine axis
- Rotation of the blade creates a drag velocity component v_t perpendicular to v_o vector.

As the blade moves through the air, although the actual undisturbed wind speed v_o is perpendicular to it (see Figure 4.6), but as far as the blade is concerned, the wind blows towards it from a different angle called the *apparent wind speed* v_{app}. It is also known as *relative wind speed*.

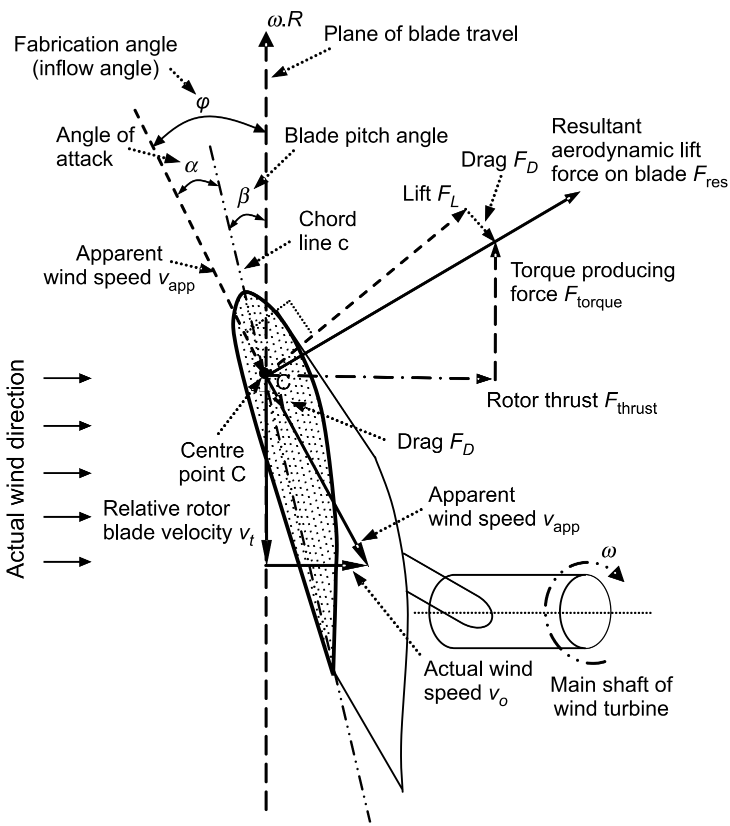


Figure 4.6 Forces on a Rotating Wind Turbine Blade: As a wind stream flows over an aerofoil, drag D is created in the apparent wind direction (v_{app}) and lift L perpendicular to it causes the blade to rotate.

$$v_{app} = \sqrt{v_o^2 + v_t^2} = \sqrt{v_o^2 + (\omega R)^2} \tag{4.2}$$

where,

ω = Angular velocity of the rotor blade
R = Radius of the blade.

It can be observed that as the apparent wind speed increases, the RPM of the blade increases. The effect of the apparent wind speed over the aerofoil is the creation of two aerodynamic forces—the lift force F_L perpendicular to v_{app} and the drag force F_D parallel to v_{app}.

The *angle of attack* α (alpha) is defined as the angle between the maximum chord line and v_{app}. The *plane of rotation* is the plane in which the blade tips lie as they rotate. The blade has a certain (constant or variable) angle to the plane of rotation called the *pitch* (*blade*) *angle* β (beta), which is the angular deviation between plane of the blade axis and the maximum chord of the cross section of the blade. The *inflow* (*fabrication*) *angle* φ (phi) is the angle which v_{app} makes with the vertical plane and it is the sum of β and α. At a given wind speed, $\beta = \varphi - \alpha$ (see Figure 4.6).

Resolving the lift and drag forces (perpendicular and parallel to the axis of the turbine respectively), the torque producing force F_{torque} and the thrust force component F_{thrust} emerge out (see Figure 4.6). The resultant aerodynamic life force F_{res} is the resultant of the torque producing force component F_{torque} and the thrust force component F_{thrust}.

The torque producing force F_{torque} is a useful force which is applied in the plane of rotation and makes the rotor to revolve. F_{torque} is not same as F_L. F_{torque} that propels the rotor looks quite small in relation to F_{thrust}, but the power is quite large, since the RPM of the WPP is very high. For improved performance, the blade aerofoil creates a strong F_{torque} in combination with a good angle of attack given by:

$$F_{torque} = F_L \sin \varphi - F_D \cos \varphi \tag{4.3}$$

Multiplying the force F_{torque} by the equivalent distance from the hub and by the number of blades, the torque transmitted to the shaft is obtained.

The drag force F_D creates a thrust force F_{thrust} parallel to the nacelle axis. The thrust force F_{thrust} is not useful for the rotation. It acts perpendicular to the plane of rotation and causes stress on the rotor support. It tries to bend the tower but it gets absorbed in the tower foundation transmitted through the main shaft, main bearing and the tower, given by:

$$F_{thrust} = F_L \cos \varphi + F_D \sin \varphi \tag{4.4}$$

v_{app} changes with the change in v_o. Hence, to maintain a good angle of attack α, the blade angle β must be adjusted accordingly. v_{app} (resultant of the blade speed ω and v_o) is stronger than the actual wind speed and the lift force F_L contributes to the torque force F_{torque} on the rotor. Then, there is the lift and drag coefficients that greatly affect the performance of rotor blades. The total lift force F_L of a wind turbine rotor is given by the *lift equation*:

$$F_L = 1/2\ \rho A v^2\ C_L \tag{4.5}$$

where,

F_L = Lift force (in newton)
ρ = Air density (in kilogramme per metre cube)
A = Aerofoil plan area [i.e. Chord × Span of blade (in metre square)]
v = Wind speed (in metre per second)
C_L = Lift coefficient (a dimensionless number).

Typical value of C_L is equal to 0.8. It could range from 0.8 to 1.25. The lift coefficient C_L can also be known from tables of aerofoil data. It should be noted that the lift coefficient is not a constant, but varies with the angle of attack α.

The drag force F_D that is perpendicular to lift force is given by the *drag equation*:

$$F_D = 1/2\ \rho A v^2\ C_D \tag{4.6}$$

where,

C_D = Drag coefficient (a dimensionless number).

The resultant of these two forces on the blade (F_D and F_L) results in a resultant aerodynamic force F_{res} (see Figure 4.6). As the angle of attack α increases, the lift force F_L also increases until a point is reached, when it dramatically begins to decrease and the drag force F_D increases.

Aerofoil performance is also determined by the *lift-to-drag ratio E* (or *efficiency*) E of the blade given by:

$$E = \frac{C_L}{C_D} \tag{4.7}$$

This ratio can be affected severely by dirt or roughness on the blade. For maximum efficiency of the blade, it is necessary that the blade is placed at such an optimum angle of attack, that the lift to drag ratio E remains maximum. C_D and C_L of an aerofoil can be established by wind tunnel experiments. The lower is the drag force in comparison with the lift force F_L, the higher will be the efficiency E.

Under *stall* conditions, the efficiency E of the aerofoil is considerably reduced and the aerodynamic behaviour becomes unsteady with the formation of a turbulent *wake* as seen in the curves of the two coefficients C_D and C_L as a function of the angle of attack (see Figure 4.7). It can be observed that the lift coefficient C_L is approximately proportional to the angle of attack for the values lower than 15°. The lift coefficient can become negative with the result that the lift force can change its direction (negative lift), unlike the drag coefficient C_D.

An aerodynamic *pitching moment* about an axis perpendicular to the aerofoil section, described by the pitching coefficient C_M is given by:

$$C_M = \frac{\text{Pitching moment}}{\text{Dynamic moment}}$$

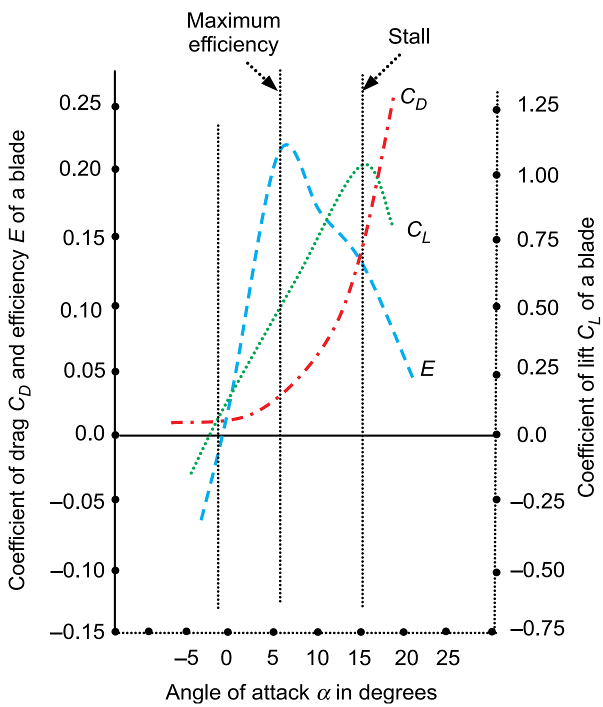


Figure 4.7 **Aerofoil Lift and Drag:** Lift and drag coefficients greatly affect the performance of wind turbine rotor blades. Hence, care needs to be taken for their design.

i.e.,

$$C_M = \frac{M}{1/2\,\rho\, A\, L\, v^2} \tag{4.8}$$

where,

C_M = Pitching coefficient (a dimensionless number)
M = Pitching moment
L = Lift.

Another factor that affects the lift and drag forces is the Reynolds number R_e which is the ratio between the gravitational force and the viscous force given by:

$$R_e = \frac{vC}{\gamma} \tag{4.9}$$

where,

v = Wind velocity
C = Chord length
γ = Kinematic velocity of fluid (for air at 20°C, the value is 15×10^{-6} m/s).

However, in preliminary calculations, R_e is not considered, as it has only second order effect on the lift drag characteristics.

With regard to the performance of the wind turbine rotor, it can be summarised as follows:

- Both lift and drag increase with the square of the wind speed.
- Both lift and drag increase in proportion to the density of air.
- Cold air gives more drag than hot air.
- Drag, may vary quite drastically with the surface roughness of the blade, requiring blades to have smooth and clean surfaces to minimise drag. Especially, the blades of stall-regulated WPPs are susceptible to fouling (build-up of insects and dirt on leading edge which may considerably decrease power production).
- For high power coefficient C_p, it is essential to use aerofoil shapes which have a very high lift to drag ratio, i.e., the rotor blades which provide considerable amount of lift with a small drag. This is particularly necessary in the section of the blade nearer to the tip where the relative speed of air is much higher than at the centre or root of the blade. Hence, the lift-to-drag ratio is designed to vary along the length of the blade to optimise the WPP energy output at various wind speeds.

4.4 FACTORS AFFECTING PERFORMANCE OF ROTOR

WPP has the maximum efficiency at the nominal wind speed (or rated wind speed), i.e., the wind speed at which the nominal (or rated) power of the WPP is reached (somewhere between 11 m/s and 16 m/s) depending on the design. Apart from the angle of attack, the performance of a WPP also depends on some other factors which are as follows:

(i) Aerodynamic efficiency C_p
(ii) Tip speed
(iii) Tip speed ratio (TSR) λ
(iv) Solidity σ
(v) Blade count
(vi) Blade twist
(vii) Blade taper
(viii) Wake losses and aerofoil pressure distribution
(ix) Yaw error.

4.4.1 Aerodynamic Efficiency

The *aerodynamic efficiency* C_p (also known as *power coefficient*) of a WPP (see Figure 4.8) is the instantaneous efficiency of the conversion of the wind energy into mechanical energy at the shaft. Albert Betz, a scientist from Gottingen, Germany proved that the entire energy in the wind cannot be harnessed. Betz showed that 1/3 of the retardation of the wind speed happens just in front of the WPP rotor and 1/3 just behind the WPP rotor after the wind has passed through the rotor blades. The change of the wind speed does not happen stepwise, but continuously. The undisturbed wind speed v_o is reduced to v_o $(1 - a)$ when it passes through the gaps in the rotor blades and to $v(1 - 2a)$ when it covers some distance behind it

(the retardation starts about one rotor diameter in front of the WPP and reaches its minimum about one diameter behind it). The unit a is called the *interference factor*. If this factor is 0.5, the wind speed behind the rotor will be reduced to zero, i.e., $0 < a < 0.5$.

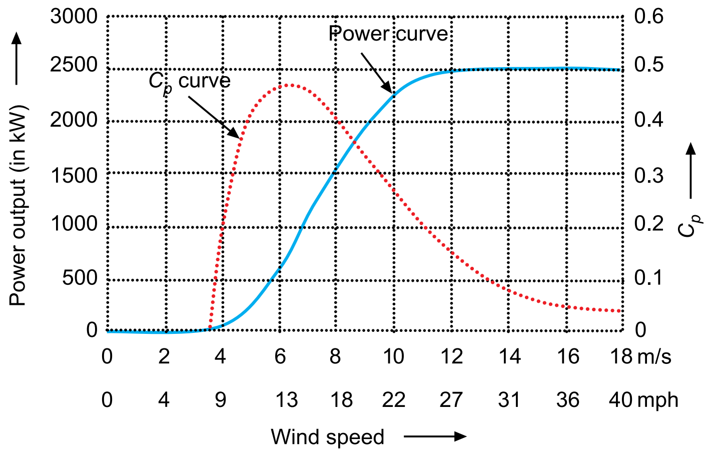


Figure 4.8 Typical Efficiency Curve and Power Curve of a 2500 kW WPP.

The theoretical maximum share of the power in the undisturbed wind that can be utilised is 16/27 and corresponds to 59.3% ($\approx$ 0.593) called the *Betz limit*. This share of the power in the wind that can be harnessed by the rotor is called the *power coefficient* C_p. The power coefficient C_p is dependent on blade pitch angle β and TSR λ (see Figure 4.9) and represented as C_p–λ curve of a WPP and it, varies for different types of aerofoils.

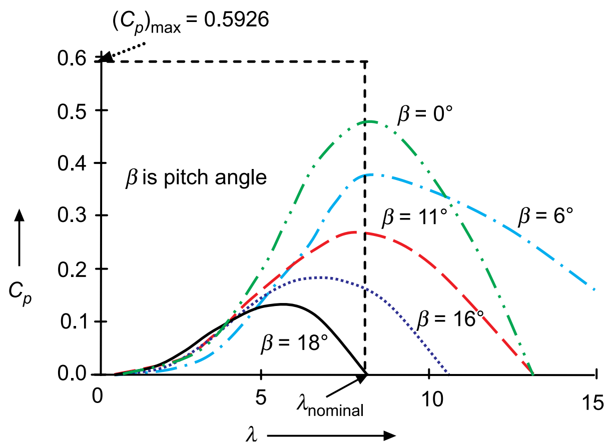


Figure 4.9 Wind Turbine Rotor Power Efficiency versus TSR.

$$C_p = \frac{\text{Actual power extracted by the rotor}}{\text{Total power available in the wind}}$$

$$C_p = \frac{P_{\text{actual}}}{P_{\text{total}}}$$

i.e.,
$$P_{\text{actual}} = C_p P_{\text{total}} \quad (4.10)$$

Hence, the actual power that a WPP can attain is expressed as:

$$P_{\text{actual}} = C_p \, 1/2 \, \rho A v^3 \quad (4.11)$$

where,

C_p = Power coefficient
ρ = Air density
A = Swept area
v = Wind speed.

But practically, C_p is still lower, due to the following causes:

- Rotation of the wake behind the rotor
- Finite number of blades
- Non-zero aerodynamic drag.

With considerable amount of research and development, modern WPPs have reached values of around 0.5 for C_p which is very near to the Betz limit. To maximise the annual energy output, the power coefficient C_p should be kept at its maximum value during WPP operation as long as possible and to maintain this, the blades must be pitched continuously, whenever the wind speed changes.

EXAMPLE 4.1

A WPP of 80 m rotor diameter is rotating at a particular windy site with the average wind speed of 6 m/s at a power coefficient of 0.4. Assuming the air temperature as 25°C with a density of 1.225 kg/m³, calculate the (a) total power available in the wind, (b) maximum power density, (c) actual power density, and (d) power output from the WPP.

Solution:

(a) Power density of air $P_{\text{total}} = 1/2 \, \rho v^3$

$$= 1/2 \times 1.225 \times 6^3$$
$$= 132.3 \text{ W/m}^2$$

(b) Maximum possible power density is limited by the Betz limit of 0.593.

$\therefore$
$$P_{\max} = 0.593 \times P_{\text{total}}$$
$$= 0.593 \times 132.3 = 78.45 \text{ W/m}^2$$

(c) Actual power density is decided by the efficiency of the blades, i.e., 40%.

$\therefore$
$$P_{\text{actual}} = 78.45 \times 0.4$$
$$= 31.38 \text{ W/m}^2$$

(d) Power output from the WPP = $P_{actual} \times$ Swept area

$$= 31.38 \times \frac{\pi D^2}{4}$$

$$= 31.38 \times 4024 \text{ W}$$

$$= 157653/1000 \text{ kW}$$

$$= 157.653 \text{ kW}$$

4.4.2 Tip Speed

Wind turbine rotors rotate between 8 RPM (for multimegawatt WPPs) to 25 RPM (for submegawatt WPPs). When the wind turbine blades rotate, the speed at the blade tip is higher than the speed at the middle of the blade and also at the blade root near the hub, where it becomes zero or near zero. The blade tip of modern WPPs can have a speed about 10 times faster than the wind speed, i.e., a wind speed of 5 m/s that rotates a WPP rotor can have a tip speed of even 50 m/s. This may seem impossible, but it is what that happens.

The force of a wind turbine blade tip is quite large during rotation as compared to the force when the blade is stationary. This large difference in force is due to the high wind speed at the blade tip (say, 60 m/s) during the rotation which is many times greater than the average wind speed (say, 9 m/s) at stationary position. The tip speed inreases with the length of the blade. If a 40 m WPP has a blade tip speed of 60 m/s, the speed at the middle of the blade will be only 30 m/s.

There is also a relation between tip speed V_{tip}, RPM and the radius of the rotors. Tip speed is calculated by the formula:

$$v_{tip} = \frac{2\pi RN}{60} \text{ m/s} \tag{4.12}$$

where,

R = Radius of the wind turbine rotor
N = RPM of the wind turbine rotor.

It is normal to shut down (park) WPPs which are operated in very high winds beyond 25 m/s, as they would generally experience much higher blade and tower loads. If they continue to operate at that high wind speeds, they may get demaged.

Since the blade tip moves faster than the blade root, it passes through more volume of air and has to sufficiently slow down that air enough to generate a greater lift force. But there are some practical limits on the absolute tip speed. With greater tip speeds, rain erosion of the blades, noise and bird impacts drastically increase.

EXAMPLE 4.2

Determine the tip speed of a wind turbine rotor of radius 20 m with a rotor RPM of 30.

Solution:

$$v_{\text{tip}} = \frac{2\pi RN}{60} \text{ m/s}$$

$$v_{\text{tip}} = \frac{2\pi \times 20 \times 30}{60} \text{ m/s}$$

$$\approx 60 \text{ m/s.}$$

Now, if the wind turbine radius is increased to 30 m with the same rotor RPM of 30, then the tip speed v_{tip} = 94 m/s. This value is environmentally not quite acceptable due to high noise levels that will be emanated at this tip speed. Hence, for the increased rotor radius of 30 m, the rotor RPM will have to be designed in such a manner that its rated speed is 19 RPM. Thus, it can be seen that the rotor blade tip can travel faster than the prevailing wind speed. Hence, in noise sensitive environments, the tip speed needs to be limited below 75 m/s (270 km/hr or 164 mph).

4.4.3 Tip Speed Ratio

More is the kinetic energy harnessed out of the wind by a WPP, more will be the wind slowed down as it leaves the blades after passing through them. If all the kinetic energy is tried to be extracted from the wind, the air would pass through the blades with zero speed, i.e., it would appear as a solid wall to the wind and the air would never leave (or pass through) the blades. In such a case, no energy can be extracted, since all of the air would obviously be prevented from entering the rotor of the turbine.

If on the other hand all the wind is allowed to pass though the blades without being hindered at all, again no energy would be extracted from the wind. Therefore, there must be some way of braking the wind which is in between these two extremes. This optimum is the ratio of the blade tip speed v_{tip} to the undisturbed wind speed v_o (i.e., before the wind is slowed down by the wind turbine rotor) and is represented by a dimensionless number called the *tip speed ratio* 'λ' (TSR). The aerodynamic characteristics of a blade are usually defined by the relation λ–C_p (see Figure 4.9).

$$\text{Tip speed ratio } \lambda = \frac{\text{Blade tip speed } v_{\text{tip}}\ (\omega R)}{\text{Undisturbed wind speed } v_o}$$

i.e.,

$$\lambda = \frac{\omega R}{v_o}$$

or

$$v_o = \frac{\omega R}{\lambda}$$

or

$$v_o = \frac{2\pi NR}{\lambda} \tag{4.13}$$

where,

$\omega = 2\pi N$ the angular speed (in radians per second) at the blade tip

f = Frequency of rotation (in hertz)

R = Rotor radius (in metres)

v_o = Undisturbed wind speed (in metre per second).

Covering a larger area effectively increases the TSR of a WPP at a given wind speed, thus increasing the energy extraction capability. Ideally, a high TSR is better, but not to the point where the WPP becomes noisy and highly stressed. The TSR determines how fast the WPP will turn which provides implications of the type of electric generator that can be adapted. For lower TSR, the rotor has greater torque, more blades and runs at slower speed.

Higher TSR rotors has lower torque and fewer blades, but run at higher shaft speed and better suited for electric power generation. Greater RPM is possible, but the added noise would be a cause for concern. This is one of the reasons why modern WPPs have larger rotor diameters and lower RPM. So, in the design of the lift-based rotor blades, the designers typically trade off on TSR in the region of 6–9 so that at the rated wind speed (generally between 12 m/s–15 m/s), the blade tip can be moved at around 75 m/s (approximately 270 km/hr).

If a WPP is operated at a constant TSR corresponding to the maximum power point $(C_p)_{\max}$, it can generate 20% to 30% more electricity every year. But this requires a good control scheme to operate the WPP at variable speeds. Rotor blades must, therefore, be designed to operate at the optimal TSR so that the maximum power can be harnessed from the wind.

The optimal TSR is stated by the manufacturer, based on the pre-production testing. Although TSR remains constant throughout the designed life of the blade, slight changes are likely to happen when the blade bows, bends or when the dust/insects/debris gets accumulated on the surface (calling for blade cleaning).

Following are the salient characteristics of TSR:

- Optimum TSR depends on the number of blades n. The lower the number of blades, the faster will be the rotation of blades to extract the maximum power from the wind (as the TSR rises).
- Shape of the curve for the relation λ–C_p depends on the WPP type (see Figure 4.9).
- There is only one TSR value for the blade aerofoil under consideration for which the power conversion efficiency reaches its maximum value $(C_p)_{\max}$.
- For lower TSR values, there is a reduction in the lift force F_L and an increase in the drag force F_D until stall condition is reached for stall controlled WPPs.
- For high TSR values, there is a reduction in the lift force F_L as well as in the drag force F_D under a so called *escape condition.*
- When the undisturbed wind velocity v_o changes, to keep TSR constant and to maintain $(C_p)_{\max}$, it is necessary to purposefully pitch the blade accordingly in pitch controlled WPPs.

By practical experience and by theoretical calculations, the optimal TSR can be calculated for different types of rotors (see Figure 4.10). If the TSR of a wind turbine is 1, it means the blade tip has the same speed as the wind. It can be seen that both the multibladed windmill and Darrieus VAWT have narrow ranges of TSRs.

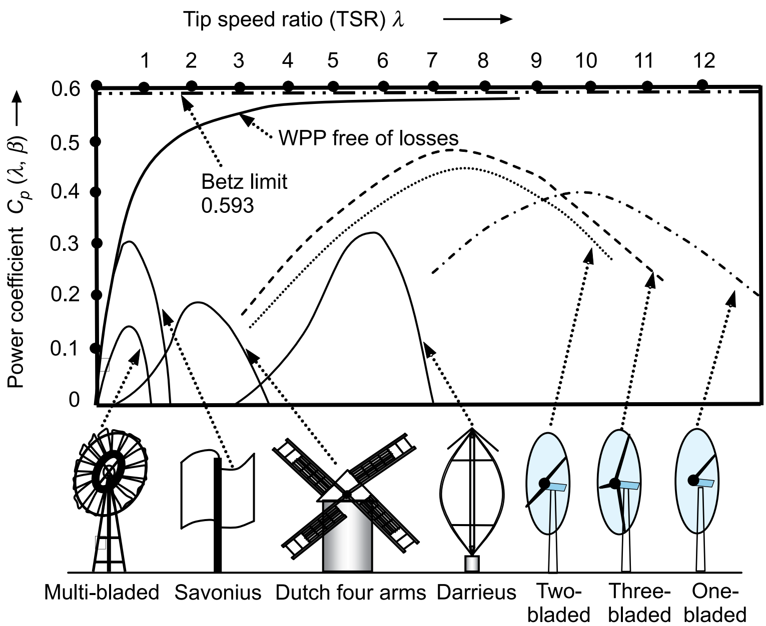


Figure 4.10 TSR and Wind Turbine Efficiencies: Relation of TSR λ and power coefficient C_p for different types of WPPs. The theoretical maximum value of C_p is 16/27 ≈ (59.33%).

EXAMPLE 4.3

A 1.2 MW direct-drive variable speed WPP rated at 12.8 m/s wind speed has a rotor diameter of 62 m and a speed range of 10 RPM to 20 RPM. Find the range of its tip speed ratio.

Solution:

The angular speed ω for 10 RPM to 20 RPM = $2\pi N/60$.

It will range from $(2\pi \times 10)/60$ to $(2\pi \times 20)/60$ rad/s

$$= 1.46 \text{ to } 2.09 \text{ rad/s}$$

Rotor tip speed $v = \omega R$

It will range from 1.46×31 to 2.09×31 m/s.

$$= 45.26 \text{ to } 64.89 \text{ m/s}$$

TSR λ range = $(\omega R)/v_0$.

It will range from 45.26/12 to 64.89/12

$$= 3.77 \text{ to } 5.40$$

EXAMPLE 4.4

A WPP has a rotor diameter of 80 m. The RPM is 15 and the wind speed is 8 m/s. The power coefficient is 0.4. Assuming the air density as 1.225 kg/m³, find the torque coefficient C_T. Also, determine the torque available at the rotor shaft.

Solution:

$$\omega = \frac{2\pi N}{60} = \frac{2 \times 3.14 \times 15}{60} = 1.57 \text{ rad/s}$$

Tip speed $v = \omega.R = 1.57 \times 40 = 62.8$ m/s

$$\lambda = \frac{v}{v_o} = \frac{62.8}{8} = 7.85$$

$$\lambda = \frac{C_p}{C_T} \quad \text{where, } C_T \text{ is the torque coefficient}$$

$$\therefore \qquad C_T = \frac{C_p}{\lambda} = \frac{0.4}{7.85} = 0.050$$

The torque developed at the shaft is given by $T = 1/2\,\rho A v^2 R\, C_T$
Swept area $A = \pi R^2 = 40^2 = 1600$ m²

$\therefore \qquad T = 0.5 \times 1.225 \times 1600 \times 8^2 \times 40 \times 0.05 = 1{,}25{,}440$ Nm

Maximum torque $T_{max} = T/C_T = 1{,}25{,}440/0.050 = 25{,}08{,}800$ Nm

4.4.4 Solidity

Solidity (σ) is a term to describe the proportion of a WPP rotor's swept area that is filled with solid blades. *Solidity* is defined as the ratio of the total blade area to the total swept disc area.

$$\text{Solidity } \sigma = \frac{\text{Projected blade area}}{\text{Total swept area}}$$

As the solidity increases, the TSR for maximum power coefficient C_p gets reduced. Even the *lift coefficient* affects the solidity. Higher the lift coefficient, smaller will be the chord. When the rotor planform (projected) blade area is $3a$ (see Figure 4.11) and total swept area is A, then:

$$\sigma = \frac{na}{2\pi R} \tag{4.14}$$

where,

n = Number of blades
a = Projected area of single blade
R = Radius of wind turbine rotor.

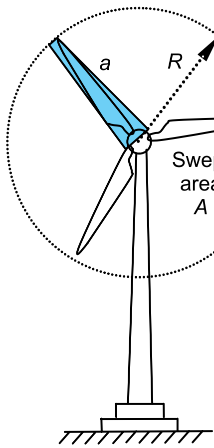


Figure 4.11 **Solidity:** As solidity increases, lift and drag forces increase and the efficiency decreases. Hence, the solidity of modern WPPs is less than 0.10.

The planform shape of the wind turbine blade is in such a manner so as to give the blade an approximately constant slowing effect on the wind over the whole rotor disc (i.e., the tip slows the wind to the same degree as the centre or root of the blade). This ensures that none of the air leaves the turbine too slowly (causing turbulence), and none of the air is allowed to pass through too fast (which would represent wasted energy).

Savonius (vertical axis wind turbine) has the maximum solidity of unity, as the projected area and the swept area are the same as the wind sees no free passage through it. For a multiblade water pumping windmill, the solidity is about 0.7. Greater solidity means greater torque, but lower speed as required by the water pumping windmills. The blades of this high solidity multiblade windmill interact with all the wind at a very low TSR. With increasing number of blades, the stress at the blade root also increases. It can also be noted that lower TSR and higher solidity for a wind turbine tends to make it relatively stiff ushering in more stresses for various parts.

In modern WPPs with two or three blades, the solidity is less than 0.10. There is a relationship of TSR with *solidity*. The TSR of a turbine also depends on the number of blades. When the number of blades decreases, the TSR increases and less blade area leads to lighter and less expensive blades.

Modern WPPs running at higher speeds of low solidity have higher TSRs but lower starting torques. Lower solidity means lower torque but high speed, as required for electrical power generation. The chord and the width decrease with the decrease in solidity. Therefore, the load on the drive train also becomes lesser. Today's WPPs have thinner, longer and lighter blades that are more flexible, thereby reducing the stresses on the drive train. However, the chances of blade tower hits are more due to greater deflection of the thin rotating blades. Further, in WPPs with thinner blades, flapwise stresses as well as the possibility of vibrations tend to be higher.

The aerodynamic behaviour of a thick blade profile is not so effective. Therefore, in wind turbine blade designs, there is a trade-off of requisite strength (thicker blade profile) and good aerodynamic properties (thinner profile) with the need to avoid high aerodynamic stresses.

To do the same amount of work for the same efficiency and same rotor diameter, and to produce the same power from the wind, both the one-bladed or two-bladed WPPs are enabled to spin at higher RPM than a three-bladed WPP. Thus, the blades of a lower solidity WPP travel faster to virtually fill up the swept area in order to interact with all the wind passing through them.

4.4.5 Blade Count

The question of the optimum number of blades for a WPP is quite common. Down the years, one-bladed, two-bladed and three-bladed WPPs have been experimented and manufactured. The determination of the number of blades involves design considerations of aerodynamic efficiency, component costs, system reliability and aesthetics. It is proven that the noise emissions from the blades' trailing edges and tips vary by the fifth power of blade speed. Even a small increase in tip speed can make a large difference. Noise emissions are also affected by the location of the blades (upwind or downwind of the tower) and the RPM of the rotor.

(a) Single-bladed WPP

The single-bladed WPP (see Figure 4.12) is the most structurally efficient for the rotor blade, as it has the greatest blade section dimensions with all the installed blade surface area in a single beam. Such rotors minimise energy loss from drag forces.

Figure 4.12 One-bladed WPP. This is a downwind design. (*Courtesy*: www.ades.tv/en)

One-bladed design also allows interesting parking strategies (with the single blade acting as wind vane upwind or downwind behind the tower) which may minimise storm loading impact. It has a higher TSR and the costs are also low because of a single blade. But this saving in cost may not look substantial because a counterweight has to be attached to the rotor to eliminate the torque fluctuations and therefore, the mass becomes almost equal to a two-bladed wind turbine. Although it is not lighter, it is easier to install.

With a counterweight used to balance the rotor statically, there is also the reduced aerodynamic efficiency and complex dynamics requiring a blade hinge to relieve loads. One-bladed WPP has to rotate at higher speed than a two-bladed or three-bladed WPP to sweep the rotor disc area effectively. The higher speed helps to reduce the gearbox ratio and thereby decreases its mass. But faster rotational speed emits more noise and has increased tip losses. For the same rating, some studies say that it captures 10% less energy than the two-bladed ones; but this claim needs to be verified.

Off-late Spanish manufacturer ADES is manufacturing one-bladed downwind WPPs (see Figure 4.12) on a commercial basis, in the range of 60 kW to 2 MW. These are called *pendular wind turbines* where the cyclic torque variations of the WPP are compensated by allowing the generator to swing like a pendulum on the gearbox output. Both constant speed and variable speed WPPs are being marketed.

(b) Two-bladed WPP

The primary advantage is a lighter, less costly system with a longer blade chord (blade width). Since a blade profile is characterised by its relative thickness (blade thickness to blade chord ratio, normally 15%–20%), increased chord (see Figure 4.13) allows for a thicker and stronger beam and less structural material. The result is a lighter, less expensive two- blade design. As a two-bladed WPP may be slightly less efficient (2%–3% annually) than a three-bladed one of the same rating, a 1% increase in WPP rotor diameter fully compensates for such efficiency difference.

For the same rating, a two-bladed rotor spins more rapidly than a three-bladed one and therefore the gearbox is of relatively smaller size and hence, relatively cheaper. Assembly and lifting up of two-bladed rotors with the nacelle can be done with single crane while two cranes are required for a three-bladed rotor and hence, lesser logistics and costs.

Although there are considerable discussions, the two-bladed rotor WPP design is technically at par with the established three-bladed design. Two-bladed WPPs have lower solidity than the three-bladed ones. They have a lower moment of inertia when the blades are vertical to the ground as compared to that when they are horizontal to the ground. However, due to the gyroscopic imbalance, the two-bladed rotor has to adapt a pitch-teeter coupling that allows the blades to move with gust-induced variations in thrust loads instead of resisting them. The teetering hinge allows the two blades of the rotor to move as a single beam through typically $\pm 2°$ in and out of plane rotation. Allowing this small motion can much relieve the loads in WPP, although some critical loads return when the teeter motion reaches its end limits.

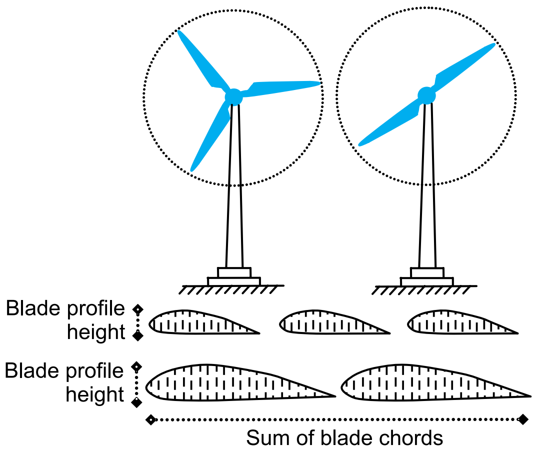


Figure 4.13 Blade Thickness to Blade Chord Ratio: Increased chord of two-bladed WPP allows for thicker and stronger beam.

(c) Three-bladed WPP

A three-bladed WPP (see Figure 4.14) has become a more common choice of designers and investors, as its polar moment of inertia is constant with respect to yawing and is independent with respect to the azimuth position of the rotor. This contributes to a relatively smoother operation while yawing. Moreover, it has greater dynamic stability than the two-bladed ones. Further, the gyroscopic forces developed are balanced enough and hence, does not require a teetering hub.

While aligning the WPP with the changes in wind direction (yawing), each blade experiences a cyclic load at its root end depending on the blade position. This is true for one, two, three or more blades. By using a teetering hub, one-bladed or two-bladed WPPs can nearly eliminate the cyclic loads from the drive shaft and system especially during yawing. However, these cyclic loads when combined together at the drive train shaft and symmetrically balanced for three blades, yield smoother operation during yawing operation.

4.4.6 Blade Twist

Blade twist is given to the blade, partly to ensure that the rotor blade stalls (in stall controlled blades) gradually rather than abruptly when the wind speed reaches its critical value. So, the apparent (or relative) wind speed v_{app} changes and with this, the undisturbed wind speed v_o also changes. So, the angle at which the apparent wind velocity approaches the blade also becomes different at different points of the blade section, i.e., from the blade root to the tip.

The design of a stall regulated (discussed in the next chapter) wind turbine blade is different from a pitch regulated wind turbine blade. To optimise the energy capture, the angle of attack α on the stall regulated wind turbine blade needs to be kept constant for a given average wind speed.

Figure 4.14 **Blade Twist:** To get the same angle of attack all along the entire rotor blade length, it is twisted and tapered out from the root to the tip.
Courtesy: Klaus Rockenbauer, Austria.

Closer to the blade tip, the blade moves faster through the air and so the apparent wind angle is found to be greater. The apparent wind direction also moves towards the vertical plane, thereby changing the direction from root to tip. Therefore, the blade needs to be turned further at the blade tips than at the root. In other words, it must be built with a twist along its length (see Figure 4.14). The requirement to twist the blade has implications for the complexity of manufacture as well.

If the blade angle and the RPM are kept constant, the angle of attack changes continuously and hence, the lift and drag on different parts of the blade also get changed. By twisting the blade angle $\beta = \varphi - \alpha$, the angle decreases towards the tip and the angle of attack can be kept constant (for a given wind speed). This gentle blade twist renders the stall phenomenon gentle and progressive as the average wind speed increases or decreases.

The *Betz theory* allows the calculation (see Figure 4.15) of the optimal geometry of a rotor blade (thickness of blade and blade twisting). For this, apparent wind direction along a rotor blade with an average undisturbed wind speed v_o (say, 9 m/s) is retarded to 2/3 just in front of the rotor disc as follows:

$$2/3 \times v_o = 6 \text{ m/s}$$

when,

$v_{\text{tip}} = 60$ m/s $\quad \varphi = 6°$
$(v_o)_{8R} = 48$ m/s $\quad \varphi = 7°$
$(v_o)_{6R} = 36$ m/s $\quad \varphi = 9°$
$(v_o)_{4R} = 26$ m/s $\quad \varphi = 14°$
$(v_o)_{2R} = 12$ m/s $\quad \varphi = 27°$.

As the wind speed increases, it becomes necessary to decrease the angle of attack from the hub along the blade length to its tip. This can only be happen if the blades are twisted from the blade root (where the twist will be maximum) to

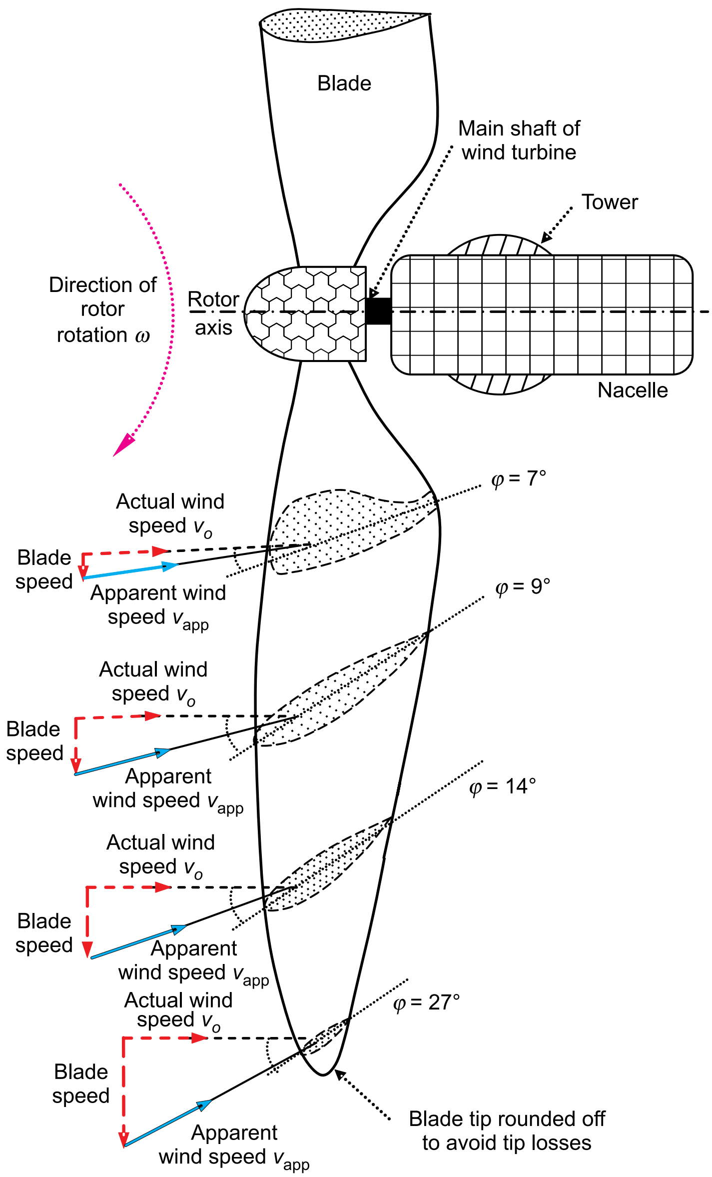


Figure 4.15 **Blade Profile and Twist:** The angle in relation to the plane of rotation will decrease towards the blade tip.

the blade tip (where twist will be minimum). The rotor blade has to be given a slight twist so as to achieve an optimal angle of attack throughout the length of the blade. So, for maximum blade efficiency and ideal lift-to-drag ratio C_L/C_D, the blade is given an edgewise non-linear twist ranging from 10° to 20° at the blade root to almost 0° at the blade tip.

4.4.7 Blade Taper

High TSR blades generally possess a strong taper. The lift on a blade profile is proportional to the wind speed and width. The outer one-third part of the blade generates the maximum lift. The tip of the blade moves faster than the root where the speed is almost zero. As the area swept by the inner portion of blades is relatively small, wind turbine blades can be wider at the base and narrower at the tips (see Figure 4.16). The tip has to pass through more volume of air to generate a greater lift force by slowing down the air. Since the lift force increases with the square of the wind speed, the greater speed of the tip allows for that. Tapering also reduces the noise levels.

Figure 4.16 Blades Taper from Root to Tip: The root profile is thick near the blade hub to resist forces and stresses.
Picture by author.

To get the same lift force along full length of the blade, it is necessary to widen the blade area where the blade speed is low (at the root) and high (at the blade tip). In fact, the blade can be narrower close to the tip than near the root and still, it can generate enough lift. The taper gives an added boost in start-up due to the wider root and is slightly more efficient. The optimum tapering of the blade planform (as it goes outboard) can be calculated. As a thumb rule, the chord length should be inverse to the radius. This relationship breaks down close to the root and tip where the optimum shape changes on account of tip losses.

Wind turbine rotor blades are shaped to harness the maximum power from the wind at the minimum material cost. Although, the main objective is the aerodynamic requirements but economics also comes into the picture to keep the strength and

cost of construction reasonable. For example, close to the blade root where the stresses due to bending are the greatest, the blade tends to be thicker than the aerodynamic optimum requirement.

4.4.8 Wake Losses and Aerofoil Pressure Distribution

The lift force on the wind turbine blades generates a torque that has an equal and opposite effect on the flowing wind, tending to push it around tangentially in the opposite direction. The result is that the air on the leeside of the WPP has swirl or *wake* (see Figure 4.17), i.e., which impacts the wind to spin in the opposite direction to that of the blades. This swirl is considered as a lost power which is reduced from the available power that can be extracted from the wind because any rotational energy in the wake is the energy that is lost and unavailable.

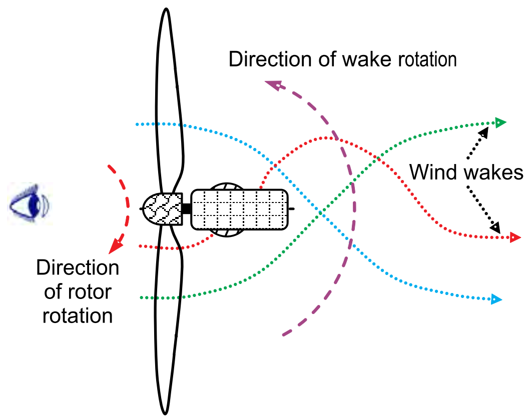


Figure 4.17 Wake Loss in Wind Turbine Blade Rotor: The lift force on the blades generates a torque that has an equal and opposite effect on the flowing wind on the leeside of the rotor blades, tending to push it around tangentially in the opposite direction resulting in wake losses.

The wake from one WPP is detrimental to the wind speed and turbulence at downwind WPPs. The blade length, pitch and angle at which each blade is attached to a WPP, significantly impact wake formation as well. Practically, a minimum physical separation between WPPs of 3 to 4 diameters is usually specified. Smaller separations introduce additional uncertainty in the wake loss calculations. Secondly, lower RPM requires higher torque for the same power output and hence, a lower tip speed results in higher wake losses.

4.4.9 Yaw Error

Depending on the wind direction, the WPP has to be yawed so that the wind always perpendicularly impinges on the blades. If this is not perpendicular, then it is called a *yaw error*. A yaw error implies that only a lower share of the wind energy would

pass through the rotor area (the share will drop to the cosine of the yaw error). The yaw error also causes the blades to bend back and forth in a flapwise direction for each turn of the rotor and therefore, the blades are subjected to larger fatigue loads accelerating the failure.

4.5 THRUST AND TORQUE ON ROTOR

The WPP extracts wind energy causing a difference in the momentum between the upstream and downstream air flow (see Figure 4.18) and gives rise to two forces—the *torque force* that turns the blades (connected to the shaft) and the *thrust force* that tries to tip the tower.

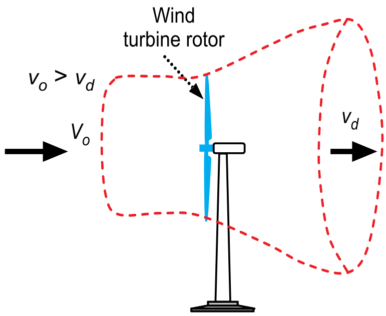


Figure 4.18 Wind Stream Tube: Shape of wind stream tube due to wind turbine rotor. Here, v_o represents undisturbed upstream wind and v_d represents disturbed downstream wind.

The aerodynamically shaped rotor blades are so aligned that as they move along wind stream direction, the drag force is minimised and the lift force is maximised so as to give the required torque to the wind turbine rotor.

4.5.1 Thrust Force

Thrust is necessary for torque. While developing a torque in the wind turbine rotor blades, they generate more downwind force that exerts far greater stress on the tower. The thrust force applied in the rotor axis direction exerts a load on the tower and foundation.

The thrust force F_{thrust} (see Figure 4.18) must be equal to the loss of momentum of the air stream v_d.

i.e.,
$$F_{\text{thrust}} = \frac{1}{2}\rho A (v_o^2 - v_d^2)$$
$$= \frac{1}{2}\rho \frac{\pi}{4} D^2 (v_o^2 - v_d^2)$$
$$= \frac{\pi}{8} D^2 \rho (v_o^2 - v_d^2) \tag{4.15}$$

where,

v_o = Undisturbed wind velocity in front of wind turbine rotor
v_d = Downstream wind velocity at the back of the rotor after energy extraction
A = Swept area
D = Rotor diameter.

It is known that for maximum output, $v_d = 1/3\ v_o$

$$\therefore \quad (F_{\text{thrust}})_{\max} = \frac{\pi}{8} D^2 \rho \left(v_o^2 - \frac{1}{9} v_o^2 \right)$$

$$= \frac{\pi}{8} D^2 \rho \frac{8}{9} v_o^2$$

$$= \frac{\pi}{9} D^2 \rho v_o^2 \tag{4.16}$$

4.5.2 Torque

Torque is necessary for wind energy extraction. The physical size of any electric generator is governed by the torque, as it is required to absorb. If the wind imparts a torque T_{aero} on the blades, then the blades must be imparting a torque on the wind. The actual rotor torque T_{aero} would occur when the circumferential force F_{torque} (see Figure 4.6) acts on the rotor blade at radius R.

i.e.,
$$T_{\text{aero}} = F_{\text{torque}} R \tag{4.17}$$

Maximum theoretical torque $T_{\max}$ would occur if the circumferential force F_{torque} acts at the tip of the rotor blade. But practically, the wind turbine rotor produces a torque which is only a fraction of this value.

The ratio of the actual torque T_{aero} developed by the rotor to the maximum theoretical torque $T_{\max}$ is termed as the *torque coefficient* C_T given by

$$C_T = \frac{T_{\text{aero}}}{T_{\max}} \tag{4.18}$$

$$\therefore \quad T_{\text{aero}} = C_{\text{T}} T_{\max} \tag{4.19}$$

When a WPP shaft is turned at an angular speed ω, the actual power P_{actual} developed by a WPP is the product of the rotor torque T_{aero} (in Newton metre per radian or watts) and angular speed ω (in radians per second).

$$P_{\text{actual}} = T_{\text{aero}}\ \omega \tag{4.20}$$

It is known that out of the total power available in the wind, the actual power extracted by the wind turbine rotor is given by the following equation:

$$P_{\text{actual}} = C_p P_{\text{total}} \tag{4.21}$$

Substituting the value of P_{actual} and T_{aero} in Eq. (4.20), it becomes

$$C_p P_{\text{total}} = C_T T_{\max}\, \omega \tag{4.22}$$

It is known that:

$$T_{\max} = \frac{P_{\text{total}}}{v_o} R \tag{4.23}$$

Now, substituting the value of $T_{\max}$ in Eq. (4.22), it becomes:

$$C_p P_{\text{total}} = C_T \frac{P_{\text{total}}}{v_o} R\omega$$

$$\therefore \quad C_p = \frac{\omega C_T R}{v_o}$$

$$\therefore \quad \frac{C_p}{C_T} = \frac{\omega R}{v_o}$$

But it has been proved that:

$$\lambda = \frac{\omega R}{v_o}$$

$$\therefore \quad \frac{C_p}{C_T} = \lambda \tag{4.24}$$

i.e., when the value of C_p is maximum, i.e., 0.593, as per Betz criterion, then:

$$(C_T)_{\max} = \frac{(C_p)_{\max}}{\lambda} \tag{4.25}$$

Hence, the machines with higher speeds will have low values of $(C_T)_{\max}$ or in other words, lower starting torque.

4.6 POWER CURVE

Each WPP model is tested by the manufacturer and certified by a third party for the electric power output at different wind speeds by the power curve. The power curve of a WPP is its hallmark, indicating the performance of a WPP. On the vertical axis, the power curve (see Figure 4.19) depicts the expected electric output of the turbine at specific wind speeds shown on the horizontal axis. It is one of the main parameters that portray the performance of that particular model of WPP. It represents the relation between its power output in kilowatts (or megawatts) and the wind speed (in metre per second). It shows how much power the WPP will produce at different wind speeds. This relation is usually presented as a table or as a graph or both.

It can be noted that there is not enough energy in the wind to even rotate the wind turbine at light breeze (when the leaves rustle). At cut-in or start-up wind speed (2.5 m/s to 4 m/s) the wind turbine rotor just starts to rotate, but it cannot

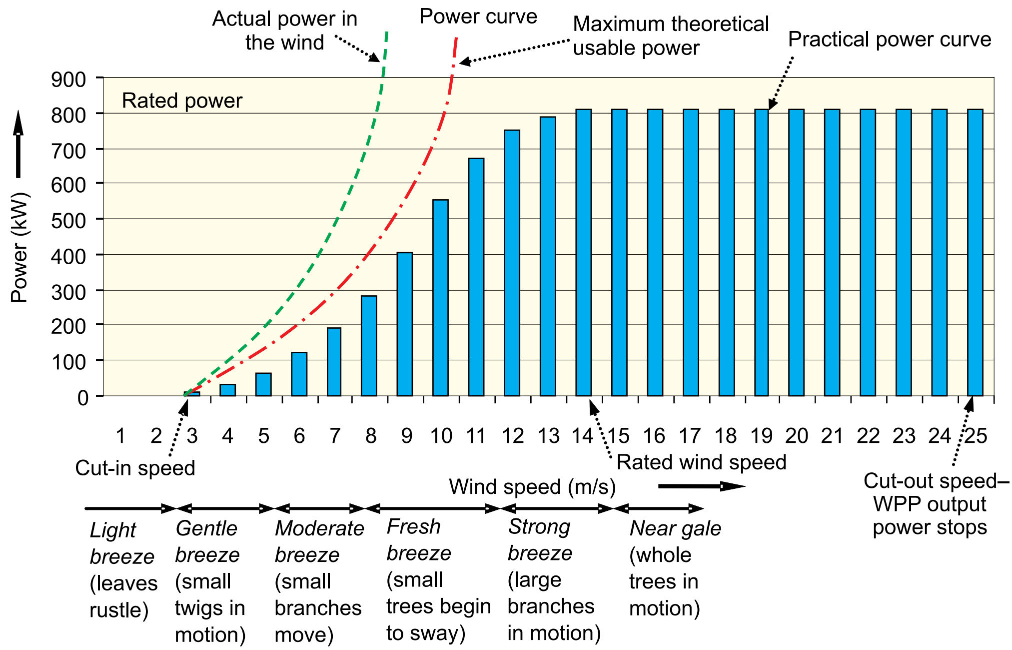


Figure 4.19 Power Curve for a Pitch Regulated 800 kW Rated WPP: It can be seen that the cut-in speed is 3 m/s in this power curve for this wind turbine, rated speed is 15 m/s for 100% rated output, cut-out speed is 25 m/s and power captured is determined by the area under the power curve. The dashed line shows the actual power potential in the wind.

be connected to electric grid. At such low speeds, the WPP is not capable of producing any power, as there is too little energy in the wind at this speed to overcome system losses. The wind turbine is then said to be idling, a phenomenon which is also required so that the lubricants in the various components of the wind turbine do not solidify. In regions of low winds, it is necessary to install WPPs with low cut-in speeds.

As the wind speed increases beyond the cut-in speed (when small twigs are in motion), the WPP starts producing more power and continues to do so till the rated power is reached at the rated wind speed. This value differs for different types of WPPs and generally lies between 12 m/s to 15 m/s. It can be observed that during the period between cut-in speed to rated speed, for even small changes in the wind speed, there are substantial increases in the power produced, as it is proportional to the cube of the wind speed.

At the rated wind speed (when large branches of trees are in motion), the WPP rated power output is reached and it is held constant thereon and hence, the power curve is flat-topped. As the wind speed increases past the WPP's rated speed, the power control mechanism of the WPP rotor limits the power harnessed from the wind to keep the drive train torque constant within the specified limits. This is achieved by stall control, active-stall control or by reducing the angle of attack through blade pitch angle adjustment or in combination with power electronics control. Above the

rated wind speed, the wind turbine continues to produce the same rated power but at lower efficiency.

At near gale or cut-out wind speed of 25 m/s (when whole trees are in motion) which is not quite often, the power curve drops suddenly which means that the WPP has stopped. This is designed purposefully so as to avoid the WPP from being destroyed due to high mechanical stresses that may set in. Such strong winds are quite rare, occurring only for brief moments of the year and therefore, to overdimension the WPP parts to work for such small time durations is technically and economically unviable. In case of such rare strong winds during the brief periods, it is cheaper to spill away part of the excess energy of the wind to avoid damaging the WPPs or stop it completely.

4.7 LIFT-BASED VAWT

Vertical axis wind turbine (VAWT) is an omnidirectional machine, i.e., at cut-in wind speed, it rotates in the direction in which the wind blow. These modern large VAWT also work on the lift principle. The *Giromill* (also called *H-Darrieus rotor*) is also a VAWT (see Figure 4.20) which works on the principle of lift and it consists of straight vertical blade sections attached to the central tower with horizontal supports. This type of VAWT is much simpler to build but results in a relatively massive structure and requires stronger blades. A major drawback of the Giromill VAWT design is the pulsating torque during each revolution and to minimise this effect, the egg-beater design was adapted by Darrieus. Today, the largest one seen is the 4.2 MW VAWT at Canada.

Figure 4.20 Modern 200 kW three-bladed Giromill prototype VAWT, Falkenberg, Sweden. *Picture by author.*

In the VAWT design which may be two-bladed, three-bladed or four-bladed, the blades are symmetrically arranged around a vertical axis and the angles of the blades are set optimally in such a manner that it works on the lift principle. For a rotating VAWT, the blades encounter two forces—its own rotating speed and the incoming wind speed (see Figure 4.21). There is a tangential force pulling the blade around and a radial force acting against the bearings of the vertical axis. Both speeds get added vectorially yielding a total apparent wind speed v_{app} at an incoming angle of attack α. The incoming air stream which is parallel to the blade yields high and low pressure regions on the blade, yielding overall lift and drag forces. The resulting oblique lift force creates a torque on the shaft to which the blades are attached making them rotate in the direction of the blades in which they are already travelling. The VAWT yields an overall positive torque that can be extracted as electrical power through the generator.

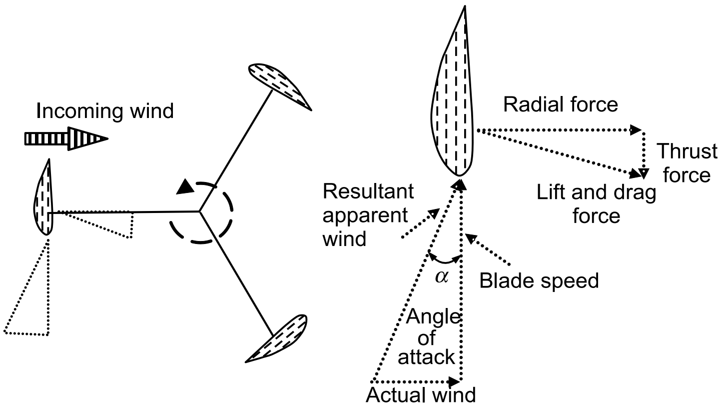


Figure 4.21 Lift Principle of Three-bladed VAWT Rotor: The aerofoils of the blades are adjusted for the optimum angle of attack α so that maximum wind energy is converted to the electrical energy.

A major limitation of the VAWT is that it is not self-starting due to symmetry of the blades. Hence, to generate a torque on its own, starting is achieved by operating the electrical generator as a motor and then speeding up the VAWT sufficiently for the wind to pass over the blade aerofoils to create the lift force and then run in the generating mode. Torque is caused by a change in the apparent wind direction relative to the moving blades. Further, these VAWTs require a relatively large footprint on the ground to mount and secure the tower and hence, the farmers are not very happy about large VAWTs on their agricultural land, as farming area gets reduced.

The disadvantages of the VAWT are more than its advantages and hence, it is yet to become popular for large capacity wind power applications. Hence, there are only few large VAWTs in production today. However, small VAWTs are considerably popular in the small wind turbine sector, alongside the small HAWTs (discussed in the last chapter).

SUMMARY

This chapter discusses how the wind turbine rotor rotates when sufficient wind blows, the principles which cause them to rotate and also about the vertical axis wind turbine and horizontal axis wind turbine. The various factors that govern the performance of a WPP are also discussed. The factors related to the power curve of WPPs are also highlighted.

EXERCISES

4.1 Explain the fundamental reason for the movement of an object in a fluid system.

4.2 Distinguish the difference between drag and lift type WPPs.

4.3 Explain the lift principle applicable to streamlined objects.

4.4 Explain the significance of the centre point C of an aerofoil.

4.5 Explain the lift principle of a wind turbine blade with sketch.

4.6 Justify the high lift-to-drag ratio of a WPP.

4.7 Explain the significance of the lift coefficient and drag coefficient.

4.8 With the help of WPP power efficiency curves versus TSR, describe the performance of a WPP.

4.9 A WPP of 60 m rotor diameter rotates at a particular windy site with an average wind speed of 7 m/s. Assuming that the air temperature is 30°C with a density of 1.225 kg/m^3 and power coefficient of 0.35, calculate the (a) total power available in the wind, (b) maximum power density, (c) actual power density, and (d) power output from the WPP.

4.10 The blade tip of modern wind turbines can move at about ten times faster speed than the wind speed. Comment in about 500 words.

4.11 Calculate the solidity of a WPP with two blades having a 40 m diameter and blade area of 3.5 m^2.

4.12 For the same diameter, explain why the one-bladed and two-bladed WPPs have to move faster than a three-bladed WPP to produce the same power ouput.

4.13 Give the reason for the blade to be (a) twisted, and (b) tapered.

4.14 Describe the phenomenon of wake in WPPs.

4.15 Derive the equation $C_p/C_T = \lambda$.

4.16 A WPP has a rotor diameter of 80 m. The RPM is 14 and wind speed is 8 m/s. The power coefficient is 0.45. Assuming the air density as 1.226 kg/m^3, find the torque coefficient. Also, determine the torque available at the rotor shaft.

4.17 Explain the significance of the power curve of a WPP.

4.18 With sketches, explain the lift principle of a three-bladed VAWT.

4.19 Describe the energies which comprise the total aerodynamic energy captured by the wind turbine rotor.

5

Wind Turbine Aerodynamics

... LORD drove the sea back by a strong East Wind.

—Exodus 14:21

Learning Outcome

On studying this chapter, you will be able to distinguish the different types of aerodynamic control methods of horizontal axis large wind power plants.

CHAPTER HIGHLIGHTS

5.1 *Introduction*

5.2 *Aerodynamic power regulation*

5.3 *Stall-controlled WPP*

5.4 *Pitch-controlled WPP*

5.5 *Active-stall controlled WPP*

5.6 *Halting a WPP*

5.7 *Other methods of aerodynamic control*

5.1 INTRODUCTION

Every wind power plant (WPP) is fully unmanned and its operation and control is performed by a microcomputer with custom-designed software. It can be said that there is a three-fold purpose in the control of small and large WPPs:

- Speed regulation—to restrict the noise levels whereby the tip speeds of WPPs are limited to ~120 m/s.
- Load mitigation—to ensure that the torque of the WPP is under control to operate safely by limiting the various forces.
- Power regulation—to get as much energy as possible out of a WPP.

The speed and power at which a WPP operates must also be regulated in order to:

- Optimise the aerodynamic efficiency of the WPP rotor during light winds.
- Keep the WPP rotor and hub within their centripetal force limits, as the spinning of the rotors increase with the square of the RPM, since the WPP structure is sensitive to overspeed.
- Keep the generator within its speed and torque limits to produce electric power of grid quality.
- Keep the WPP rotor and tower within their strength limits, as the power of the wind increases with the cube of the wind speed. WPPs are built to survive much higher wind speeds (such as gusts of wind) than those from which they can practically generate power. Since the blades generate more downwind force (and thus, put far greater stress on the tower) when they are producing torque, most WPPs have ways of reducing the torque in high winds.

The aerodynamic power regulation is discussed in this chapter while the electric power regulation is discussed in the other chapters.

5.2 AERODYNAMIC POWER REGULATION

The power regulation of WPPs is done by aerodynamic, electric and electronic control. The following aerodynamic control methods are popularly being adapted by the manufacturers to regulate the power of large wind turbine rotors, although other types of aerodynamic control are still under experimentation and research:

- **Stall-control** (It is also called *stall-regulated*): In this, the stall profiled rotor blades are mounted at a fixed angle on the hub.
- **Active-stall control** (It is also called *active-stall regulated*): In this, the stall profiled rotor blades are pivotable for few angles in the longitudinal axis.
- **Pitch-control** (It is also called *pitch-regulated*): In this, the rotor blades are almost infinitely pivotable in the opposite direction to the active-stall blades from 0° to 90° in longitudinal axis.

The selection of any of these types of power regulation significantly affects the design of wind power plant technologies adapted by different manufacturers and the design of the blade aerofoils as well.

5.3 STALL-CONTROLLED WPP

The WPP technological revolution in late 1970s and 1980s was begun by the adaption of the simplest so called Danish concept, three-bladed, fixed speed, stall-controlled WPP with squirrel cage induction generator. Stall is a potentially fatal event for an aircraft wing aerofoil, whereas WPPs make purposeful use of the stall as a means of limiting the power and loads in high wind speeds. This passive control of the WPP is based on the fixed blade inherent characteristics. *Stall*, from a functional standpoint, is the breakdown of the normally powerful lifting force when the angle of attack over a blade aerofoil becomes too steep.

The progressive way in which stall phenomenon occurs over the wind turbine rotor blades is proved to be a thoroughly viable way of rotating a wind turbine rotor. It is a simple and passive method of naturally limiting the rotor torque. Hence, the power output during strong winds or gusts makes it very popular to be used even now. It is one of the unique aspects of wind technology in which the blades are rigidly bolted to the hub at a specific blade angle best suited to the wind regime at that particular location and it is finely adjusted once again (if required) at the time of installation.

5.3.1 Stalling Phenomenon

Stall method of power regulation is simple, reliable and efficient. It gives the lowest possible dynamic loads on the WPP. The rotor blades have to be installed at the optimum angle of attack during the commissioning of the WPP for that particular location based on the wind resource data. This wind turbine rotor works on the fact that the angle of attack increases with the increase in wind speeds in such a manner that, at a certain angle corresponding to a particular pre-designed wind speed, stalling effect gets initiated, usually a little earlier than the rated wind speed. In other words, the rotor blade is completely passive while it is the wind speed that causes the stall effect and the power regulation to happen. In this process, the performance coefficient C_p falls at a higher rate beyond the nominal wind speed of the WPP.

Since the blade speed is constant and the WPP is connected to the grid, the variable wind speed determines the angle of attack α. This angle proportionally increases with the increase in wind speed till the *critical angle* is reached (see Figure 5.1). After this point, the lift force begins to decrease on its own for increasing wind speeds due to the design of the blade profile.

Depending on the particular aerofoil adapted and other factors, the critical angle could vary usually between 14° to 16°. This critical angle is referred as the *stall angle*. Stall regulated blades limit power in high winds which reduces drive train loads. Stall regulation is well understood technically and much simpler mechanically than the competing pitch regulation technique.

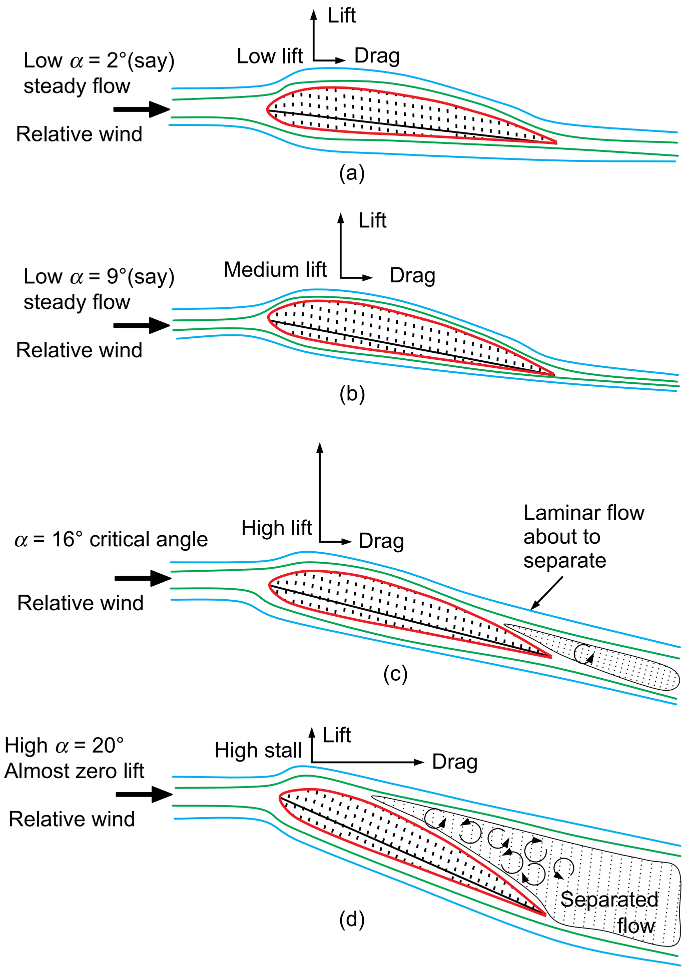


Figure 5.1 **Typical Stall Actions of a WPP Blade:** (a) At an angle of attack, say 2°, the air flow is laminar. The lift force is greater than the drag force and the rotor produces some power, (b) At a greater angle of attack, say 9°, the air flow continues to be laminar and the rotor produces more power, (c) At critical angle, stall action gradually sets in but lift force is the highest, and (d) At this angle, drag force is greater than the lift force and the blade rotation stops.

When the wind impinges on the wind turbine rotor blade at an angle of attack, say 2° [see Figure 5.1(a)], the air flow over the aerofoil is laminar and hence, sticks (attaches) to the blade surface from the leading edge to the trailing edge. It is this laminar flow that creates a lift force (which is greater than the drag force) on the blade aerofoil and the blade starts rotating, as the blade has only one degree of freedom and free to move only in that plane.

As the wind speed goes on increasing, for a constant speed rotor, the angle of attack [see Figure 5.1(b)] on the stall blades also goes on increasing, say up to 9°.

This laminar flow over the blade continues to be there creating a greater lift force that applies a greater pressure on the rotor blade to turn the electric generator to produce more power.

As the wind speed continues to increase further, the lift force also goes on increasing till a critical angle [see Figure 5.1(c)] is reached generally around 16° at which the coefficient of lift C_L reaches its maximum. At this critical angle of attack, lift force is the highest. At this angle, the laminar air stream does not reach the trailing edge, i.e., the air stream that was sticking onto the upper part of the blade surface is about to separate from it. Any further increase of the wind speed will only worsen the situation and more air stream will separate and turbulence (whirls get created) will set in on the blade surface, spoiling the lift force. At this region, lift force decreases and the drag force rapidly builds up.

At all angles above this critical angle [see Figure 5.1(d)], the laminar flow over the upper blade surface is disturbed and the air stream experiences a turbulent region on the blade's upper surface by which the lift force is reduced. The air suddenly whirls around in irregular vortices, a condition known as *stall* or *stalling action* sets in. The wind flow direction is reversed, i.e., it flows from the trailing edge backward to the separation line. This flow separation automatically limits the power capture and it depends on the air density and the quality of the aerofoil's surface finish. The aerofoil blade section now extracts much less energy from the wind.

The aerodynamic profile and properties of the rotor blade are designed such that, when the wind speed exceeds a critical limit, the lift action gets spoilt due to the non-laminar wind flow turbulence, beginning at the trailing edge that goes on increasing to the leading edge till the blade stalls or stops the rotation of the rotor as the wind speed goes on increasing beyond the designed limits. The stall blade is also designed in such that the stall effect and the turbulence start to set in a little earlier to bring in a gradual stall rather than an abrupt stall. The turbulent flow increases drag and decreases the efficiency of the aerofoil. Hence, it can be said that stall action:

- Arises due to separation of laminar flow from aerofoil.
- Results in decreasing lift coefficient with the increasing angle of attack.

5.3.2 Stall Power Curve

Since the wind speed and the air density ρ cannot be controlled and the radius of the blades R is fixed, the performance coefficient C_p is the only means for torque control. Hence, this stall controlled wind turbine rotor blade profile is shaped in such a way that C_p steeply falls at the start of the predetermined high wind speed at the stall angle.

As the blade angle is fixed in stall controlled WPPs [refer section 5.5, Figure 5.9(a)] no external control is possible for this type of WPP. Starting is done by connecting the induction generator to the grid and running it as a motor near to synchronous speed. The output power depends on the wind speed which may not exactly maintain a constant value at the rated power level for which it is designed. During wind gusts, the passive stall WPPs get overloaded for brief periods as depicted by the peaky power curve

(see Figure 5.2) characteristic. In fact, as the wind speed increases, it overshoots the rated power for a short period which then comes down as the wind speed increases further. The WPP then starts losing power more quickly at higher wind speeds. This behaviour is not there in the pitch controlled WPP discussed in next section.

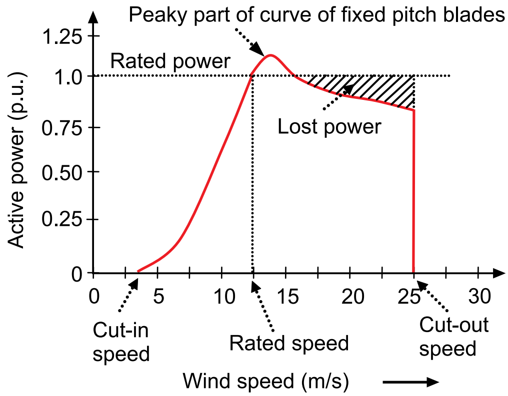


Figure 5.2 Stall Controlled WPP Peaky Power Curve: The stall phenomenon slowly sets in much earlier than the cut-out speed. Here, it is around 16 m/s and the shaded area depicts the lost power at higher wind speeds even before the cut-out speed is reached.

5.3.3 Vortex Generators

The design requirements of stall regulation have led to new aerofoil developments and also the use of devices such as vortex generators, (see Figure 5.3) stall strips, fences and gurney flaps for fine tuning rotor blade performance. Vortex generators are small panes (usually about 1 cm in length) that are mounted on the blade upper surface alternatively inclined towards left and right opposite to each other at a certain angle that causes *counter-current eddies* in the air flow.

Large stall controlled WPP manufacturers, therefore, use vortex generators to fine-tune the stall properties for a flat-topped power curve (as desired) and thereby, not to overload the electric generator. When the wind speed starts increasing beyond the rated wind speed and if the stalling action sets in along the entire length of the blade at the same moment, the rotating motion may become jerky, which is not desirable at all.

By using vortex generators beginning from the root on the upper surface of the blade, the aerodynamics of the blade controlled stalling action occurs. The vortex generators initiate a small turbulent air flow on the blade surface, much before the full stall action. Different segments of the blade surface at different times and the jerky stall motion is eliminated.

Vortex generators delay flow separation and aerodynamic stalling, thereby improving the effectiveness of the blades. The delta wing shaped vortex generators are usually placed in an array of pairs near to the leading edge of the blade. When the wind passes over the blade, the vortex generators create a pair of contra-rotating vortices which transport the momentum from the upper part of the boundary layer

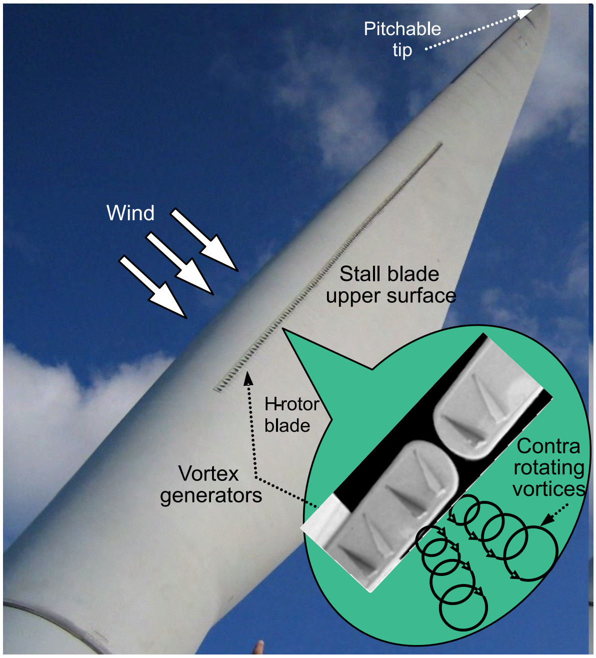


Figure 5.3 Vortex Generators on a Stall Blade: Small panes about 1 cm in length are mounted on the upper surface of blade, alternatively inclined towards left and right.

to the lower part of the boundary layer, thereby increasing the mixing closer to the surface. This leads to a fuller streamwise velocity profile and causes the boundary layer to better withstand the adverse pressure gradient and thereby delaying the separation.

These vortex generators are fixed in a form called *stall strip*. If the stall strip is attached close to the blade root, it makes the stall gentler and progressive. This is a small sharp-edged strip which when attached near to the leading edge of a rotor blade, controls and initiates the stall action at a predetermined speed. Since the rotor blades tend to stall near the blade root, where the blade profiles are thick, the stall strips (each of about 1 metre long) are mounted on the blade inlet side near the blade root. The distance between the panes is designed such that the turbulent layer of air suspends precisely at the rear part of the blade edge.

The stall action starts close to the root of the blade at predetermined wind speed (a little before the rated wind speed) and as the wind speed further increases, the stalling slowly spreads over the rest of the lengths of the blade so that the power levels out when the rated power/wind speed is reached. In this way, the overshooting of the power generated, i.e., peak of the power curve is also minimised. It is interesting to note that these tiny turbulences prevent the blade to stall at lower speeds. Vortex generators can boost blade performance by 4%–6%.

5.3.4 Features of Stall Controlled WPP

The following salient features of the stall regulated WPP sustains its popularity even today:

(i) Based on the simplest wind turbine technology.
(ii) Since the power is always controlled aerodynamically, it produces less fluctuating power output, as compared to that produced by a pitch regulated WPP.
(iii) Responds much more quickly to gusts than the pitch regulated WPPs (where mechanical pitch adjustments require a finite response time to effect it).
(iv) Cheapest among all types of WPPs.
(v) Time-tested WPP for its reliability and robustness.

There are many demerits as well which are given below:

(i) The main demerit of the passive stall regulated constant speed WPP is that it does not have the possibility of active electric power control, except when using mechanical brakes on the main shaft or when connecting and disconnecting the electrical generator from the grid.
(ii) Limited control of reactive power makes it more difficult to control network voltages.
(iii) During network disturbances (such as a sudden fault in the network), such a WPP is likely to aggravate the situation.
(iv) It is not self-starting.
(v) It is suited for relatively stronger grids.
(vi) The power of the electric generator must be overdimensioned so that it does not lose synchronism during wind gusts.
(vii) The blade aerofoil (which is quite complex) may not be exactly matched with the wind resource characteristics at that particular site. Hence, it may not produce optimal electric power even in the best windy conditions.
(viii) Being rigidly attached to the hub, to withstand the high aerodynamic loads, the strength and the stiffness of the rotor blades must be relatively higher than the pitch regulated WPPs.
(ix) If the atmospheric conditions change, the power prediction may not match the specifications of the stall controlled WPPs leading to deviations even to the order of 10%.
(x) The aerodynamic properties of the blade aerofoil get altered due to corrosion of the blades and insect deposits disturbing the streamlining effect, which calls for the periodic cleaning of stall blades.
(xi) It has a lower efficiency at lower wind speeds.
(xii) Stall control is not preferred much for megawatt capacity WPP as the pitchable tip become unwieldy and other associated problems for activating them with ease.

5.4 PITCH CONTROLLED WPP

The pitch controlled (also called *pitch regulated*) WPP which got developed in 1990s, turns the whole length of the rotor blades in and out of the wind along the longitudinal blade axis to regulate the power extracted from the wind. Pitch control can maximise the energy capture even below the rated wind speeds. Due to greater control (a feature demanded by the electric grid operators), many in the wind industry who prefer large WPPs have a greater preference for this more complex method of aerodynamic torque regulation which prevents mechanical overspeed in addition to other benefits.

5.4.1 Pitching Action

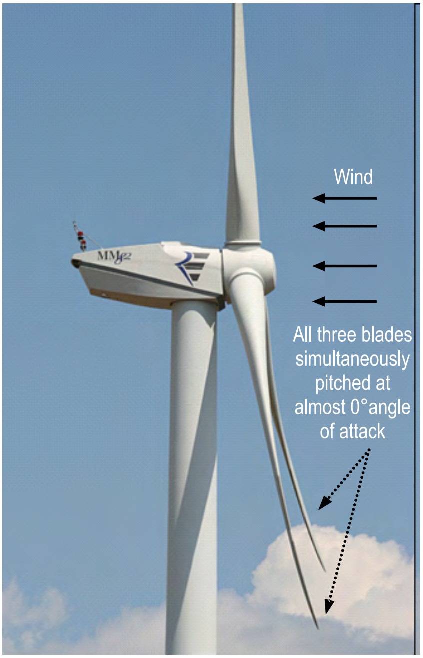
The angle that the blade chord makes with the rotor disc is the *pitch angle*. Pitch control can be undertaken to reduce as well as to increase the angle of attack to modify the lift and drag values to regulate the power harnessed from the wind.

The pitching action of each blade is achieved independently by geared electric motors mounted on each blade bearing or group controlled by hydraulically operated lever mechanisms. Pitch regulation allows the energy capture to be optimised for constant and variable speed operation of WPPs and at the same time, provide overspeed protection by large pitch angle adjustments (see Figure 5.4). The power coefficient C_p of a WPP is, thus, changed by adjusting the blade angle to optimise angle of attack of the blades. Almost all variable speed WPPs use pitch control.

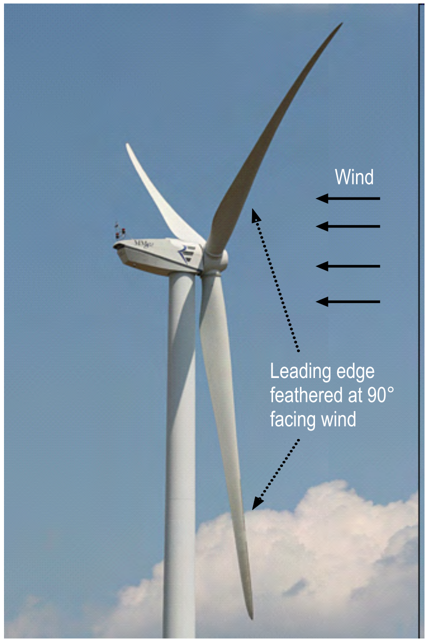
Conventionally, blade pitch is often controlled by a simple proportional integral (PI)-based collective blade pitch controller which receives its input signal from the error in electrical generator speed. The microprocessor (or microcomputer)-based electronic controller checks the various parameters received from the sensors of the operating WPP several times per second. The microcomputer adjusts the pitch of the blades to a few degrees to maintain the rotor blades at an optimum angle in order to maximise the output power for all wind speeds. Blade adjustment is generally not continuous, but at some small fixed intervals based on a certain logic (otherwise the pitch mechanism would be worn out quickly and maintenance would be high).

Pitch control is achieved where the pitch angle of each blade is controlled independently. It can also be achieved collectively when all the blades are moved to the same pitch angle (cyclic pitch control) in which the pitch of each blade is same as the others at the same rotor azimuth angle. The former method offers more aerodynamic independent braking systems for speed control, but has a drawback of requiring a very precise control on the mating angle of each blade so that the unacceptable differences of the angle can be avoided during normal operation.

Pitch controlled constant speed WPPs use the active variation of such angle for starting up and control of the power produced above the rated wind speed. They actively vary with the pitch angle to get an aerodynamic torque which accelerates the rotor upto the rated operation speed and consequently, the generator is connected to the grid.



(a) Rotating



(b) Stopped

Figure 5.4 **Pitch controlled WPP:** (a) Operating pitch controlled WPP. Based on the wind speed, 2.5 MW blades are continuously pitched at optimum angles to maximise the harnessing of energy. (b) 2.5 MW wind turbine is in stopped position with the leading edge of the blade facing the wind at 90° to the wind.
Courtesy: www.thewindpower.net

5.4.2 Pitch Power Curve

A typical pitch controlled WPP has a flat-topped power curve (see Figure 5.5) at the rated power, unlike the peaky stall WPP power curve as seen earlier. The bumps are smoothened out due to the controlled pitching action of the blades resulting in lesser stresses on the various mechanical and electrical components as well as the electric grid. The power curve of WPP can be divided into following four categories:

(i) Region I (low wind)—WPP is not connected to grid.
(ii) Region II (medium wind)—WPP is connected, but produces less than rated power.
(iii) Region III (higher wind)—WPP is connected, produces only rated power.
(iv) Region IV (cut-out wind)—WPP is disconnected and stopped.

In region I of the power curve (see Figure 5.5), the wind speed is very low and the rotor does not rotate, the pitch angle of the blades are turned approximately at 45° and the generator is not connected to the grid. This gives a maximum start

moment to rotor when the wind speed increases. At low wind speeds with constant TSR, the speed variation ($dP/d\omega$) of the output power P from the electric generator is a function of the rotor speed ω and is quite small.

In region II of the power curve (see Figure 5.5) when the wind speed increases and the rotor rotates, the electronic controller pitches the blades to 0° into the wind and at the cut-in speed, the generator is connected to the grid. When the electric generator produces power, it causes a torque in opposition to the mechanical torque of the wind turbine rotor. As the wind speed increases, the rotor speed increases in case of variable speed WPP, but not for constant speed WPP and the generated power also increases. When the wind speed is below the rated speed of the WPP, the main aim is to extract maximum power from the wind at those speeds for which optimal power coefficient C_p and constant TSR is maintained and hence blade pitching is not used but kept at a constant value (almost 0°). To achieve this constant TSR, electric generator torque is used to control the rotor speed curve (see Figure 5.5). At moderate wind speeds for constant speed operation, ($dP/d\omega$) may be quite high.

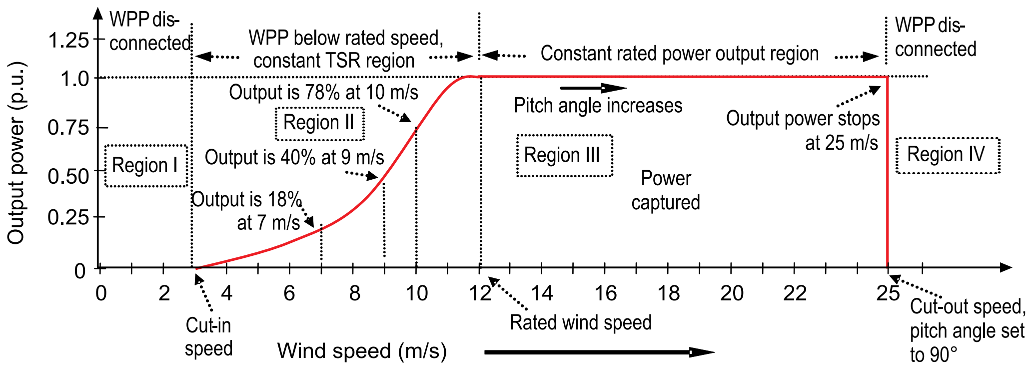


Figure 5.5 Pitch Controlled WPP Power Curve: Unlike the peaky power curve of the stall controlled WPP, the power curve of pitch control WPP is flat-topped due to the pitching action of the blades resulting in lesser stresses on the various mechanical and electrical components.

Practically, in region II, when the wind speed increases, the aerodynamic torque increases the rotor speed resulting in increased electric generator speed to capture more power. When the wind speed decreases and the produced power becomes negative, the generator will be disconnected from the grid.

In region III of the power curve (see Figure 5.5), the main goal is to limit the power output. After the rated power is reached, the combined action of the generator torque and the pitch is used to control the electric power output. This is done to keep the power at the rated value P_{rated}, as well as to control the blade rotor speed to maintain it within acceptable limits around the rated speed. For high wind speeds, ($dP/d\omega$) is close to zero, since the output power is kept constant.

As the wind speed increases in region III, the blade pitch angle [refer Section 5.5, Figure 5.9(c)] rapidly responses to control the instantaneous power to match

the generator torque in order to produce grid compatible electric power. Practically, what happens in this region is given below:

- By pitching, also called feathering, the blades:
  - Angle of attack decreases
  - Aerodynamic forces decrease
  - Rotor blades spill away the extra power
- Error signal, $e = \omega_{gen} - \omega_{rated}$
- Proportional integral (PI) controller is used to drive 'e' to zero.

In region IV of the power curve (see Figure 5.5), when the wind becomes too strong (above 25 m/s), rotor blades are feathered to 90° [see Figure 5.4(b)] to shutdown the WPP and the generator is disconnected from the grid.

Due to the pitching action of the blades, the starting current (see Figure 5.6) in the electric generator can be controlled within its limits, unlike the electric generator in the stall controlled WPP.

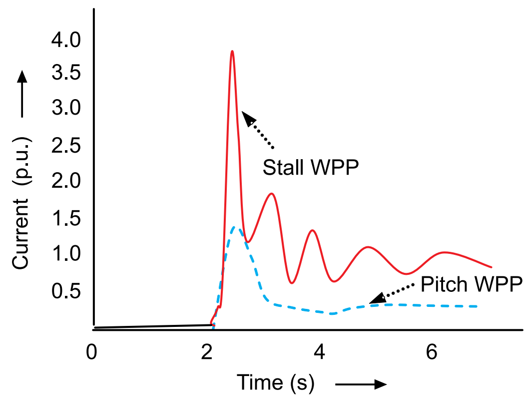


Figure 5.6 Comparison of Stall and Pitch Controlled WPP Starting Currents.

(a) High Wind Ride Through (HWRT)

The high-wind-ride-through (HWRT) innovation pioneered by Siemens, allows a WPP to operate at near cut-out wind speeds and enables more stable energy production. To avoid damage to the WPPs, typically they are shut down when the wind speed exceeds 25 m/s (ten-minute average) and are restarted when the average wind speed falls below 20 m/s (see Figure 5.7) causing the so called *hysteresis losses* (shaded part) which is almost about 2% of the rated output. A shutdown may also have a severe impact on grid stability as production goes from full capacity to zero instantly.

Equipped with HWRT, the WPP gradually reduces the power output (see Figure 5.8) instead of shutting down the WPP completely resulting in a more stable power output and it extends the operating range of the WPP at high wind speeds while the load remains neutral. It can also be seen that for the frequency of period greater than 25 m/s, about 1.5% more energy can be captured. No sooner the rated power output is reached, HWRT is achieved by intelligently pitching the blades out of the wind

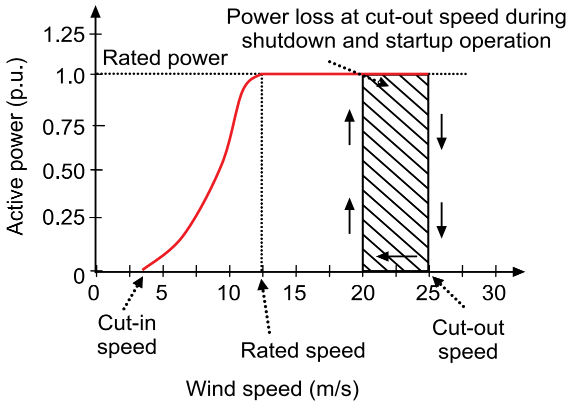


Figure 5.7 Power Curve of a Typical Pitch Regulated WPP during a Shutdown and Startup Operation: There is a power loss during the shutdown at high wind speed of 25 m/s and also during startup, there is a power loss when the wind speed falls to 20 m/s (at ten-minute average).

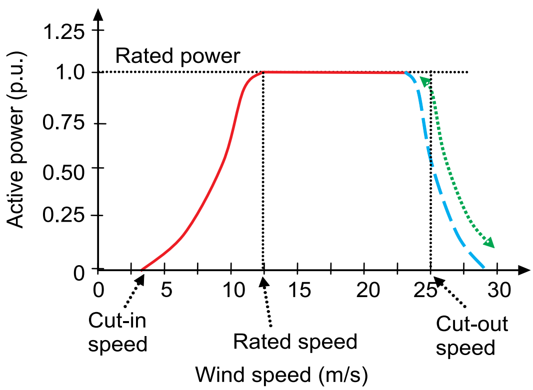


Figure 5.8 WPP Power Curve with Siemens HWRT: Due to HWRT, extended operation (dashed line) is made to be gradually possible instead of a sudden shutdown.

and limiting the RPM in proportion to the increase in wind speed and turbulence intensity. This does not affect the structural integrity of the WPP and also, lesser wear and tear are caused due to lesser stops originated because of high winds. This gradual derating of the produced power before cut-out speed is reached eliminates abrupt cut-outs which significantly improve the grid stability as well as increases the power production.

5.4.3 Pitching Mechanisms

Full blade pitching of the wind turbine blades for the aerodynamic control is achieved by the following means:

- Electric pitching mechanism
- Hydraulic pitching mechanism

- Belt pitching mechanism
- Mechanical pitching mechanism.

(a) Electric Pitching Mechanism

The electrically driven pitching system consists of three independent geared AC motor systems for each blade located inside or outside the hub of the WPP. Depending on the wind speed and based on the inputs to the electronic controller, it signals all the three motors to pitch simultaneously to the requisite degree to optimise power production by the WPP or to halt it. Generally, such pitch systems employ three-stage slewing planetary gear units, typical maximum torque of which could vary from 5,800 Nm to 10,000 Nm depending on the size and the weight of the blade to be pitched. The planetary structure helps to withstand very high torque values while maintaining the reduced dimensions. There is a battery backup or ultra-capacitors to tide over power outages.

(b) Hydraulic Pitching Mechanism

Many WPPs adapt the hydraulic pitching mechanism, especially in the submegawatt range. But with more reliable hydraulic systems in the market, hydraulic pitching is also popular with megawatt range WPPs. The microcomputer decides at what pitch angle every blade has to be set, so as to implement the hydraulic actuator. In the submegawatt range, generally, the main hydraulic system situated in the nacelle behind the gearbox actuates a back and forth moving pitching rod (taken into the hub through the centre-bored main shaft and gearbox) by the pitching lever arrangement inside hub in order to turn the blades in and out of the wind. In larger WPPs, each blade is equipped with individual hydraulic pitching cylinders inside the hub.

(c) Belt Pitching Mechanism

This is a recent innovation. *Regenpowertech* and *Vensys* WPPs use the belt type of pitching system. It is made possible by the use of toothed synchronous belt drives for controlling the pitching of the blades in their direct-drive WPPs. The forces are distributed over the teeth of the belt to minimise wear. The toothed belt drive does not require lubrication and is not affected by moisture or dirt and hence, needs relatively lesser maintenance.

(d) Passive Pitching Mechanism

In passive pitching mechanism, there is no hydraulic or electric pitching system. The force of the wind beyond a certain pre-determined wind speed activates a spring lever mechanism located in the hub to pitch the blades when the wind speed goes above the rated wind speeds. The blades remain in their most optimum predetermined angular position for that particular wind regime determined during the commissioning period. They get activated to change the blade angle only when the wind speed crosses the rated wind speed (say, 13 m/s) of the WPPs. Wind

speeds less than the rated speed do not activate the lever mechanism to change the blade angle. *WindEnergySolutions* and *Carter* WPPs employ this mechanism for their two-bladed WPPs.

Wind speeds above the rated speed increase the wind turbine rotor speed, as the extra power produced by the rotor is not absorbed by the electric generator. Therefore, the increased speed and pressure on the blades cause a force which intends to reduce the projected area and increase the blade angle, thereby reducing the efficiency of the blades. Consequently, the rotor speed is reduced and the passive blade angle adjustment gets activated to pitch the blades. When the wind speed is reduced, the spring forces the blade back to its original (most optimum angular) position to produce power.

5.4.4 Features of Pitch Controlled WPPs

The salient features of pitch controlled WPPs are:

(i) The greatest advantage is the increased energy capture than the stall WPPs.
(ii) Self-starting and controlled startup is possible.
(iii) In contrast to stall controlled WPPs, the rotor blade profile for pitch regulated WPPs is not so critical.
(iv) Pitching helps to reduce the aerodynamic loads, peak torques and hence, lowers the fatigue loads.
(v) It helps the wind farm to withstand voltage dips, as pitching limits the mechanical power on the main shaft resulting in greater grid elasticity. In other words, pitching partially damps the mechanical power variations resulting in lesser voltage variations being passed onto the grid.
(vi) Pitching can also be used for frequency control, mainly when over-frequencies occur and also, during under-frequencies.
(vii) Pitching limits the mechanical power on the main shaft of the WPP to its rated power. So the active power delivered to the network is limited to the maximum active power that the WPP can withstand.

However, there are some limitations as well:

(i) For the same rating, the extra energy that can be obtained practically is only about 2%–4% as compared to the stall WPP.
(ii) Main limitation is that during high wind speeds, even small wind speed variations result in large variations in power output to which the pitch mechanism is not fast enough to respond. To limit the power excursions especially during the gusts, the pitch changing has to act rapidly, say 6°/s to 7°/s or even better.
(iii) Fatigue loading is also higher than that of the stall WPPs due to the rate of change of the lift coefficient.
(iv) Hub of pitch controlled WPP is more sophisticated, as it has to hold the pitch bearing and pitching mechanisms.

5.5 ACTIVE-STALL CONTROLLED WPP

Active-stall controlled (ASC) turbines (also called *active-stall regulated*) came into the scene to tide over the disadvantages of the passive stall WPPs. One reason, why this strategy became popular is that when the WPP ratings went up beyond 1 MW capacity, the rotor blade profile became too unwieldy for the pitchable tips to operate reliably in submegawatt WPPs.

In ASC turbines, at low wind speeds, the stall profiled blades are controlled to pitch their blades similar to a pitch controlled WPP, but only for a few number of steps. The desired power is achieved by full span blade pitching but they are pitched to stall in the opposite [see Figure 5.9(b)] to that of the pitch controlled WPPs.

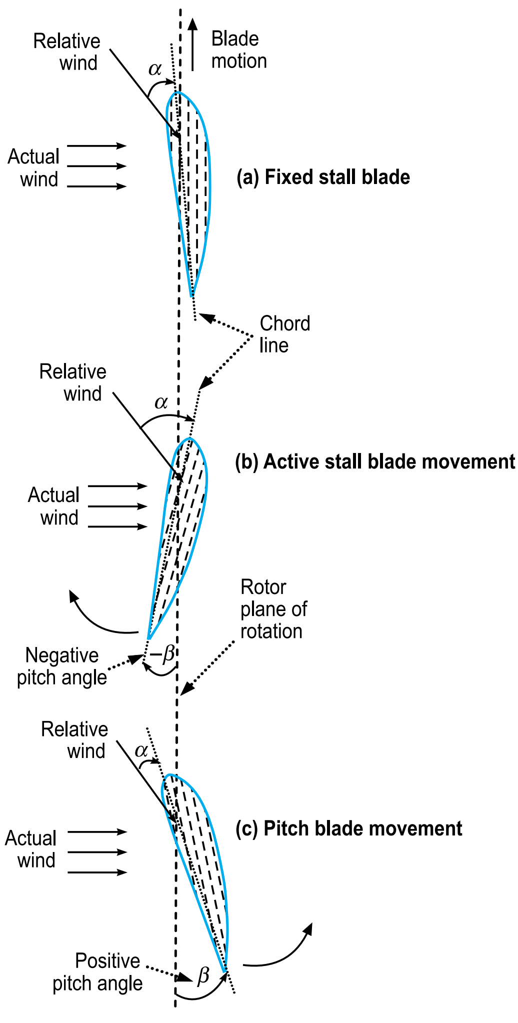


Figure 5.9 WPP Aerodynamic Power Regulation Techniques.

By the limited pitching mechanism, the control circuit becomes slightly less complex. When the WPP reaches its rated power value, the blades are pitched in the direction of a deeper stall action which is opposite to that of a pitch profiled blade to control output power. ASC pitching is also called the *negative pitch control*. However, this needs the pitch angle 'β' to be decreased only by a small amount. Hence, the rating of pitch drive mechanism is relatively smaller for ASC wind turbines, thereby reducing the cost and complexity as compared to the pitch controlled WPPs.

5.5.1 Active-stall Action

The blades of a ASC wind turbine are pitched in such a way so that the stall is caused or delayed according to the wind speed. An ASC turbine is also referred to as A2 type WPP having a control of pitch in the negative direction (i.e., between –90° to 0°). The rate of the negative pitch control in the WPP is normally less than 5°/s, although the pitch rate may exceed 10°/s during emergencies. Moreover, the rotor blades can also be kept at their optimum angle of attack with respect to the actual wind speed during partial load operation.

After a grid disturbance, the rotor speed of a SCIG may become so high that it may not return to the prefault value at the earliest. This may lead to induction generator's *rotor speed stability* problem. This rotor speed stability of a SCIG can be improved by active-stall control. In transient conditions, the active-stall controller uses natural stalling of the stall blades to control the pitch angle β, but in the negative direction to increase the stall further using a simpler pitching system to reduce wind turbine rotor torque. This action helps to reduce the acceleration of the rotor speed and improves the rotor speed stability.

5.5.2 Active-stall Power Curve

ASC wind turbines work on an eclectic principle, i.e., it utilises the good characteristics of both the stall and pitch control. The normal passive stall WPP has usually a droop in the power curve for higher wind speeds, as the rotor blades go into deeper stall. However, the power curve of an ASC turbine is almost similar to the power curve of a pitch regulated WPP (see Figure 5.10). It can be seen that the peaky power curve is eliminated by the active-stall operation. Unlike the passive stall WPP, the ASC turbine can be run almost exactly at rated power at all high wind speeds. The active power output of an active-stall WPP can be varied at any time by pitching the blades.

While pitching towards stall, the maximum turning angle of the ASC blade required to stall is –10° (see Figure 5.11) as compared to +70° for a pitch controlled WPP when turning the blades to feather. In general terms:

- Stall profiled blades control short term, faster phenomena such as rapid gusts.
- Blade pitching system then holds the average power constant.

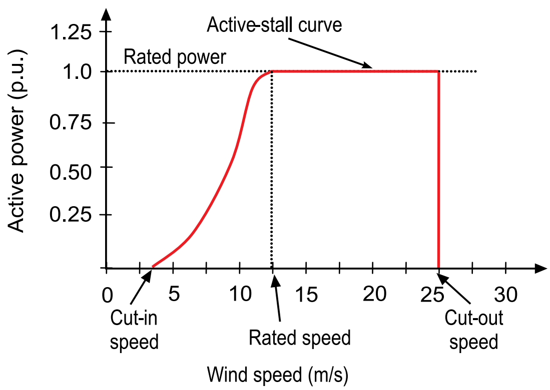


Figure 5.10 **Power Curve of Active-Stall Controlled Wind Turbine:** During wind gusts, the pitching action of the active-stall blades does not overload the generator and keeps the power curve flat.

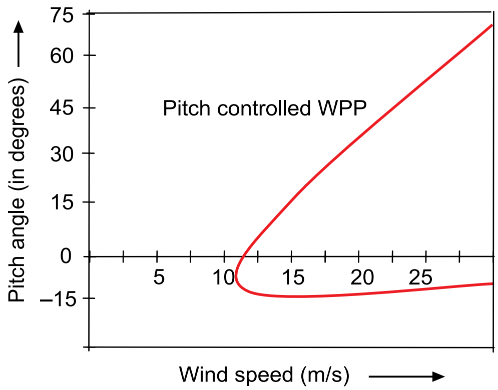


Figure 5.11 **Typical Pitching Angles of a Active-Stall Controlled Rotor Blade:** It can be seen that the pitching action of the ASC blade (0° to –15°) is opposite to the pitching action of the pitch controlled WPPs (0° to +70°).

During wind gusts, the output power in an ASC wind turbine can be controlled more accurately than the passive stall WPPs, thereby avoiding the overshooting of the rated power and overloading of the electric generator during the brief initial periods of the wind gusts. After attaining the rated power by the WPP, if the electric generator is about to be overloaded, this WPP will pitch in the opposite direction to pitch towards the further stall. In the stopped condition, it can be observed that it is the trailing edge of the blade that is facing the wind.

5.5.3 Features of Active-stall Controlled WPP

In short, it can be said that if the grid is strong, active-stall is attractive to investors due to the following major features:

(i) WPP is not strained during gusty winds, as the control of the power output is more accurate than the passive stall (to avoid overshooting peaky curve).
(ii) It has a robust controller.
(iii) WPP can be run almost at rated power at all high wind speeds which is not the case with the normal passive stall controlled machine.
(iv) At startup, it is possible to make a much smoother cut-in to the grid and also, a smoother cut-out at shutdown. This gives much less noise on the grid and at the same time, it extends the lifetime of the power train and electrical system in the WPP.
(v) In the dual-speed SCIG mounted on certain active-stall WPPs, switchover between the small and the large takes place more gently.
(vi) During severe *fault-ride-through (FRT)* conditions, when the voltage drops to a low level and the WPP has to remain connected to the grid, the active-stall system can regulate the aerodynamic power input relatively better than the passive stall WPP.
(vii) It is possible for the WPP to down-regulate the produced power if the local grid has a high loading. However, this demands a special unit for grid surveillance.
(viii) Besides providing power control, the blade pitch system is also used to accelerate the rotating blades from idling speed to operational speed more quickly and bring the rotor back to a safe idling speed in case of a grid loss or any other functional errors.
(ix) It is possible to quickly change the power level from 100% to 20% in few seconds.

The major limitations of the ASC wind turbines are as follows:

(i) Blades need to be more stiff.
(ii) Uncertainty of aerofoil characteristics results in load uncertainty.
(iii) These WPPs have relatively higher price than the passive stall regulated WPPs.

5.6 HALTING A WPP

A WPP needs to be halted for routine maintenance purposes or at cut-out speed. When the wind speed becomes very high, the structural loads on the WPP become too high and so the WPP is taken out of operation depending on whether the WPP is optimised for low or high wind speeds, i.e., between 17 m/s to 25 m/s. Following are the methods that can be adopted for halting:

(i) Aerodynamic stopping is the primary braking method for large WPPs.
(ii) Mechanical stopping is the secondary braking method. The mechanical disc brakes for large WPPs also serve as a backup in case of failure of aerodynamic braking which is quite rare. Disc brakes are quite sparingly used in direct-drive WPPs except for emergency stops or for maintenance operation.
(iii) Electromechanical braking is newer but effective method for secondary braking of large WPPs.

(iv) Furling is a more preferred method for slowing and stopping of small wind turbines.
(v) Electrodynamic braking is more preferred for micro and mini wind turbines.

It should be noted that in large modern WPPs, both the aerodynamic and mechanical brakes are designed to form a redundant system and they work together to render it fail-safe which means that each of them gets activated (even without the electronic controller signal) to stop the WPP in case of emergency. Through a *watchdog function*, a loss of the computer function activates an emergency stop. This means that if by chance, the hydraulic pressure in the WPP is not put on or is missing during the starting of the WPP or it trails during normal production operation or rotation of the rotor, the aerodynamic brake would go into a fail-safe operating mode, i.e., becomes active due to a spring force and centrifugal force to bring the WPP to a complete halt. By design, the safety system will always take precedence over other control systems.

5.6.1 Aerodynamic Braking of WPP

At very high wind speeds, typically 25 m/s (cut-out speed) and above, the WPP accelerates to dangerous speeds that may destroy it due to severe mechanical stresses in the drive train and the tower. Hence, most WPPs have to be shut down at cut-out speed. The WPP operation resumes when the wind speed drops back to a safe level. Another situation is when any large capacity power plant gets disconnected from the grid which causes the electric generator in the WPP to rapidly accelerate to run away speeds within a few seconds, which may destroy it.

The primary braking is always aerodynamic. If any large WPP has to be stopped during its normal working, aerodynamic braking, also called *soft braking*, is the primary strategy. The same principle of slowing down the aircrafts aerodynamically is used for stopping the rotation of a WPP. By aerodynamic braking the lift action is spoilt, whereby the rotation of rotor is suddenly slowed down. This method of softly braking the WPP reduces the huge driving forces and moments in a few seconds. Hard mechanical braking by the disc creates considerable amount of stresses on various parts of the drive train, thereby increasing the failure rate of mechanical parts.

(a) Braking of Stall Controlled WPP

In a WPP, the maximum lift force occurs at the outer one-third part of the wind turbine rotor blade. Hence, when a fixed blade (i.e., stall controlled) WPP needs to be stopped during normal operation, aerodynamic braking is achieved by operating the pitchable tips (also called tip brake) that are an integral part of the blade aerofoil situated at the outer tip of each rotor blade (see Figure 5.12).

During the normal operation, this tip brake is held in line with the main blade profile against centrifugal force by a hydraulic cylinder. A spring loaded centrifugal latch releases the tip brake when an overspeed condition occurs or it has to be purposefully stopped. The tip is allowed to move outboard and a cam rotates it until

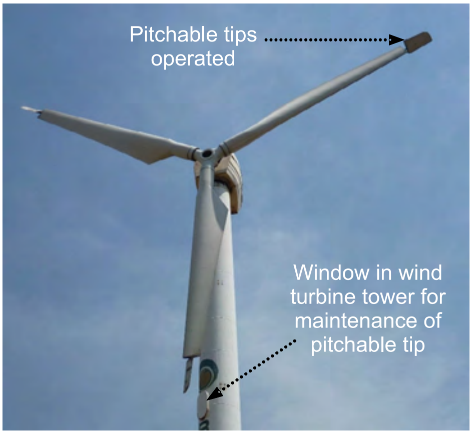


Figure 5.12 **Tip brake:** Tip of 250 kW (activated) spoil the lift force to stop the WPP. *Picture by author.*

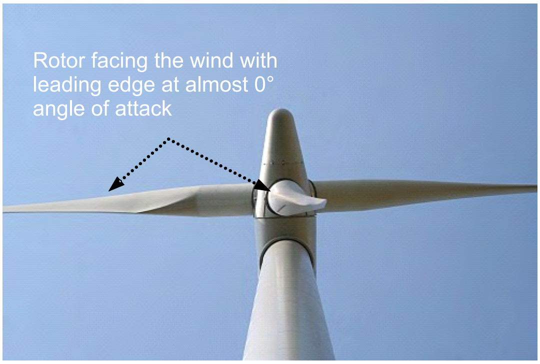
it is almost perpendicular to the plane of rotation by about 90°, thereby providing the drag needed to brake the WPP aerodynamically. Structurally, this blade tip is separate from the rest of the blade and is about 10% of the entire blade length. It is interesting to note that the WPP can always be shut down even with only one blade tip being deployed.

(b) Braking of Pitch Controlled WPP

In the normally operating pitch controlled WPP, the blade angles of the pitching system are continuously and minutely monitored by the microcomputer of the WPP. In this type of WPP, the full length blade is turned longitudinally by 90° to feather (flag-like position) with the leading edge facing the wind [see Figure 5.4(b)] to spoil the lift force and stop the WPP. All the three blades have the same angular setting and are simultaneously actuated. In case of the electric motor pitching, each of the three blades has the provision to be independently pitched at the same angle while the pitch cylinder renders the same function in hydraulic pitching. In case of differences in the angular setting of even one of the three blades or sudden changes of measured angles are encountered by the angle encoder, the WPP is programmed to come to a halt with the leading edges pitched at 90°.

(c) Braking of Active-stall Controlled WPP

It is to be noted that the blades of the active-stall controlled WPP have the stall properties. However, unlike the fixed blade stall controlled WPP, the blades can be pitched. But unlike the pitch controlled WPP, they are pitched in a few steps in the opposite direction [see Figure 5.9(b)] so that the rotor goes into a deeper stall and if it is pitched still further till the trailing edge faces the wind [see Figure 5.13(b)], the lift action is spoilt and the WPP comes to a halt.



(a)

(b)

Figure 5.13 Active-Stall WPP: (a) Active-stall 2 MW wind turbine with blades pitched at 0° and rotating to produce electric power. (b) Active-stall 2 MW wind turbine in stopped position with trailing edge facing the wind at 90°.
Courtesy: Klaus Rockenbauer, Austria.

5.7 OTHER METHODS OF AERODYNAMIC CONTROL

There are several methods of aerodynamic power control (see Figure 5.14). The aerodynamic control methods shown in Figure 5.14(a) to (d) have already been discussed in the preceding sections.

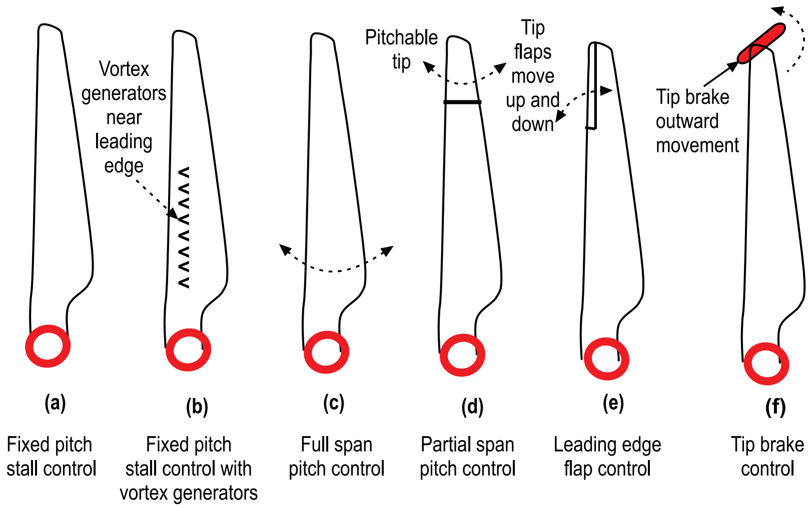


Figure 5.14 Different Methods of Wind Turbine Rotor Aerodynamic Control.

Tip flaps (or *ailerons*) can be used to change the blade geometry over the tip part of the blade to reduce the lift coefficient and increase the drag on their surface. Some earlier Danish DWP 150 kW WPPs of 1980s used ailerons at the tip of the blade [see Figure 5.14(e)] to add a negative torque to the rotor blade and limit the

power extracted in high winds. Such WPPs became popular and some of them can still be seen in the wind farms near Porbandar in Western Gujarat of India and may be in other parts of the world as well.

The *tip brake* (or *tip vanes*) control is incorporated in certain WPPs such as the American ESI 100 kW [see Figure 5.14(f)] WPP. This tip brake disrupts the air flow around the blade tip and modifies the lift and drag forces to stop it when operated. If the rotor gains overspeeds, the tip flaps fly out spoiling the lift force of the blades and bring it to a halt. As soon as the high speed of the wind comes to the desired level, the compressed spring (or the electric power control) restores the blade tip to its original position to start the operation of the WPP automatically. Though it is simple, this strategy did not become popular with higher capacity WPPs.

The *yaw control* is another simple strategy in which the whole nacelle and the rotor are turned out of the wind to reduce the power captured by the WPP. The underlying principle is that it alters the effective rotor area in the free air stream. Yaw control has been successfully experimented in Italy with 1 MW, 60 m diameter, two-bladed Gamma-60 WPP having a yaw rate of 8°/s. But still, this control is not an attractive proposition to the WPP manufacturing industry because of various reasons such as the cyclically varying stresses that occur in the rotor which may ultimately damage the entire structure. Nowadays, yaw control is used only for small wind turbines, as it is a simple and cheap strategy.

For changing wind speeds, it is difficult to have a rapid response (which is the actual need) for large WPPs. Due to the large moment of inertia of the nacelle and rotor, it creates mechanical stresses on the blades and also creates a loud noise during yawing. It is observed that even significant yaw changes, say 8°/s which is significantly high, the power reduction is only of a few percent (this is because the power decreases as a function of the cosine relationship between the perpendicular component of the wind speed to the rotor disc and the yaw angle). Whereas, by the pitching action, the blade pitch angle of the same value easily halves the power output at high undesirable wind speeds. Further, the hub must be able to withstand gyroscopic loads resulting from the yawing motion.

SUMMARY

In conclusion, it can be said that modern WPPs work on the principle of lift force and not on the principle of drag. As discussed in this chapter, the WPPs can be aerodynamically controlled by stall controlled, pitch controlled or active-stall controlled technologies adapted by different manufacturers to suit different situations and needs. It has been also seen that every WPP has a fail safe braking system.

EXERCISES

5.1 Comment on the major three-fold purpose of controlling WPPs.

5.2 Distinguish between the three major methods of aerodynamic control.

5.3 Explain the stalling action of the blades.

5.4 Describe the pitch regulation of a WPP.

5.5 Compare the differences between the pitch and active stall regulation.

5.6 With the help of sketches of the power curves, explain the differences between the three types of aerodynamic WPP regulation.

5.7 Describe the WPP using vortex generators to facilitate the action.

5.8 Explain the four regions of the pitch controlled WPP power curve.

5.9 Explain the three phenomena when blades are feathered to the incoming wind.

5.10 With sketch, explain the torque and pitch angle relationship characteristics of a pitch controlled WPP.

5.11 Describe the four types of pitching mechanisms used in WPPs.

5.12 Compare at least five merits of (a) pitch controlled WPPs, and (b) active-stall controlled WPPs.

6

Wind Power Control Strategies

An east wind from the LORD will come,
blowing in from the desert.
—Hosea 13:15

Learning Outcome

On studying this chapter, you will be able to discriminate the working of different types of aerodynamic power control strategies and power electronic converters adapted in wind power plants.

CHAPTER HIGHLIGHTS

6.1 *Introduction*
6.2 *Power control classification*
6.3 *Integrated aerodynamic and electric control strategies*
6.4 *Power electronic converters*
6.5 *Constant speed and variable speed WPPs*
6.6 *Back-to-back PEC in WPP*

6.1 INTRODUCTION

Controlled power generation is an essential requirement for the efficient working of any power plant, not only for the personnel but also for the safety of the generating plant itself and the environment. Wind power plants (WPPs) are not an exception in this regard. *Power control* means that the WPP limits the share of the available power in the wind using both the aerodynamic control (already discussed in the preceding chapter) and the electric generator control. The major goal of wind power control strategies discussed in this chapter is to maximise the energy production and at the same time, keep the WPP operation within safe limits.

6.2 POWER CONTROL CLASSIFICATION

There are two major strategies for the power control of WPPs. Although following two control strategies are independent, they can be closely interrelated.

- Aerodynamic control
- Power electronic control.

Aerodynamic control method of limiting the power from the wind is generally adapted when the power available in the wind is higher than the power for which the WPP has been designed (as discussed in the preceding chapter). This method of control is also called the principle of *positive feed forward control.* The acceleration and deceleration of the rotor blades have to be controlled to limit the electrical load on the generator and the mechanical stresses on the rotor blades, the hub (to some extent) and the rest of the drive train as well. However, continuous control of the rotor speed by pitching of the blades leads to continuous fluctuation of the power output to the grid which is not desirable. If a quick variation of speed is possible by this control when there is a large difference between the input power and output power, then the stress on the blades is increased on account of the large torque needed.

Power electronic control is the ability of the WPP to adapt its electric generator rotor speed during normal energy production operation. This control depends on the type of electric generator used in the WPP and is called the principle of *negative feedback control*. This method of speed control technique offers a smooth operation, as it does not involve any mechanical action. Power electronic control is applicable when there is a power electronic converter (PEC) interface between the electric generator and local grid.

Control strategies are different for constant speed and variable speed WPPs. Their controls in coordination with aerodynamic and power electronic control are depicted in Figure 6.1(a) and (b). It is seen that the control strategies for the WPPs are different for condition A when the wind speed is $v_{\text{cut-in}} < v_o < v_{\text{rated}}$. The control strategies are again different for condition B for wind speeds $v_{\text{rated}} < v_o < v_{\text{cut-out}}$. The undisturbed wind speed is v_o, $v_{\text{cut-in}}$ is the cut-in wind speed, v_{rated} is its rated wind speed and $v_{\text{cut-out}}$ is the wind speed at which the WPP will be halted. These concepts

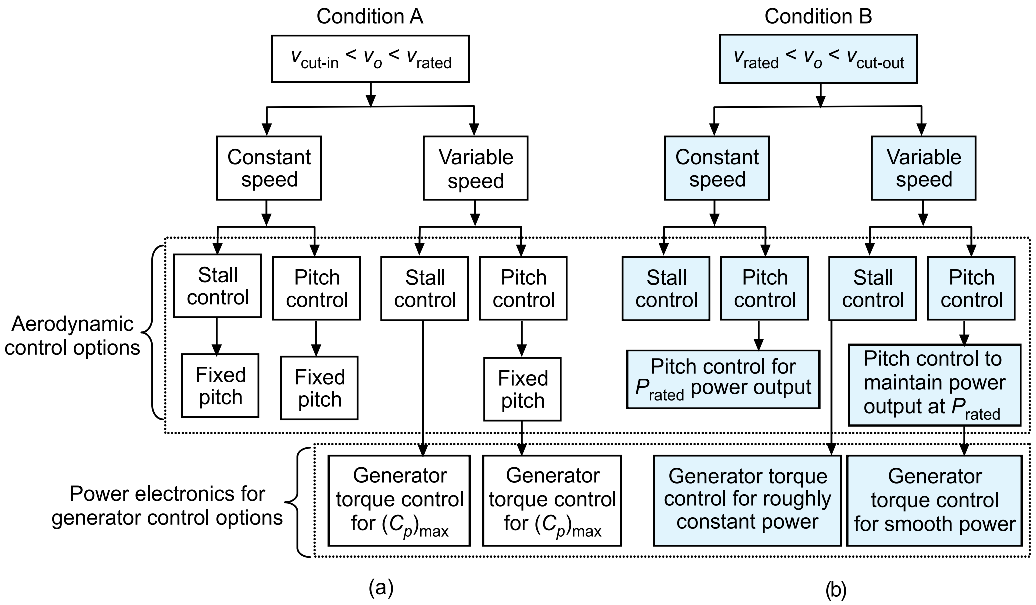


Figure 6.1 **Control Strategies for WPPs when $v_{cut\text{-}in} < v_o < v_{rated}$ and $v_{rated} < v_o < v_{cut\text{-}out}$:** $v_{cut\text{-}in}$ = Cut-in speed; v_0 = Undisturbed average wind speed; v_{rated} = Rated wind speed; $v_{cut\text{-}out}$ = Cut-out speed.

are discussed in the following sections and also in the rest of the chapters as well.

The instantaneous difference between mechanical and electrical power, the rotor speed changes according to the following equation:

$$\frac{Jd\omega}{dt} = \frac{1}{\omega}(P_m - P_e) \tag{6.1}$$

where,

J = Polar moment of inertia of the rotor
ω = Angular speed of the rotor
P_m = Mechanical power produced by the WPP
P_e = Electrical power delivered to the load.

Integrating the above equation, we get:

$$\frac{1}{2}J(\omega_2^2 - \omega_1^2) = \int_{t_1}^{t_2}(P_m - P_e)\,dt \tag{6.2}$$

By the PEC, the value of P_e can be controlled. WPP power control algorithms for variable speed WPPs at above rated wind speed conditions are for rotor speed regulation by pitch actuation as well as for electrical power production by generator torque control. Rotor speed regulation is achieved by the feedback of rotor speed. Whereas, the rotor acceleration of pitch angle is achieved by the feedback of the proportional derivative (PD) control and pitch angle by the feedback of the proportional integration (PI) control.

6.3 INTEGRATED AERODYNAMIC AND ELECTRIC CONTROL STRATEGIES

For an economical WPP design, the maximum performance of the generator and gearbox needs to be limited to an appropriate level for the overall WPP's safe operating environment. The ideal situation for the wind turbine rotor is to be able to extract as much power as possible from the wind till the rated power of the electric generator is reached and then limit the power extraction at that rated level even if the wind speed increases further. For this to happen, the WPPs are designed to work at maximum aerodynamic efficiency between cut-in speed and rated speed in region II (see Figure 6.2). For higher than rated wind speeds in region III but below cut-out speed, the WPP is controlled by stall, pitch or active-stall action to maintain the loading of electric generator rating. The following control strategies are the combinations of aerodynamic and electric control which render it possible to manage the WPP functionality for different strategies of operations:

(i) Constant speed generator fixed pitch (CSG-FP)
(ii) Constant speed generator variable pitch (CSG-VP)
(iii) Variable speed generator fixed pitch (VSG-FP)
(iv) Variable speed generator variable pitch (VSG-VP).

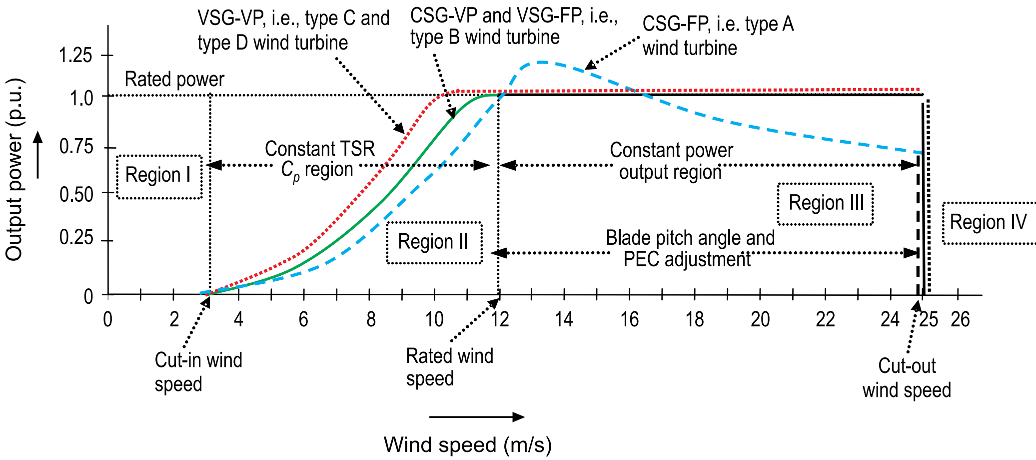


Figure 6.2 Integrated Aerodynamic and Electric Control of WPPs: It can be seen that out of the different WPP topologies, a variable speed WPP combined with pitch control is the best strategy because even at lower than rated wind speeds, more power can be captured.

6.3.1 Constant Speed Generator Fixed Pitch (CSG-FP) Configuration

In this strategy, the electric generator speed is constant and rotor blades are permanently fixed at an angle of attack 'α' for the most optimum blade position based on the wind data of that particular site. In this topology where the induction generator is used in the WPP, the stator is directly connected to the electric grid

causing the generator speed to be locked to the electric power line frequency to keep the RPM fixed. It runs at approximately constant speed even in high winds producing more power and yet achieving this without any change to the rotor geometry. The grid behaves like a large flywheel holding the speed of the WPP nearly constant, irrespective of the changes in wind speed.

These WPPs are aerodynamically controlled by using passive stall methods for high wind speeds, as seen by the dashed line power curve (see Figure 6.2). As the wind speed increases and the rotor speed is held constant, flow angles over the blade sections steepen. The blades become increasingly stalled and this limits the power to acceptable levels without any additional active control. The gearbox ratio selection is critical for this passive control because it ensures that the rated power is not exceeded. It should be noted that the rated power of the WPP is achieved only at one wind speed and it operates with its maximum efficiency only at a particular wind speed in the region II of the power curve.

6.3.2 Constant Speed Generator Variable Pitch (CSG-VP) Configuration

In this strategy, the electric generator speed is constant, but the blade pitch angles are varied continuously (see Figure 6.2) based on the wind speed. However, the feathering of blade takes a significant amount of control design. Stalling action increases the unwanted thrust force, as the wind speed increases.

Below the rated wind speed, this type of WPP has a near optimum efficiency in region II, as seen by the solid line in the power curves (see Figure 6.2). To limit the captured power at full load rating when operating above the rated wind speed (generally around 12 m/s), the blade pitch is continuously adjusted at 10 minute averages for IEC wind class I and II WPPs. It does not pay to design for very strong wind speeds beyond the rated speed, as they are quite rare. For IEC wind class III wind turbines, cut-off wind speed value is in the range of 17 m/s–20 m/s. However, the microcomputer initiates the emergency stop in case of damage or other critical reasons.

6.3.3 Variable Speed Generator Fixed Pitch (VSG-FP) Configuration

In this type of WPP, the electric generator runs at a variable speed (see Figure 6.2) but blade pitch angles are fixed at the most optimum angle of attack relevant to that wind site. To limit the power captured, stall control method (as in Jeumont J48 WPP) is adapted (see Figure 6.3) which relies heavily upon the aerofoil blade design to limit the electric power generated.

The power control in such WPPs is by the PECs to regulate the generator electromagnetic torque. By regulating the generator torque, the blade rotor speed can be adjusted and the WPP can be operated at the point of optimal TSR within the generator and rotor design operation constraints. When the maximum design blade rotor speed is reached, the WPP is operated at a constant speed mode (see Figure 6.4) with passive stall regulation.

Figure 6.3 **VSG-FP Configuration:** This 750 kW Jeumont J48 variable speed WPP has an axial flux permanent magnet variable speed generator and is stall controlled; conspicuous by the operated tip brakes.
Courtesy: Riaan Smit, South Africa.

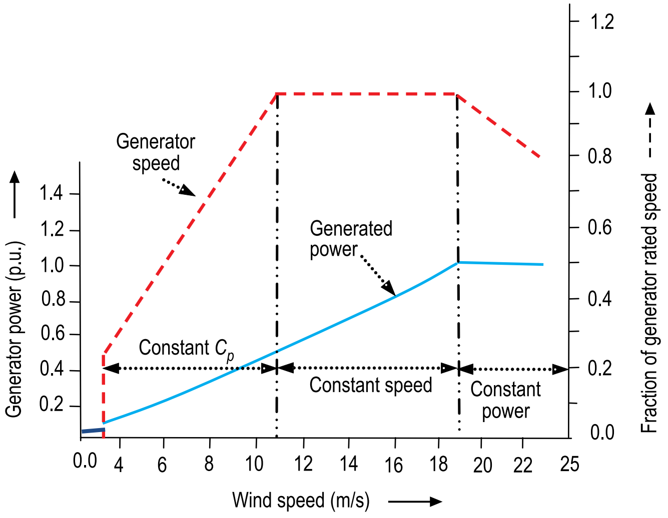


Figure 6.4 **Variable Speed Generator Operation and Fixed Pitch of a Stall controlled WPP.**

The efficiency is maximised at low wind speeds but rated power can be achieved at only one wind speed. However, in case of lower wind speed, VGS-FP can capture more energy and improve power quality. As the wind speed increases and the extracted power exceeds the generator rated power, the WPP is operated in a constant power

mode and the rotor speed is regulated to limit the power extracted from the wind by the increased stalling action due to the stall blade characteristics resulting in reduced blade efficiency.

6.3.4 Variable Speed Generator Variable Pitch (VSG-VP) Configuration

VSG-VP is the only control strategy that theoretically achieves the ideal power curve. In this strategy, the electric generator runs at a variable speed (see Figure 6.2) and simultaneously the pitch angles vary depending on the wind speed in coordination with the synchronous generator speed (or doubly-fed induction generator speed) through PEC to maximise the energy capture (see Figure 6.5) and improve the power quality. Most of the type-D WPPs are operated in this mode.

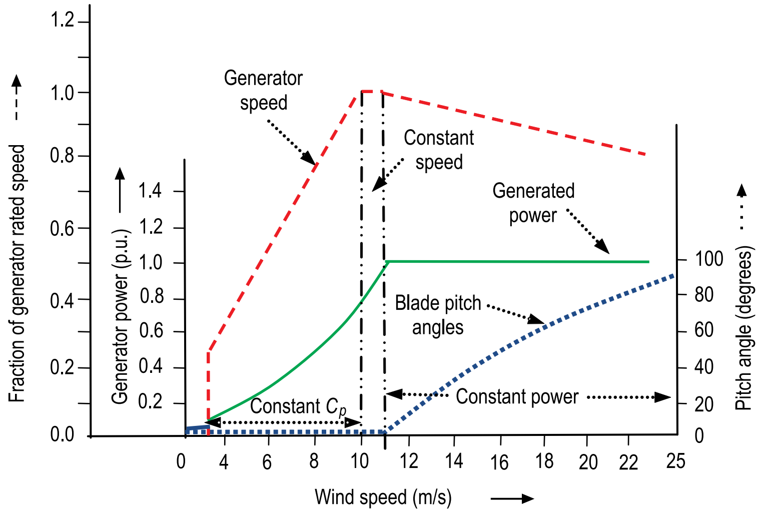
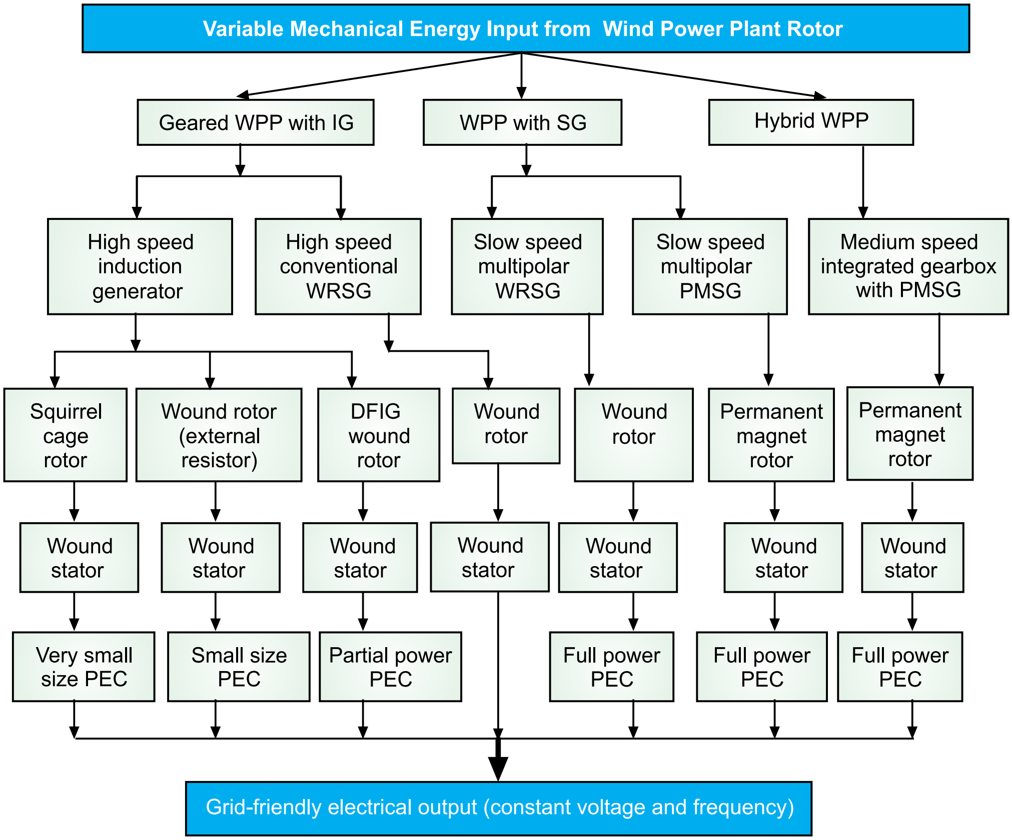


Figure 6.5 Variable Speed Generator and Variable Pitch Operation of a Pitch Regulated WPP.

6.4 POWER ELECTRONIC CONVERTERS

The inventions and advancements in electronics, power electronics and computer technology have rendered the WPPs technologically and economically viable. From the late 1970s and early 1980s when the WPPs started to feed power to the electric grid, power electronic devices like thyristors and electronic circuits integrated with microcomputers have invariably become part and parcel of all WPPs, to render them fully unmanned and grid-friendly. All modern large WPPs invariably use some or the other power electronic device to control the WPP in some form or the other (see Figure 6.6) and in general, they are called *power electronic converters (PEC)*. It is designed to operate either as a converter or inverter depending on the need and hence, the term *converter* or *power electronic converter* is a commonly used term



Legends

- WPP - Wind power plant
- IG - Induction generator
- SG - Synchronous generator
- WRSG - Wound rotor synchronous generator
- PMSG - Permanent magnet synchronous generator
- DFIG - Doubly-fed induction generator
- Very small - Standard thyristor
- Small - Bidirectional PEC devices like MOSFETs, etc.
- Partial - Partially control PEC using four-quadrant control
- Full - Fully controlled PEC using four-quadrant control
- PEC - Power electronic converter

Figure 6.6 Overview of PEC Applications Used in Different Types of WPPs.

which means anyone of them or both. Depending on the application, the PEC acts as an interface and may allow power flow in both directions between the WPP and the grid network.

In fact, it is the deployment of PECs in WPPs that has permitted the use of alternative electric generator technologies such as DFIGs, WRSGs and PMSGs in

direct-drive and medium speed hybrid (semi-geared) WPPs for improved efficiencies. Apart from allowing variable speed operation for maximum power capture during partial winds, the use of PECs in WPPs allows for mechanical decoupling from grid events and wind turbulence and fault ride through (FRT) operations. Several benefits of incorporating PECs in WPP are as follows:

- Greater controllability of WPP operation
- Controllable active and reactive power during faults within a matter of milliseconds
- Improved power quality and stability
- Reduced loads on the drive train and reduced noise.

The main requirements of the PECs for WPP applications can be summarised as follows:

- High speed switching
- Low loss conduction
- Higher efficiency
- Reliability for a wide range of medium voltage applications
- Lower cost.

Power electronic devices used in various adaptations of PECs in different types of WPPs can be of following types:

- Simple PEC soft starters used in constant speed WPPs.
- Partial or full power complex PECs in variable speed WPPs.

Simple PECs are used in constant speed WPPs in the form of soft starters (see Figure 6.7) using power diodes and standard thyristors for controlling inrush starting currents and capacitor switching.

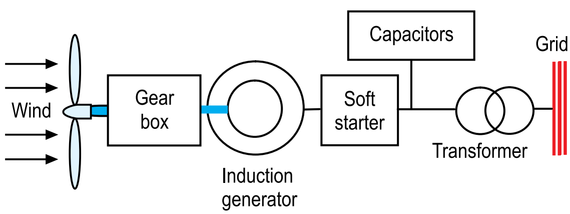


Figure 6.7 Simple PEC and Constant Speed WPP.

The electric power generated by a variable speed WPP is not grid compatible and hence, there is a requirement of a PEC to convert this undesirable variable power to DC and then, back to grid compatible AC. More complex PECs are used in variable speed WPPs with different topologies (see dashed lines in Figure 6.8).

Two types of inverters are possible—line commutated and force commutated. Out of the various PEC topologies available, back-to-back, tandem, matrix, multilevel and AC link converters, force commutated back-to-back PEC (refer to Figure 6.13) is most commonly used in variable speed WPPs.

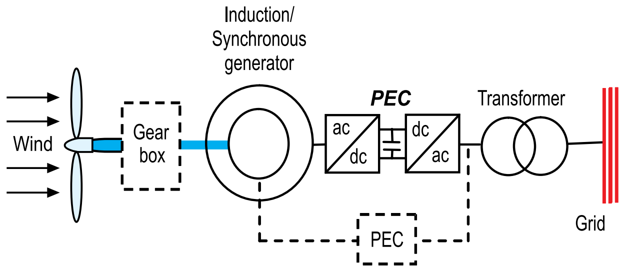


Figure 6.8 Complex PEC and Variable Speed WPP.

In general, the two main aims of PECs for WPPs can be concluded as follows:

- Control the magnetisation of electrical generator so that it remains synchronous with the grid frequency.
- Act as an energy buffer for the power fluctuations caused by the inherently gusty wind and also control the disturbances coming from the grid side, i.e., voltages sags, swells and transients.

6.5 CONSTANT SPEED AND VARIABLE SPEED WPPs

The prime mover of the WPP is moving air, i.e., the wind cannot be controlled and it fluctuates randomly. Therefore, electrical generating systems of WPPs are different from the generators used in conventional power plants. Based on the electric generators used, WPPs are broadly categorised as constant and variable speed WPPs.

Based on the type of control, constant speed WPPs can further be classified as follows:

- Type A constant speed WPP with a speed variation of 1% to 2% from the synchronous speed.
- Type B narrow range variable speed WPP having a range of 0% to 10% speed variation from the synchronous speed.

The grid operators require a constant output for power system stability. But due to the wind gusts and limited response speed of the pitching mechanism (i.e., limited bandwidth), the instantaneous power fluctuates around the rated value.

Wind gusts and air turbulence cause rapid changes in the wind turbine rotor torque called the *torque ripple* that get transferred to the drive train and the grid network (see Figure 6.9) of a constant speed WPP. This can result in immediate damage or long term fatigue unless the WPP is properly designed to reduce these spikes or torque ripple. Practically, wind turbulence causes small modifications to these power curves and creates momentary fatigue loads, so proper care must be taken for this while designing a WPP.

To harness wind energy over a wider range of wind speeds, two-speed stall regulated WPPs (to work during high and low wind speeds) emerged during 1980s and 1990s as a cheaper compromise in place of expensive and complex variable speed

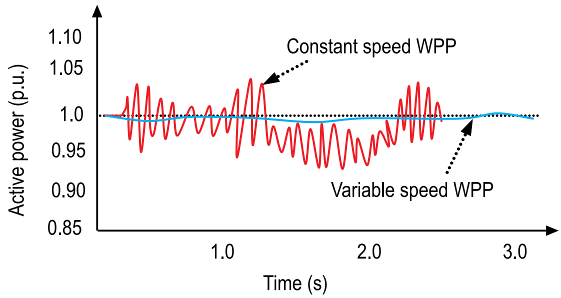


Figure 6.9 Typical Power Variations of Constant and Variable Speed WPP: Wind speed fluctuations have a bearing on the stresses of the mechanical components.

WPPs for improving the energy capture and noise emission. Two separate induction generators in a single nacelle were adapted as a cheaper way of achieving variable speed operation in 1980s. In early 1990s, single dual-speed induction generator was adapted which is still used as a cheaper compromise in place of complex variable speed WPPs and attain better TSRs. But practically, this is a constant speed operation (discussed further in the chapter of constant speed WPPs).

On comparing with the same capacity ratings of WPPs, it is observed that the efficiency (see Figure 6.10) of a variable speed WPP is better than that of a constant speed WPP. Constant speed WPPs have their share of limitations as well which are given below:

- Due to varying wind speeds, the fluctuations from the wind turbine rotor are directly translated as torque pulsations onto the gearbox which may accelerate the failure rate.
- The constant speed WPPs cannot operate at maximum efficiency (they work suboptimally) except at the wind speeds corresponding to its designed TSR. Constant speed WPPs are around 10% less efficient than the variable speed WPPs.
- There are difficulties in the control of both active and reactive electric power.

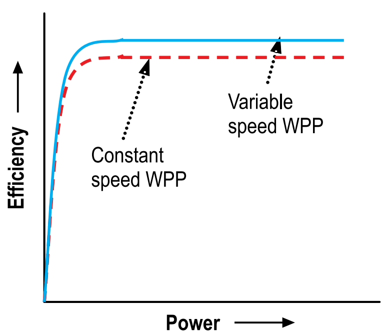


Figure 6.10 Efficiencies of Constant and Variable Speed WPP: Although the efficiencies may not be substantial, but annually, it does make a difference.

The major benefits of variable speed WPPs are as follows:

- They can be connected to the grid even at lower wind speeds. They speed up in proportion to the increased wind speed and thereby, enable increased energy capture even below the rated power.
- Variable speed capability above the rated power (even over quite a small speed range) can substantially relieve loads, ease pitch system duty and greatly reduce output power variability.

As the wind speed increases and the rated power of the WPP is reached (as seen in the power curve), the rotor reverts to nearly constant speed operation with the blades being pitched as required to regulate the power. Variable speed operation of the WPP allows the rotor blade angles and the wind speed to be matched so that the rotor blade angle could, thereby, maintain the best flow geometry for maximum efficiency. Although the development of variable speed WPPs, using PECs was undertaken largely to reduce mechanical loads, the reactive power control was the most useful by-product. It reduced the WPP's effect on the grid network during a sudden fault.

Different classes of variable speed WPPs based on the type of control are:

- Type-C limited range variable speed WPP with a range of –30% to +40% speed variation from the synchronous speed.
- Type-D wide range variable speed WPP with a range of about 2.5 times the rated speed.

The evaluation of different types of electric generators required for WPP applications can be assessed and selected on various criteria. These are:

- Speed range
- Dynamic behaviour of constant speed parallel operation with grid
- Reactive power
- Controllability
- Synchronisation
- Efficiency
- Maintenance and reliability.

6.5.1 Constant Speed WPP Operation

Till the beginning of 1990s, the squirrel cage induction generators (SCIG) were the ones in all constant speed WPPs that were connected through a gearbox to the wind turbine rotor and running at constant speed determined by the grid frequency, the gear ratio of the gearbox as well as by the number of poles of the electric generator. The rotors of these generators prevented from turning much faster than the synchronous RPM, even if there was a slight change in the RPM caused by generator slip of the order of 1%–2%.

In other words, the SCIG is electrically locked to the grid to which its stator is directly connected. Therefore, for all practical purposes, they are called *constant speed WPPs*. An increase in wind speed does not affect the speed of the SCIG greatly,

up to a certain limit. However, it affects the electromagnetic torque which varies with the increase in load angle δ and hence, there is an increase in the electrical power generated and fed into the grid upto the designed upper limit of the SCIG. Beyond this upper limit, the SCIG does not remain locked with the grid, but runs out of synchronism and comes to a halt.

Later the wound rotor induction generator (WRIG) was also used in WPPs. It also work on the same principle as SCIG but because of the external resistors, a slightly more variable speed range could be obtained and hence a little more increase in the power output.

On analysing the power curve in region I (see Figure 6.11), it can be seen that since the wind speed is below the cut-in level, the wind turbine rotor does not rotate, but in some WPPs, the wind turbine rotor idles away to prevent the grease and oil from drying up and reduce the mechanical stresses. However, the stator of the generator continues to be disconnected from the electrical grid.

In constant speed WPPs, the electric generator always runs at a constant speed even in region II (see Figure 6.11), regardless of however fast the wind may blow. At lower than rated wind speeds, the power P captured is directly proportional to the cube of the wind speed v and the torque T is directly proportional to the square of the wind speed which is most desirable. For each particular aerodynamic (aerofoil) shape of the blade, the TSR has a fixed value, as it is a characteristic of a given WPP. The energy yield can be optimised over a full range of the wind turbine rotor speeds if it is made to operate at or near this TSR. For constant speed WPPs, the TSR varies over a wide range due to continuously changing wind speeds leading to inefficiencies in energy capture. Therefore, the selection of gearbox ratio is critical for obtaining the optimal power coefficient C_p corresponding to the most frequent wind speed for that particular windy location.

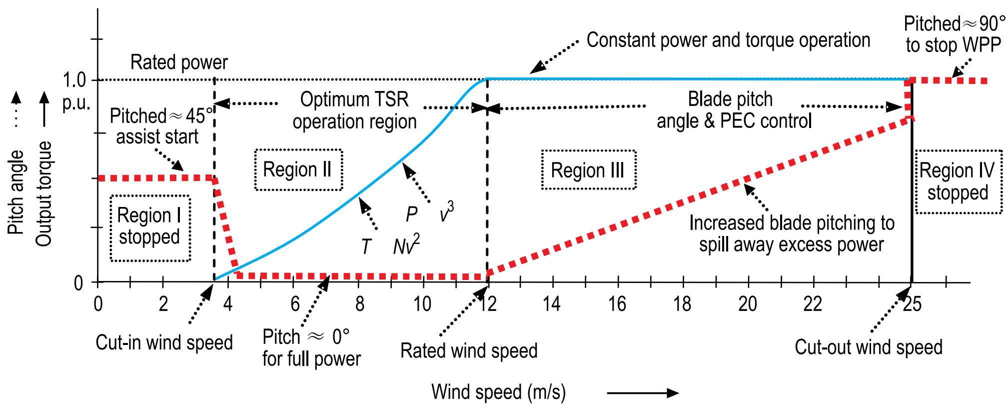


Figure 6.11 Torque, Speed and Pitch Angle Characteristics for Maximum Power from a WPP.

When the wind speed increases to levels above the rated wind speed of the WPP, it leads to the overloading of the electric generator. Therefore, the aerodynamic efficiency of the rotor must be reduced or limited in order to limit the power extracted from the wind to the constant rated power, as in region III (see Figure 6.11). In

this region, the C_p is lower and the power is not proportional to the cube of the wind speed but increases at a lower rate than that of region II. If the wind speed continues to rise (especially during wind gusts), the rotor speed is again reduced by pitching the blades further to spill away the excess energy and the C_p further moves away from the optimum value so that the electric generator power continues to remain constant.

Therefore, at higher wind speeds in region III, C_p is not very efficient but with greater wind speeds, this inefficiency becomes a benefit, as the generator is then less likely to be overloaded. Such designs are more suitable for stall regulated WPPs. Some WPPs use a dual winding SCIG (a lower speed winding for low wind speeds and a higher speed winding for stronger winds) which helps the rotor to operate close to the optimum TSR for a larger range of wind speeds. The energy capture can then even go up to 90% over the full year, even during the times of lower wind speeds. However, over a full year, even for a well designed constant single speed WPP, it is possible to extract about 80% of the energy available at the site as compared to 100% for a fully variable speed WPP.

Beyond the cut-out speed in region IV (see Figure 6.11), the pitch regulated WPP is halted by feathering the blades to 90°. In this region, the active-stall regulated WPP is also halted by pitching in the opposite direction, the stall regulated WPP is halted by operating the tip brakes to fully spill away the excess power and protect the electric generator and the PEC from getting damaged.

The power curve is in a quasi-static depiction of the blade performance with respect to the rated RPM, as it does not take into account the turbulence effects, blade vibration or bending of the blade or other asymmetries such as tower shadowing and others. However, it does provide a simpler means of incorporating the otherwise quite complex details of the aerodynamic conversion process for modelling of the performance of WPPs. Quasi-static rotor modelling, i.e., an algebraic relationship between the wind speed and the mechanical power extracted from the wind is used in power system studies.

6.5.2 Variable Speed WPP Operation

Variable speed drives enable extraction of more of the power offered by wind, by broadening the band of wind speed over which WPPs can operate. Two major reasons spurred the use of variable speed WPPs in the early 1990s. First, by running the wind turbine rotor in a wider wind speed range, energy capture is greatly increased, as the rotor blades could be operated at its optimal TSR. The second reason for variable speed operation was that it allowed precise control of the torque and kept the loads limited at rated and above rated capacity. Moreover, the advancements in digital electronics and power electronics accelerated the evolution of different types of variable speed WPPs.

Variable speed WPPs are designed to attain the maximum aerodynamic efficiency in a wide range of wind speeds. It is possible to continuously adapt (by accelerating or decelerating) the rotation speed of the blades to the wind speed, thus keeping the TSR constant at an optimum value. During the start up of a variable

speed WPP in region I (see Figure 6.11), the rotor speed ω is very low and hence, the TSR λ is also very low. Low TSR results in a low performance coefficient C_p and low aerodynamic power. The wind turbine blades are, therefore, kept pitched at 45° for pitch regulated WPPs to get a better starting torque. When the rotor starts rotating at the cut-in speed, the blades are pitched back to 0° to its normal operating position to obtain the maximum lift force.

In region II, as the wind turbine catches up speed, more electric power is pushed into the grid. Optimum energy captured by the rotor requires a constant TSR for which variable speed operation is more suitable. The electronic controller adjusts the wind turbine rotor speed to operate at a constant TSR corresponding to the maximum C_p value and the power produced is proportional to the cube of the wind speed v. In this region, the variable speed WPPs need not regulate the blade angle, since RPM increases with the increase in wind speed to keep the angle of attack constant (and optimised).

When the wind speed is between cut-in wind speed and rated wind speed in region II, the WPP is said to operate in the highest C_p region. Due to the flywheel effect, a variable speed WPP stores the varying wind gusts as rotational energy, thereby releasing the stresses on the mechanical structure. In other words, the energy from wind gusts can be partially transferred into the acceleration of wind turbine rotor and therefore, there is no need to reduce the blade pitch angle instantaneously.

As against constant speed WPPs, variable speed WPPs keep the electromagnetic torque constant and the wind speed fluctuations are absorbed by the flywheel effect as the rotor speed changes. The electric generator torque in variable speed WPPs is kept fairly constant, as the variations in wind are absorbed by the changes in the generator speed leading to a smoother delivered power to the electrical grid. However, the electrical control system for variable speed WPPs is more complex than that for the constant speed WPPs.

In region III, to deliver a grid compatible power in variable speed WPPs, there is a close coordination between the pitching system, PEC and generation operation to maximise the production of energy within the safety limits.

(a) Maximum Power Point Tracking (MPPT)

The characteristic of the optimal power produced by a WPP is strongly non-linear and is in the shape of bell curve (see Figure 6.12). For every change in speed of the wind, the WPP has to find the optimal RPM for the maximum power to be produced. In Figure 6.12, the dotted line indicates the locus of the points of maximum power for every speed change; the WPP will only function continuously when the operating point is to the right of the line of maximum power. For maximum ideal wind power extraction, the control system of the WPP requires a perfect follow-up of the dotted curve and this control is called the *maximum power point tracking* (*MPPT*) curve.

For every new wind speed, there is a different rotor speed for maximum power production. The control system of these variable speed WPPs maintains the mechanical power of the wind turbine rotor at its rated value to develop their peak aerodynamic efficiency C_p for the optimum TSR through MPPT. The MPPT curve maximises the efficiency of the WPP.

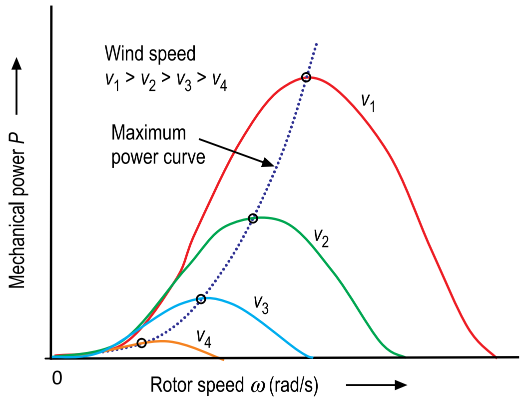


Figure 6.12 Mechanical Power versus Rotor Speed Characteristics.

By variable speed operation, the wind speed is constantly tracked by the WPP mitigating the torque ripples caused due to the varying wind speed. The strategy consists of controlling the electromagnetic torque to adjust the mechanical speed in order to maximise the generated electric power. Through MPPT implementation, the annual average energy yield can even go up to 10% to 15% more energy. This is quite a significant revenue increase over 20 to 25 years of life of operation of a WPP.

By adapting MPPT, when the wind speed changes, the wind turbine rotor speed also changes. Concurrently, the electric generator speed should be able to adjust simultaneously for maximum energy extraction, as in region II and region III (see Figure 6.11), if a variable speed pitch regulated WPP is employed. Hence, variable speed WPPs are becoming more popular. But, it should be noted that both constant and variable speed WPPs reach their maximum rated power in strong winds for which they are designed.

As the variable speed WPP is allowed to be driven in line with the varying wind speeds resulting in electrical power production which has variable voltage and current, it has to be fed inevitably through a PEC to render it grid compatible at constant voltage and frequency.

One of the major limitations of variable speed WPPs is the high cost of power electronics and its complexity of maintenance. But with years passing by and the costs of power electronics dropping down substantially, variable speed WPPs have become a more economic alternative. Another limitation is the power loss in PECs which may go upto above 2% which is quite substantial when calculated annually.

6.6 BACK-TO-BACK PEC IN WPP

The back-to-back PEC (see Figure 6.13) for rendering the power output of the variable speed electric generator compatible to the grid are quite common in variable speed WPPs. The general working of this PEC, in context of typical variable speed WPP, is discussed over here. Its main advantages are its comparatively simpler,

proven technology and the possibility of building redundancy into the string of series connected switching devices, usually IGBTs.

This PEC has two converters linked by a DC link bus—a rotor (or generator) side converter and a grid-side converter. Each device in the inverter side has an anti-parallel bypass diode to permit active and reactive power flow in either direction. It employs voltage source inverters (VSI) with insulated gate bipolar transistors (IGBT) using force commutation to synthesise AC voltage from a DC voltage source.

A capacitor on the DC side acts as a DC voltage source. The pulse width modulation (PWM) in this PEC eliminates the low frequency harmonics so that the first harmonic has a frequency around the switching frequency of the inverters which is sufficiently high, thus requiring small grid filters.

However, some shortcomings of back-to-back PEC are its large physical dimensions, massive weight, excessive volume/footprint of the DC link capacitor or the inductor, low reliability of DC capacitor, poor line power factor and harmonic distortion. But more research and development can do away these shortcomings away or else some other PEC topology may replace this back-to-back PEC with some other type of PEC.

6.6.1 Generator-side Converter Control

The varying voltage V_s and varying frequency f_s (due to the varying wind speeds) of the generator-side converter (see Figure 6.13) do not match with the constant grid side converter voltage and frequency. It is the grid-side converter that converts it to match the grid parameters. The PEC controls the '*d*' and '*q*' components for independent active and reactive power control on the grid. The generator side converter controls the active power output of the WPP helping it to operate over a wide variable speed range and produce power at unity power factor.

6.6.2 DC-Link Bus

DC-link bus (capacitors) decouples the two converters (or inverters) whereby one does not influence the other (see Figure 6.13). The DC-link bus is also for energy storage in order to keep the voltage variations (or ripple) in the DC-link voltage small. This voltage is kept constant by the rotor side converter control and the active power of the generator is transferred via DC-link to the grid side converter. As constant stator voltage control is beneficial and to ensure that the generated active power is fed through the DC-link to the grid, the DC-link voltage must be kept constant ensuring that no energy is dissipated in the DC-link. The size of the DC-link is very large which is not desirable.

6.6.3 Grid-side Converter Control

The grid-side converter is not involved in the reactive power exchange between the WPP and the grid. The grid-side converter (or inverter) has to keep the DC-link capacitor voltage at a set value, regardless of the magnitude and the direction of

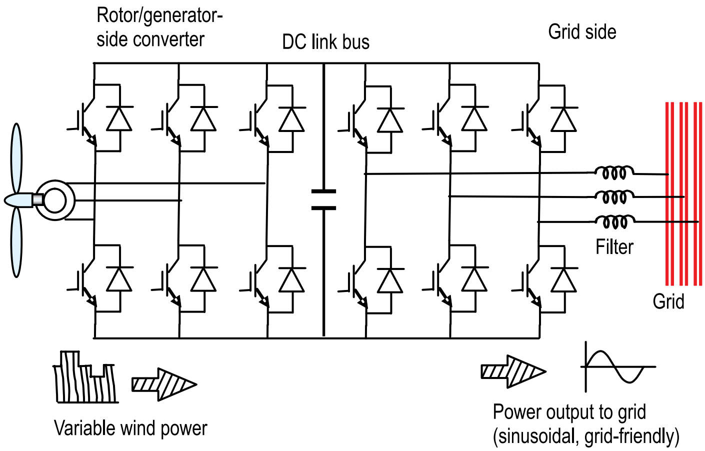


Figure 6.13 **Typical Simplified Back-to-Back VSI-based PEC commonly used in Variable Speed WPPs.**

the rotor power to guarantee converter operation at unity power factor. To achieve full control of the grid current, the DC-link voltage is boosted to a level higher than the amplitude of the grid line-to-line voltage. Thus, the active power production of the WPP can be controlled by the grid-side converter.

The grid-side converter must be an active inverter (GTO, IGBT or IGCT as switching elements, depending on the capacity of the WPP), since it converts DC-link voltage to AC grid voltage with fixed frequency of the power system. The grid-side converter (DC–AC) maintains the DC-link voltage constant and ensures unity power factor operation.

6.6.4 Four-quadrant Control PEC in Variable Speed WPP

To operate a WPP over a wide range of wind speeds and thereby, to increase the annual energy output, the advancements in power electronics and the PEC came to the rescue for greater control of WPPs leading to the development of more advanced and high technology Type-C and Type-D WPPs in the market (discussed later in this book). Since the power flow is bidirectional through the PEC, they have to operate in a four-quadrant mode (see Figure 6.14). For example in a Type-D WPP, making assumptions for linearity of operation and neglecting stator losses, the torque T_{gen} of the electrical generator equation can be written as:

$$T_{gen} = \frac{3E_s \dfrac{V_s}{X_s}}{\omega_r \sin \delta} \tag{6.3}$$

where,

ω_r = Rotor angular frequency in mechanical radians per second

δ = Generator power angle (load angle).

Using the expression for internal emf (electromotive force) and the relation between electrical and mechanical angular speed, the above equation could be written as

$$T_{gen} = \left(K_T \varphi \frac{V_s}{\omega_r L_s} \right) \sin \delta \tag{6.4}$$

and $$K_T = 3K_s p/2$$

where,

p = Number of generator poles

L_s = Stator inductance.

From Eq. (6.4), it can be seen that under variable wind speed conditions, the torque T is constant if its V_s/ω, i.e., V/f is held constant, provided the other parameters remain the same. It also shows that the generator power angle δ depends on the torque applied by the wind turbine rotor (see Figure 6.14). Therefore, Eq. (6.4) can be used to control the torque-speed characteristic of the generator when it is connected to a voltage source inverter (VSI).

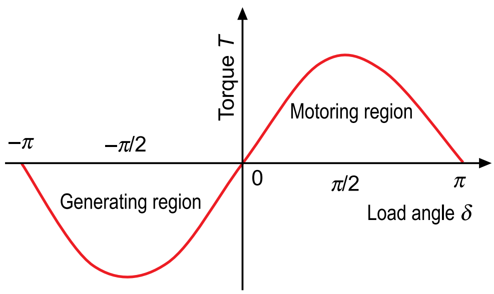


Figure 6.14 Four-quadrant Operation of a PEC in Type-C and Type-D WPPs.

It can also be seen that the torque changes continuously from driving torque (through zero) to retarding torque with the torque angle moving smoothly from –90° to +90°. Beyond these two limits, the machine becomes unstable, i.e., it pulls out of synchronism or in other words, either it accelerates to runaway destruction or stall respectively. The torque Eq. (6.3) can also be written as:

$$T_{gen} = 3\frac{E_s I_s}{\omega_r} \cos \gamma \tag{6.5}$$

where,

γ = Phase angle of the load current with respect to the internal emf phasor

and $T_{gen} = K_T \varphi I_s \cos \gamma$. (6.6)

Equation (6.6) can be used to control the speed–torque characteristic of a synchronous generator when it is connected to a current source inverter (CSI). In other words, looking at both Eqs. (6.3) and (6.4), it can be seen that control of a synchronous generator requires position and speed sensors. The position sensor is required to adjust the angle between the voltage (or current) and the main flux. The synchronous generator can have following special characteristics in some applications:

- For PMSG, the product of $K_T \times \varphi$ is constant (as the excitation is constant due to permanent magnets) while in a WRSG, it is adjustable up to its rated value, as it has rotor windings.
- For a WRSG, the stator terminal voltage V_s and stator current I_s are in quadrature (zero power factor) $\varphi = -90°$.
- For grid connected WRSG, the V_s/ω is constant.
- For a WRSG connected to a phase controlled rectifier, the load presented has an inductive component ($Z = R + j\omega L$).
- For a WRSG connected to a diode bridge rectifier, the load presented is a resistive load (unity power factor) $\varphi = 180°$.

SUMMARY

It has been seen that for control of WPPs both aerodynamically and electrically, there are many combination of offerings provided by different WPP manufacturers using various types of aerodynamic controls and electrical generators in combination with electronics, power electronics and computers. Considerable amount of research and modelling continues to be undertaken through simulations using different computer-aided engineering tools such as DIgSILENT® PowerFactory, PSCAD and other software to study how WPPs behave under different conditions. It is not reasonable to compare the efficiency of a WPP with that of conventional power plants, as the conversion efficiency for a WPP is actually not so important as the fuel, i.e., the wind is abundant and free.

EXERCISES

6.1 Discuss the negative feedback and positive feed forward control in WPPs.

6.2 Differentiate the four power control strategies of WPPs.

6.3 Describe the four aerodynamic and electric control strategies.

6.4 With the sketch of power curve, explain the four aerodynamic and electric control strategies.

6.5 With sketcher describe the PEC applications used in different types of WPPs.

6.6 Describe the benefits and main requirements of incorporating PEC in WPP.

6.7 Justify the use of the most common PEC topology.

6.8 With a sketch, explain the working of a back-to-back PEC.

6.9 Using a sketch, compare the torque, speed and pitch angle characteristics for maximum power of a WPP.

6.10 With a sketch, explain the concept of MPPT in WPPs.

6.11 Describe the four-quadrant control of PEC for variable speed operation of a WPP.

7

Constant Speed Wind Power Plants

HE sends lightining with the rain and brings out the wind from his storehouses.
—Jeremiah 10:13

Learning Outcome

On studying this chapter, you will be able to differentiate the technologies adapted in different types of constant speed wind power plants.

CHAPTER HIGHLIGHTS

7.1 INTRODUCTION

From the beginning years in 1970s and early 1980s, the most popular WPPs have been the so-called *Danish Concept* stall controlled constant speed Type-A WPPs employing SCIG (see Figure on facing page). Under the constant speed classification discussed in the preceding chapter, Type-B WPPs were later developed employing wound rotor induction generators (WRIG) instead of the SCIG. These work in a slightly wider range of wind speeds to harness more power from the wind. Both these technologies categorised as constant speed WPPs are discussed in this chapter with the assumption that the reader has a basic understanding of electrical engineering principles.

7.2 TYPE-A WPP

Since decades, Type-A WPP (see Figure 7.1) with the SCIG has been the workhorse of the wind power industry, as it has an inherent torque–speed curve that fits the WPP application quite naturally. Although, the overspeed variations in SCIG are very small (1% to 2%), its mechanical simplicity, robust construction and relatively lower cost have made it quite popular in the wind industry for a considerable amount of time.

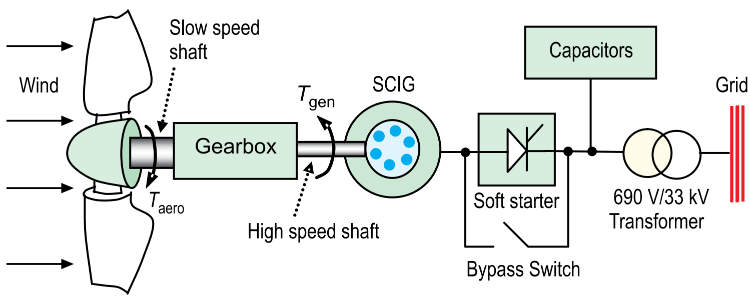


Figure 7.1 Type-A WPP: Stator of the SCIG is directly connected to the electrical grid through a soft starter. Capacitor banks are used for power factor correction.

An interesting mechanical property of Type-A WPP is that whenever the torque varies, the speed of the SCIG increases or decreases only a little, thereby resulting in less tear and wear of the gearbox (lower peak torque). This is the most important reason for using induction generator rather than a synchronous generator in a WPP.

7.2.1 Working Principle

Type-A WPP can either be a fixed blade stall controlled rotor or it could be a pitch controlled rotor. In either case, the rotors are connected to a slow speed (ranging from 15 RPM to 25 RPM) main shaft of a gearbox to step up the speed to around

1500 RPM. When the wind interacts with the rotor blades, it produces an aerodynamic torque T_{aero} (see Figure 7.1) on the low speed, high torque shaft. This torque is transferred through the gearbox to step up the speed to match the generator rotor shaft. The high speed generator shaft torque T_{gen} reacts with aerodynamic torque T_{aero} which must be equal and opposite for the constant speed machine to accelerate or decelerate.

The high speed output shaft of the gearbox is connected to the rotor shaft of a SCIG. The stator of the SCIG is directly connected to the electrical grid. Below the synchronous speed of SCIG, the induction machine functions as a motor drawing power from the grid.

The soft starter operates for 2 s to 3 s to limit the inrush currents upto the rated value. The reactive power is then compensated by the capacitor banks. The capacitor banks are switched in 4–5 steps with a time delay of about 1 s. When the wind thrust applies more torque through the wind turbine rotor to make the generator rotor to spin greater than the stator's rotating magnetic field, the machine is said to run at supersynchronous speed. The machine then becomes an induction generator and starts producing electric power rather than consuming it.

The grid behaves like a large flywheel holding the wind turbine rotor speed nearly constant, irrespective of the changes in wind speed, as it is electrically locked with the rotating magnetic field and hence, locked with the grid. When the generator shaft is rotated a little faster than the synchronous RPM (by the wind turbine rotor), say +1% higher (i.e., 1515 RPM for a four-pole generator), it starts functioning as a generator and feeds power to the grid. The harder the wind cranks the wind turbine rotor, the more is the electrical power produced. It is worth noting that as the wind speed increases, the shaft speed of Type-A WPP does not increase proportionately. Instead of this, more electrical power is produced.

At faster than rated wind speeds, the output power is limited to the rated value by the stall action of the blades (in stall controlled WPPs) or by the pitching action of the blades (in pitch controlled and active-stall WPPs).

To improve the harvest of wind energy, matching of the torque–speed characteristic of an induction generator (refer Figure 7.3) to that of a WPP rotor speed is necessary and the following options are available:

- Use pole changing SCIG.
- Vary the resistance of the rotor windings of WRIG.
- Use a frequency converter in the rotor circuit of DFIG.
- Use a frequency converter with a SCIG.

The first two options are discussed in this chapter, whereas the remaining two are discussed in the subsequent chapter.

7.2.2 SCIG Slip

When a three-phase stator winding of the SCIG that is symmetrically distributed along the stator circumference (see Figure 7.2) is connected to a balanced three-phase source (grid) cuts the rotor squirrel cage bars radially, then a rotating magnetic

field is formed in the small air gap between the stator and the rotor. For this field, each set of neighbouring rotor bars of the squirrel cage together with the segments at the end rings forms a closed electric circuit. The magnitude of the rotating flux wave is proportional to the applied emf.

Figure 7.2 **Stator Winding of Generator:** Three-phase rotating magnetic field in air gap of stator. *Picture by author.*

Ignoring the effect of the back emf set up by the induced currents in the rotor windings, the flux density B is proportional to the applied voltage. At the start, when the machine acts as an induction motor, the slip is unity, i.e., 1, while at synchronous speed, the slip is zero (see Figure 7.3). As the rotor speeds up, the rate at which stator flux cuts the rotor starts decreasing, the slip s, i.e., the relative difference between the rotating synchronous speed N_s and the actual rotor speed N or $(N_s - N)$ also decreases. The ratio of actual flux cutting the rotor to the synchronous speed is defined as *slip* and is given by:

$$s = \frac{N_s - N}{N_s}$$

$$\therefore \quad N = N_s(1 + s) \tag{7.1}$$

The slip is said to be *positive* when the machine is in the motoring mode, say about +1%. It is said to be *negative* when the machine is in the generating mode which is about –1% to –2%, when used along with a wind turbine. If the line frequency is f and the slip is s, the frequency of the rotor current f_r is given by:

$$f_r = sf \tag{7.2}$$

If there is no mechanical motor torque load, no bearing, windage or other losses, the rotor will rotate at the synchronous speed. However, the slip between the rotor and the synchronous speed stator field develops a torque. A loaded motor slips in proportion to the mechanical load.

Initially, the current induced in the stationary rotor shorted coils is maximum and thus, the frequency of the current too. Although the rotor current is large, the magnetising current is small. The frequency of the current induced in the rotor conductors is only as high as the line frequency at motor start-up and decreases as the rotor approaches synchronous speed. Usually, the slip at rated torque is less than 2% in the safe operating region (see Figure 7.3) which results in a very little generator speed variation of the WPP.

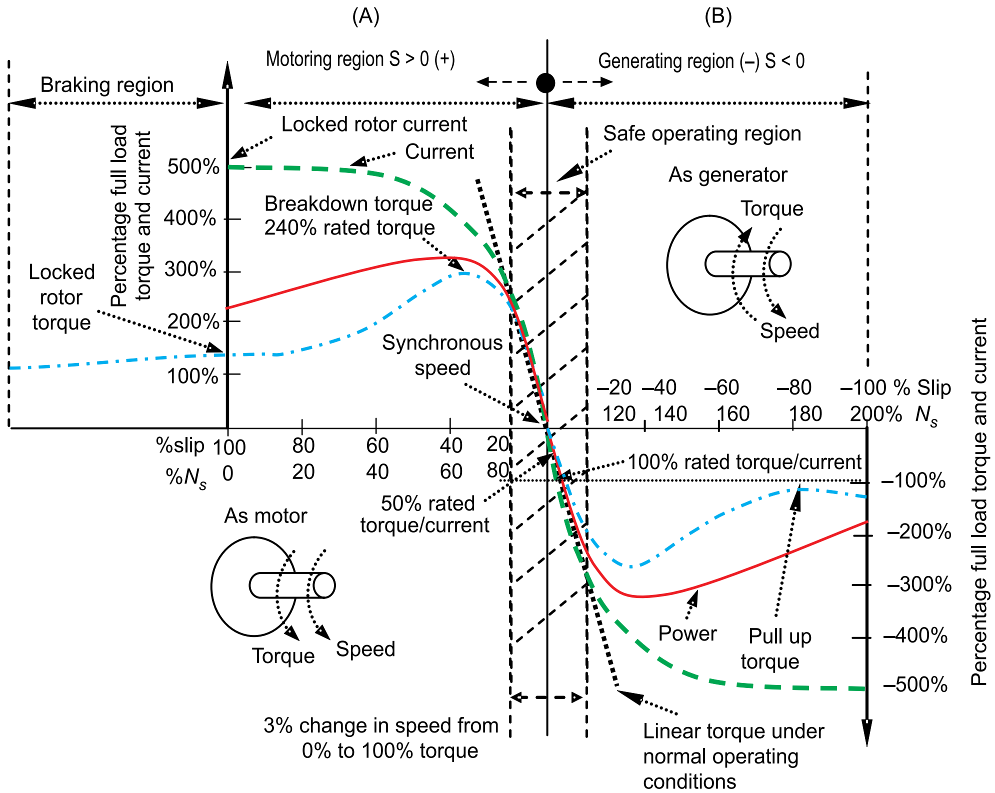


Figure 7.3 SCIG Torque, Speed and Power Characteristics: The torque is linear in the safe operating region in which the SCIG operates, beyond which the WPP is disconnected from the grid to shut down.

The speed varies only marginally with varying torque. The stable region is a quite narrow hatched zone (see Figure 7.3) a little before and after the synchronous speed is between the maximum value for the motor and generator torque region. As the induction generator derives its magnetic excitation from the grid, the response of the WPP during a grid disturbance is influenced by the extent to which the excitation is disrupted.

Whenever the generator shaft speed falls below the synchronous speed (i.e., when the wind speed becomes less), then the generator starts operating as an induction motor, consuming power from the grid. In this situation, the WPP is disconnected

from the grid. Similarly, a lower grid frequency (i.e., voltage remaining unchanged) also results in a lower synchronous speed, thereby increasing the rotor speed and reducing the aerodynamic efficiency of the wind turbine rotor blades requiring the slip to change and consume more reactive power due to reduced magnetising current (as $X = 2\pi fL$). The reactive power drawn by the induction generator is proportional to the active power generation, rotor speed and terminal voltage.

It should be noted that between zero and the rated power of the WPP, the pitch of the rotor blades remains fixed at an angle corresponding to the maximum power or full power pitch angle. When wind speed increases the aerodynamic torque also increases (say) by 50%, which causes the electrical machine rotor to accelerate beyond synchronous speed by only 1.5% and operate in the generator mode to produce power by an increase of about 50%. During wind gusts, when the SCIG is already in the generating mode, it tends to be momentarily overloaded, the pitch system (in pitch controlled WPPs) attempts to bring the rotor pitch angle to a less aggressive angle of attack to shed away the excess aerodynamic torque. From the torque–speed curve (see Figure 7.3), it can be seen that in worst case, approximately 240% torque and power can be achieved from the inherent characteristics of an induction generator. However, common overload levels for SCIGs are maintained at 25%–50%.

7.2.3 Torque of a SCIG

The interaction of the generator rotor bar currents with the rotating magnetic field in the air gap causes a tangential force on the rotor, generating a torque to rotate in the same direction as the rotating flux (in the motoring mode, it is as if being dragged along by the flux wave) or against the direction of rotation (in the generating mode, as in the case of WPPs). If the rotor runs at synchronous speed, then there is no stator flux cutting the rotor, no current induced in the rotor and hence, no torque too. It is the magnetic flux cutting the rotor conductors as it slips that develops torque. The rotor field attempts to align with the rotating stator field.

In the generating region, it is driven by a torque at greater than 100% of the synchronous speed. The peak terminal power is three times the rated power and the peak current during start-up is five to seven times the rated current. Since the rotor flux cuts the stator magnetic field in the opposite direction (leading), it induces a voltage in the stator feeding electrical energy back into the power line. Typically, the operating region of an induction machine is below 50% of the peak torque. The peak torque is about two and half times the rated one. For a slight variation of the speed, the torque (and power) can significantly reduce mechanical torque transients associated with the gusts of wind and grid side disturbances.

Due to wind thrust, when the SCIG is forced to run at speeds in excess of the synchronous speed, the load torque exceeds the machine torque and the slip becomes negative, reversing the rotor induced emf and rotor current. The magnitude of the torque T is proportional to the flux density and the induced rotor current. It is given by:

$$T = \frac{k\,s\,R_r\,E_r^2}{R_r^2 + s^2 X_r^2} \tag{7.3}$$

where,

k = Constant depending on the number of stator turns, number of phases and configuration of the magnetic circuit

s = Slip

R_r = Rotor resistance

E_r = Rotor voltage

X_r = Rotor reactance.

At normal speeds, close to synchronism, the term sX is small as compared to R_r. Therefore, for small values of slip, the torque is directly proportional to the slip.

i.e.,
$$T \propto \frac{s}{R_r} \tag{7.4}$$

As the slip increases, T also increases and becomes maximum when $s = R_r/X_r$. Further, as the slip increases, R_r becomes negligible as compared to sX_r. For large values of slip, the torque becomes inversely proportionately to slip s.

i.e.,
$$T \propto \frac{s}{(sX_r)^2} \propto \frac{1}{s} \tag{7.5}$$

Under running condition, T is maximum when the value of the slip 's' is such that the rotor resistance R_r per phase becomes equal to the rotor reactance X_r per phase. Condition for the maximum torque in the induction generator exists when $R_r = sX_r$.

Therefore, it is possible to achieve maximum torque at different values of slip by adding rotor resistance corresponding to the rotor reactance values, as done in type B WPPs where wound rotor induction generators are used.

Although the operating slip is very low (see Figure 7.3), the induction generator used in WPPs has the advantage of giving more grid compliance than a synchronous generator. Under steady conditions, for a given wind speed, the induction generator operating speed is a linear function of the torque. For sudden changes in wind speed, the mechanical inertia of the drive train limits the rate of change in electrical output.

Higher slip ratio means more elasticity in the grid system resulting in lesser power fluctuations. A six-pole or eight-pole SCIG has a higher elasticity than a generator with two poles. This elasticity is required to reduce the power fluctuations which stress the drive train and cause power peaks in the grid. For example, power fluctuation of a SCIG with 2% rated slip causes power fluctuations in the range of 20% of the rated power.

The supply voltage is dictated by the grid and cannot be controlled. An acute grid voltage dip may lead to a decrease in torque and may cause rotor instability.

7.2.4 Topologies of Type-A WPP

Type-A WPPs have the following topologies:

- Type-A0
- Type-A1
- Type-A2.

Type-A0 stall controlled WPP with SCIG (commonly known as the *Danish concept*) has the stator directly connected to the grid and the constant speed is fixed by the grid frequency and number of the pole-pairs of the SCIG. When a WPP works at rated wind speed, then the SCIG works at full load and the rotor shaft torque is not allowed to increase any further. If the SCIG becomes overloaded it may cause the windings to melt leading to WPP failure. Therefore, the excess load is spilled away by the stalling action of the blades, as discussed earlier.

This topology is the least complex of all the WPPs. It can tolerate certain overload capability and variations in wind speeds rendering it quite rugged and robust with respect to other types and hence, very reliable. Synchronisation with the electrical grid is not required. These generators do not need to be driven continuously at fixed speed which is also one of the major attractions of the WPP industry.

The variations in wind speed cause torque pulsations in Type-A0 WPP resulting in stresses on the drive train and also undesirable voltage fluctuations occur in the electrical grid (see Figure 7.4). These fluctuations are more acute during wind gusts. In strong grids, such power fluctuation may not matter much. But in weak grids where the WPP penetration is high, it is a matter of concern to the grid operators.

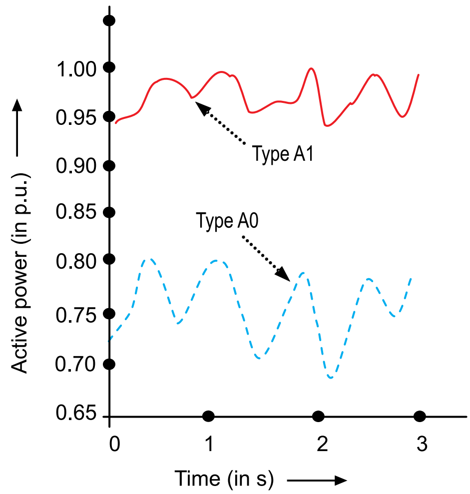


Figure 7.4 Comparison Typical Power Outputs of Type-A0 and Type-A1 WPPs.

The limitation with such a *Type-A0 WPP* is that it cannot be fully controlled during grid connection sequences. SCIGs used in Type-A0 WPPs are deliberately overdimensioned to take care of the power peaks that may occur, as seen in the power curve (see Figure 5.2). The SCIG is also designed for a larger slip to reduce:

- Fluctuations of mechanical systems and electrical output
- Mechanical stresses when the generator goes through high torque gradients during switching on and off operations.

Type-A1 WPP with SCIG is pitch regulated. The main merit of this type is a controlled start-up by the pitch regulation of the blades. The typical power fluctuations

of a pitch controlled Type-A1 WPP (see Figure 7.4) are not as severe as that of Type-A0 WPP. However, during wind gusts, before the pitch control can respond quickly to adapt the blade angle to a new higher wind speed, the nominal power could be exceeded for brief periods which is undesirable. During short wind spells of lower wind speeds, the SCIG runs as a motor to avoid the WPP switching in and switching out, often when the wind speeds are close to the cut-in wind speeds.

Active-stall controlled WPP with SCIG is called *Type-A2 WPP*. It combines the advantages of Type-A0 and Type-A1 WPPs by which emergency stopping and start-ups are facilitated. Spilling of the excess wind power during high wind speeds is done by stalling action but at the same time, it draws more power from the wind for higher wind speeds. But, it comes at a higher cost because of its pitching mechanism and associated blade design complexity, as it is still a stall blade.

7.2.5 Starting of Type-A WPP

The starting and connection of Type-A WPP (and to a small degree, disconnection also) gives rise to short duration heavy inrush of currents called transients in the electric circuits and torque spikes in the drive train and jerks on the gearbox. To minimise these effects, soft starters consisting of thyristors (power electronic circuits) are provided. Soon after the grid connection is complete, it is bypassed by a contactor, as the soft starter has limited thermal capacity to continuously bear the full load current. Moreover, losses also occur.

Type-A WPPs with SCIGs can be started by the following two methods:

- Induction motor starting
- Blades pitch starting.

(a) Type-A0 WPP: Induction Motor Start

Stall controlled WPPs use this starting method, as they are not inherently self-starting. No sooner does the anemometer signals the cut-in wind speed, the electronic controller activates the relevant circuits to connect the SCIG to the electric grid to start it as an induction motor by drawing the magnetising power from the grid, using the soft starter (to reduce the heavy inrush starting currents which may otherwise cause a voltage dip in the distribution grid). The machine then starts to run as an induction motor and gradually speeds up. When it is very near to synchronous speed, it is connected to the grid. Then, it gets locked to the grid frequency and runs as a generator feeding power into the grid. When the wind speed continues to increase beyond the rated speed, the change in rotor RPM beyond the synchronous speed is minimal but the power fed into the grid is considerable.

(b) Type-A1 WPP: Blade Pitching Start

Pitch controlled WPPs generally adapt this starting method. At the cut-in wind speed of around 3 m/s sensed by the anemometer, the disc brakes release the rotor and the blades are pitched at an appropriate angle of attack by the hydraulic or electric pitching mechanism to rotate it gradually. The rotor is then accelerated

by the wind to greater RPM. On continued observation, it can be seen that at one particular moment, the rate of acceleration of this gradually speeding up rotor becomes abruptly very fast. This sudden change in acceleration indicates that the blade's aerodynamic shape has taken a major share in the lift phenomenon due to the apparent wind speed v_{app}. This is due to the resultant wind speed formed by the combination of actual wind speed and blade's own speed of rotation. This unique quality of rapid acceleration of WPP's RPM places great demand on the electrical cut-in system that must capture and engage the WPP without releasing excessive peak electrical loads into the grid.

When the rotor has speeded up very near to the synchronous speed of the generator, then the electronic controller signals the actuator to connect the WPP to the electric grid. In fact, it is the thyristor-based soft starter that connects the generator to the grid. No sooner the generator is connected, it is pulled up by the grid and is locked to it to rotate at synchronous speed. But the wind thrust continues to pull the WPP further to make it rotate beyond the synchronous speed making the machine to go into the generating mode and start delivering power to the electric grid. A few seconds after it comes on line, the main contactor bypasses the soft starter to avoid further thyristor losses.

The WPP's output power increases almost linearly as the blades are pitched further with increasing wind speed to obtain optimum TSR and maximum C_p till rated wind speed of the WPP (around 12 m/s) is reached. Then, the microprocessor-based control loop cuts in to maintain constant power output and prevent the electric generator from getting overloaded.

If the wind speed exceeds the WPP's maximum operating limit (i.e., 25 m/s), then the control system feathers the blades to 90° to stop the WPP. When the wind speed drops below the cut-out speed, the safety systems automatically get reset and the WPP starts rotating again. At normal wind speeds, when reconnection of the WPP occurs after a grid or WPP fault, the inrush current may be significantly higher if the wind induced torque is not limited by pitching the blades.

7.2.6 Type-A WPP—Two Speed Operations

The lower aerodynamic performance of a constant speed stall WPP is due to the non-operability at its optimum TSR. To maximise the harnessing of wind power annually by Type-A WPPs even at low wind speeds, some smart strategies are used by different manufacturers. These are as follows:

- One strategy is to operate a WPP at an optimum TSR with two separate SCIGs mounted in the nacelle; one operates at normal wind speeds and the other operates at low wind speeds.
- Another strategy is to use a single dual-speed (pole changing) SCIG for the WPP to make it operate closer to an optimum TSR both during normal wind speeds and low wind speeds.

Whether the SCIG is single speed or dual speed, when it comes to availability, the WPP always benefits from the reliability of the SCIG. The power generated is

significantly better than for a single speed Type-A WPP. It is seen that the energy gain is in the range of 2%–3%, even in the case of stall Type-A0 WPPs. With this strategy, it has been practically reported that if the baseline design of a WPP is suboptimal (depending on the site conditions also), then the energy gains of upto 10% are also possible. This means that over a full year period, it is possible to extract about 90% of the energy available as compared to 100% fully variable speed WPPs which are substantially expensive and complex to maintain over a technical lifetime of 20 years.

(a) Type-A WPP with Two SCIGs

The use of two differently rated SCIGs, one for low speed operation and another for normal speed operation (specific to that region), has been tried out by some manufacturers in some medium-rated stall controlled WPPs. The advantage of two SCIGs is that energy at lower wind speeds can also be captured. This allows the WPP to work closer to its optimum TSR. The two SCIGs are connected by a V-belt on the same mainframe.

During normal operations, higher rated SCIG supplies power to the grid while lower rated SCIG remains in switched-off mode. When the wind speed drops beyond a certain designed limit, the electronic controller switches off the normal one and switches on the other to the grid.

The disadvantage of this strategy is the additional generator cost resulting in additional switchgear. Further, some amount of energy is also lost due to the switching operations due to the connection and disconnection of generators when the wind speed changes. Practically, it is seen that this design is relatively more expensive and less reliable, because two separate SCIGs are required (from maintenance point of view as well). Although these are not very popular now, still there are a few WPPs of this type functioning in a few places in India.

(b) Type-A WPP with a Dual Speed SCIG

Instead of two separate SCIGs with different speeds, it has been seen that a single dual-speed SCIG serves the same purpose at a lower capital and operating cost. Such an SCIG has two sets of windings in the stator to operate at two different speeds. One winding is configured as a six-pole stator (say) and the second winding is configured as a four-pole stator. The speed of an SCIG decreases with increasing number of poles. For both windings, output voltage and frequency are the same. When the stator poles are changed depending on the wind speed, the squirrel cage rotor adapts itself to the number of stator poles automatically.

When the WPP operates at low wind speeds, the low speed winding of the generator is connected through its corresponding contactor. As wind speed picks up after the predetermined threshold value is crossed, the low speed winding is disconnected and the high speed winding is connected. As there are two stator windings, so there are two torque-speed curves but are shifted from each other along the x-axis (see Figure 7.5).

In Type-A1 WPP, when the wind speed increases more than the predetermined wind speed, the electronic controller switches off the low speed generator winding

and switches on itself to the high speed (N_1 RPM or N_2 RPM) mode (see Figure 7.6). It can be noted that when a SCIG operates with the low speed winding, the pitch system is usually not active because wind speed is low and the turbine rotor is turned at full power pitch angle. For example, a 1000 kW/250 kW SCIG with a four-pole/six-pole can produce a maximum of 1000 kW in four-pole mode at higher wind speeds and only a maximum of 250 kW in the six-pole mode at lower wind speeds.

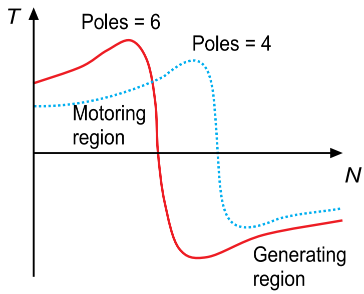


Figure 7.5 Torque–Speed Characteristics of Dual-speed Type-A0 WPP: The torque speed curve of the slower stator winding is shifted to the left.

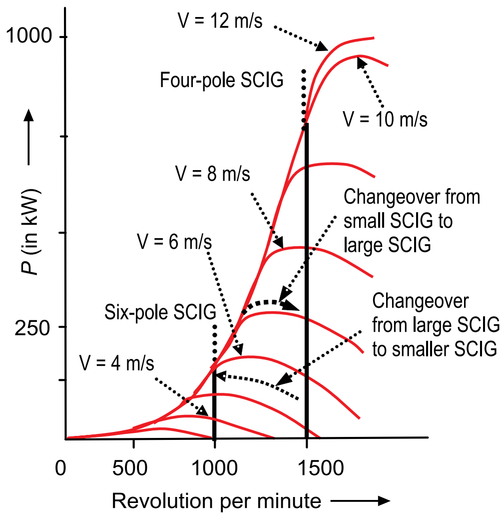


Figure 7.6 Load Curve of a Type-A0/A1 WPP with Dual Speed SCIG: This WPP can harness energy at even low wind speeds, making it suitable for low wind regimes as well.

The limitation of this topology is that the interaction between generator torque and the active pitch system remains the same (as in single stator winding SCIGs) in high wind conditions and the dual-speed SCIG does not improve the high fatigue loads associated with the rated power and turbulent wind conditions, thereby reducing the lifetime of the WPP. Another limitation is that the power factor correction capacitors are still required to reduce voltage ampere reactive (VAr) consumption. Further, as the SCIG stator is having two windings in the same (or similar) slot

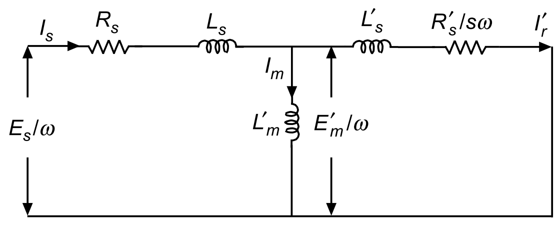
of a single speed machine, *copper fill factors* tend to be low for both windings and the efficiency of the generator can suffer significantly.

The other aspects of improved aerodynamic efficiency of this topology are:

- The amount of energy gains is about 2% to 3%.
- Lesser noise is produced.
- Cost of generator is slightly higher and an additional control switchgear is required.
- Turbine blade rotor also requires speed control for both the speeds.

7.3 EQUIVALENT CIRCUIT AND MODELLING OF SCIG IN TYPE-A WPP

Figure 7.7 shows an equivalent circuit of a SCIG with constant frequency referred to the stator side. Ideally, the resistance and leakage reactance are zero and the magnetising inductance is infinite. Practically, the magnetising reactance is about 20–50 times the leakage reactance. By controlling the angle and amplitude of the stator current in the three-stator phases, the components of the stator current space vector are impressed in the direction of the rotor flux and perpendicular to the rotor flux. With a number of computer software available, modelling goes a long way in designing a WPP for more efficiency. Figure 7.8 illustrates the typical generic model of a constant speed WPP.



R_s = Stator resistance
L'_m = Magnetising inductance
R'_s = Rotor resistance
s = Slip
V_s = Stator voltage
I_m = Magnetising current
L_s = Stator inductance
L'_s = Rotor inductance
$s\omega$ = Slip frequency
I_s = Stator current
I_r = Rotor current

Figure 7.7 Equivalent Circuit of Constant Speed SCIG Referred to Stator Side.

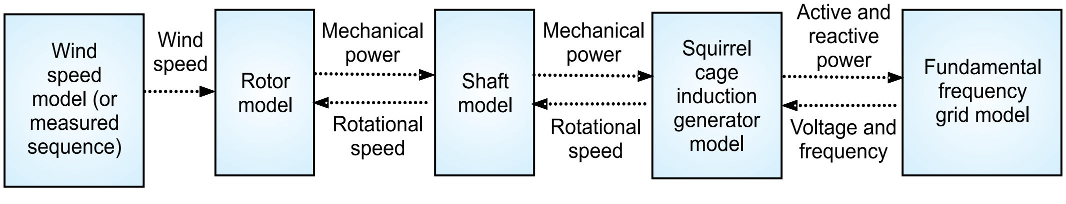


Figure 7.8 Generic Model of Constant Speed Type-A WPP.

The voltage equations of an induction machine reduced to the stator side are:

$$V_s = R_s i_s + \left(\frac{d\psi_s}{dt}\right) + j\omega_s \psi_s \tag{7.6}$$

$$V_r = R_r i_r + \left(\frac{d\psi_r}{dt}\right) + j(\omega_s - \omega_r)\psi_r \tag{7.7}$$

where,

V = Voltage
i = Current
R = Resistance
r = Rotor
s = Stator
ψ = Flux linkage.

The equations that can be used for MATLAB modelling for a typical 2 MW Type-A or Type-B WPP connected to a medium voltage network (see Figure 7.9) are as follows:

Stator equations

$$v_{qs} = -i_{qs}R_s + \omega_s \psi_{ds} + (d/dt)\psi_{qs} \tag{7.8}$$

$$v_{ds} = -i_{ds}R_s - \omega_s \psi_{qs} + (d/dt)\psi_{ds} \tag{7.9}$$

Rotor equations

$$v_{qr} = 0 = -i_{qr}R_r + S_{\omega s}\psi_{dr} + (d/dt)\psi_{qr} \tag{7.10}$$

$$v_{dr} = 0 = -i_{dr}R_r - S_{\omega s}\psi_{qr} + (d/dt)\psi_{dr} \tag{7.11}$$

Flux linkage equations

$$\psi_{qs} = -(L_{s\sigma} + L_m)i_{qs} - L_m i_{qr} \tag{7.12}$$

$$\psi_{ds} = -(L_{s\sigma} + L_m)i_{ds} - L_m i_{dr} \tag{7.13}$$

$$\psi_{qr} = -(L_{r\sigma} + L_m)i_{qr} - L_m i_{qs} \tag{7.14}$$

$$\psi_{dr} = -(L_{r\sigma} + L_m)i_{dr} - L_m i_{ds} \tag{7.15}$$

Electrical torque equation is given below:

$$T_e = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \tag{7.16}$$

where,

L = Inductance
d = Direct axis component
q = Quadrature axis component
s = Slip
m = Mutual
σ = Leakage.

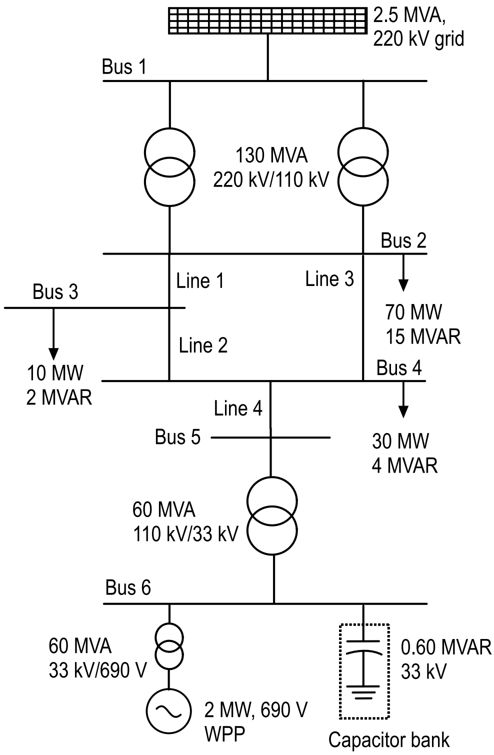


Figure 7.9 **Typical Distributed Generation:** A power system with 2 MW constant speed WPP.

Equation of motion of SCIG is given by:

$$\frac{dw_r}{dt} = \frac{T_{\text{mech}} - T_{\text{elect}}}{2H_m} \tag{7.17}$$

EXAMPLE 7.1

A RL circuit shown in Figure 7.10 has $R = 8\ \Omega$, $X_L = 12\ \Omega$ and $V = 230\ \text{V}\angle 0°$. Find the current.

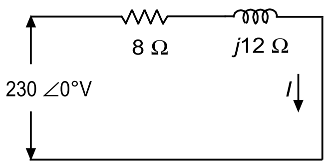


Figure 7.10 **Example.**

Solution:

A complex number z is represented in rectangular form as

$$z = x + jy$$

where,

x = Real part of z

y = Imaginary part of z

$j = \sqrt{-1}$.

The complex number can also be represented in polar form where angle is measured counterclockwise from the x-axis:

$$z = |z|\angle\theta$$

where, magnitude of $|z| = \sqrt{x^2 + y^2}$ and $\angle\theta$ and $= \tan^{-1} y/x$.

The impedance is (as shown in Figure 7.11):

$$Z = R + jX_L = 8 + j12 = 14.42\angle 56.30°$$

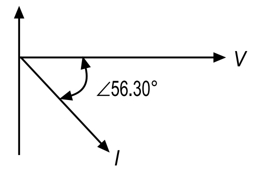


Figure 7.11 Example.

Then, the current is:

$$I = \frac{230\ \angle 0°}{14.42\ \angle 56.30°} = 15.95\ \angle -56.30°$$

EXAMPLE 7.2

A series RLC circuit shown in figure 7.12 has $R = 5\ \Omega$, $X_L = 10\ \Omega$, and $X_C = 13\ \Omega$. Determine the current, complex power, real power and reactive power delivered to the circuit for an applied voltage of 230 V. Find also the power factor.

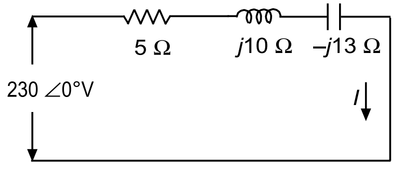


Figure 7.12 Example.

Solution:

Impedance, $Z = R + jX_L - jX_C = 5 + j10 - j13 = 5 - j3 = 5.83\ \angle -30.96°$

Assuming $V = |V|\angle 0°$ as the reference voltage, the current is:

$$I = \frac{V}{Z} = \frac{230}{5.83\ \angle -30.96} = 39.45\ \angle 30.96°\ A$$

The complex power is:

$$S = |V|\,|I|\angle\theta = |230|\,|39.45|\angle 30.96° = 9073.5\ \angle -30.96°$$

The active power supplied to the circuit is just the active power absorbed by the resistor, since reactances do not absorb active power.

$$P = I^2R = (39.45)^2 \times 5 = 7781 \text{ W}$$

It is also given by:

$$P = |V|\,|I|\angle\cos\,\theta = 230 \times 39.45 \cos 30.96° = 7781 \text{ W}$$

The reactive power supplied to the inductor is:

$$Q_L = I^2X_L = (39.45)^2 \times 10 = 15563 \text{ VAr}$$

The reactive power supplied to the capacitor is:

$$Q_C = -I^2X_C = -(39.45)^2 \times 13 = -20231 \text{ VAr}$$

The net reactive power supplied to the circuit is:

$$Q = Q_L + Q_C = 15563 - 20231 = -4668 \text{ VAr}$$

Net reactive power is also given by:

$$Q = |V|\,|I|\angle\sin\,\theta = 230 \times 39.45 \sin 30.96° = -4668 \text{ VAr}$$

Power factor = cos (–30.96°) = 0.86 leading (It means θ is negative or the current is leading the voltage).

7.4 TYPE-B WPP

Type-B WPP is a relatively cheaper solution than the Type-C WPP to harness more energy from the varying wind speeds. For the first time, *Weier* (from Germany) developed the Type-B WPP mounted with wound rotor induction generator (WRIG) that operates in a narrow range speed variation (upto 10%–16% above the synchronous speed). It overcomes many of the disadvantages of the Type-A WPP mounted with SCIG. The mechanical construction of the WRIG stator is similar to that of the SCIG. However, the rotor circuit has copper windings that are not shorted by the end rings, but are star connected to the external variable resistors (see Figure 7.13) through slip rings and brushes. The resistors lower the voltage to the required value by dropping some of the supply voltage across it. Modern Type-B WPP has done away with slip rings by mounting rotating variable resistors and the optically controlled (so-called opti-slip or flexi-slip) control circuitry is mounted on the generator rotor shaft itself whereby, the heat that is generated in the resistors is dissipated. For every 1% increase in slip, extra 1% losses occur.

7.4.1 Working Principle

As in SCIG, the three-phase stator coils are distributed in the winding slots of the WRIG so that when a three-phase supply is given, a rotating magnetic field is set up in the air-gap that exerts a torque on the rotor to rotate it. Above the rated

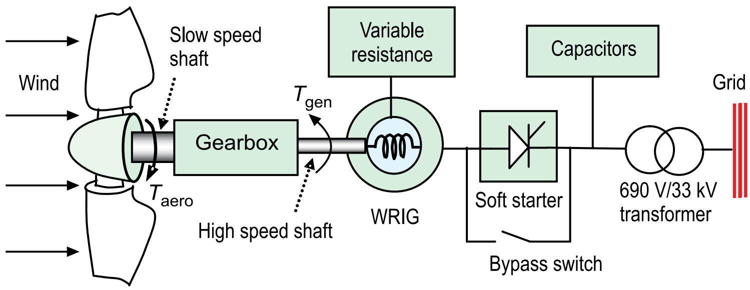


Figure 7.13 **Type-B WPP with WRIG:** The stator is directly connected to the grid. The copper windings of the rotor are connected to the external variable resistors.

speed, control of the external resistors effectively allows the air gap torque to be controlled and the slip speed to vary so that the behaviour is similar to a variable speed generator. In Type-B WPP, the stator of the WRIG is directly connected to the electric grid. Higher the rotor resistance, higher will be the slip. The energy loss in the rotor external resistors by passive load control is about 30%. By adding an external variable resistor (see Figure 7.14) in series with the rotor windings of a WRIG, it is possible to get a variation in electromagnetic torque of the generator as well as in the speed at which it is delivered. The heat loss in the external resistive load is wasted and has to be dissipated by proper cooling arrangements. The heat loss is given by:

$$\text{Resistance loss} = 3I_r^2R_{ex} \tag{7.18}$$

where,

$$R_{ex} = \text{External rotor resistance.}$$

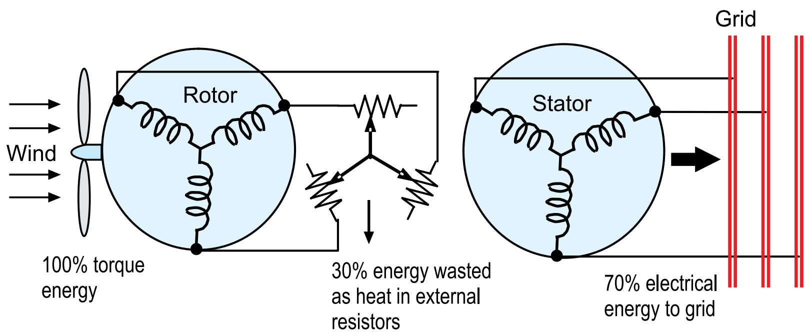


Figure 7.14 **Type-B with Passive Load:** 30% of the energy is dissipated as heat. When the WRIG operation reaches stability, the external resistance is bypassed and practically, it functions as SCIG.

At partial loads, the generator operates as a regular asynchronous generator but once the full load is reached, the rotor resistance is changed to increase the slip to allow the rotor to absorb the energy of gusts. The pitch mechanism is used to modulate the power fluctuations. However, with a WRIG, generator operation is

possible only at higher than synchronous speeds. Below the synchronous speed, the WRIG becomes an induction motor consuming power from the grid.

The real benefit of Type-B WPP is that a better power quality (as required by the grid operators) is obtained, since the fluctuations in power output are eaten up or topped up by varying the generator slip and storing or releasing (depending upon the wind speed) part of the energy as rotational energy in the WPP rotor. To avoid further losses, this resistance is then shorted as soon as the generator reaches the steady state condition making the rotor look electrically like the SCIG. During high wind speeds, the excess wind energy is spilled away by pitching the rotor blades out of the wind.

The soft starter ensures smoother grid connection. The variable slip is a very simple, reliable and cost-effective way to achieve load reductions as compared to the more complex variable speed solutions such as DFIGs, WRSGs and PMSGs (discussed in the next chapter).

7.4.2 Performance of Type-B WPP

The main aim of WRIG is to keep the rotor current at a set value, irrespective of the wind speed variations within a narrow range for a constant power output from the stator to the electric grid. Type-B WPP also help in smoothing out the power output, thereby reducing the structural loads under turbulent wind conditions. The slip, however, is a function of the (DC) resistance (measured in ohms) in the rotor windings of the generator. The induced currents in the induction generator rotor responsible for the torque is strictly a function of the generator slip which can be changed by gradually adjusting the externally connected rotor resistance to avoid the start-up current impulses and the resulting impulse torques.

The slip at which the peak torque occurs is given by:

$$\text{Slip for peak torque} = \frac{R_r}{\sqrt{R_s^2 + (X_{ls} + X_{lr})^2}} \tag{7.19}$$

where,

R_r = Rotor resistance
R_s = Stator resistance
X_{ls} = Stator leakage reactance
X_{lr} = Rotor leakage reactance.

The above equation shows that the slip at the peak torque can be increased by using a higher rotor resistance. This property is used in Type-B WPPs for narrow range variable speed operation. Increasing the rotor resistance reduces the rotor current and increases the slip, as seen by their torque-speed characteristics (see Figure 7.15). Due to the resistors in the rotor circuit of WRIGs, high torque is produced while starting. The resistance decreases the torque available at full running speed. It can be seen that the slip '*s*' is directly proportional to rotor resistance and the pullout torque is proportional to the slip '*s*'.

The torque–speed characteristic of a WRIG is shaped based on the command from the rotor circuit and can be programmed as well. By increasing the rotor

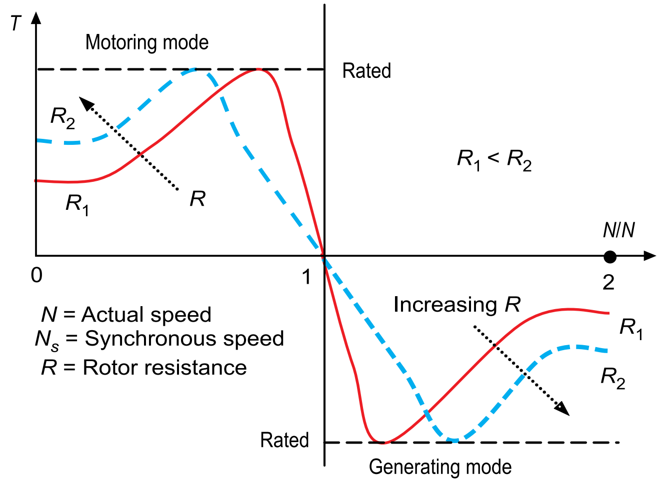


Figure 7.15 **WRIG Speed–Torque Characteristics:** It is seen that as the external resistance *R* increases, then slip increases and the torque also increases.

resistance from R_1 to R_2, the breakdown torque peak gets shifted from left to right in the generating mode. This torque peak is much higher than the starting torque available with no rotor resistance R_o.

The grid input power (which is actually the power flow across the air gap of generator rotor and stator) needs to be levelled off during wind speed fluctuations. To bring down the grid voltage pulsations and the mechanical stresses on the drive train, the strategy, is to dissipate the rotor circuit energy as heat. Therefore, one of the salient features of Type-B WPP is that it can control the torque in the drive train to smooth out the aerodynamic torque variations above the rated speed.

The slip mechanism of the generator is finely synchronised with the pitching mechanism to give optimum performance for different wind speeds and gusts. The rotor current and hence, the torque are directly proportional to the slip. Hence, there is a possibility of operating the WPP at an optimum TSR point as a function of wind as well as allowing the rotor to accelerate, changing the speed due to wind gusts, even though the losses due to Joule effect in the external resistor rise. This method renders the control for smoother WRIG characteristics and hence, allows lesser stresses on the WPP drive train.

Slip rings and brushes are one of the causes for higher maintenance problems in three-phase bidirectional PEC controlled Type-B machine. In modern Type-B WPPs, the resistances are mounted on the rotor shaft that are optically controlled, thereby avoiding the slip rings and brushes. The external resistance can be continuously varied from maximum *R* to zero without slip rings. Electrical flicker is also reduced above the rated speed. But, it does not offer increased aerodynamic efficiency below the rated speed and does not allow any control of the power factor. Since the windings are distributed, some of the odd harmonics get cancelled, producing a more sinusoidal magnetic field distribution across the poles.

7.4.3 Topologies of Type-B WPP

Type-B WPPs also have the following topologies:

- Type-B0
- Type-B1
- Type-B2.

Type-B0 WPP is a stall controlled WPP with the rotor connected to the slow speed shaft of the gearbox and its high speed shaft is connected to the WRIG rotor. The WRIG stator is directly connected to the grid. After the controlled start-up of the WRIG, the variable external resistance is bypassed to reduce the continuous heat losses. A high starting torque (which is available at zero speed) is not required at high speed, as the break down torque has shifted (see Figure 7.15). *Stall effect* is used to limit the power output at higher wind speeds. The WPP is designed to be optimally loaded only at one particular wind speed that matches the TSR for maximum aerodynamic efficiency. However, it consumes reactive power for which reactive power compensation is usually provided (e.g. capacitor banks or FACTS devices) at the generator connection point or at the point of common connection (PCC) at substation.

Type-B1 WPP is a pitch controlled WPP with the rotor connected to the slow speed shaft of the gearbox and its high speed shaft is connected to the WRIG rotor. The WRIG stator is directly connected to the grid. After the controlled start-up is over, the performance is similar to Type-A1 WPP but with greater speed variability due to the external variable rotor resistance. Above the rated speed in the generator mode, control of this external resistance effectively allows the air gap torque to be controlled and the slip to vary the speed around 10% to 16%.

Type-B2 WPP is an active-stall controlled WPP with the rotor connected to the slow speed shaft of the gearbox, the high speed shaft of which is connected to the WRIG rotor. The WRIG stator is directly connected to the grid. Spilling away of the excess wind power during high wind speeds is done (to some extent) by the limited pitching action in opposite direction of Type-B1 to produce the rated power. This type combines the advantages of Type-B0 stall controlled WPP and Type-B1 pitch controlled WPP by which emergency stopping and start-ups are also facilitated. But then, it comes at a higher cost because of its pitching mechanism and additional complexity.

Table 7.1 provides an overview of various types of constant speed WPPs discussed thus far. Further details of the electric generators can be obtained from different manufacturers' websites.

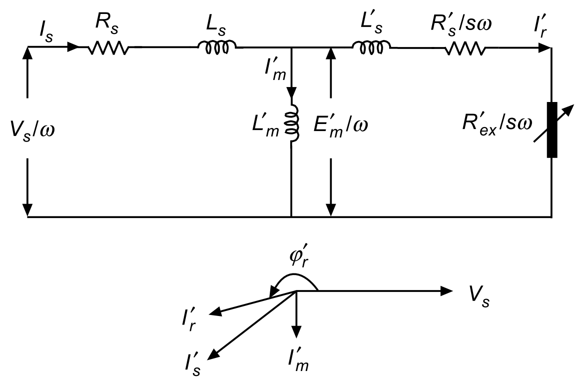
Table 7.1 Comparison of Constant Speed WPPs

WPP Type	Aerodynamics and Electrical Generator (with examples)		
	Stall	Pitch	Active-stall
Type-A: Constant Speed Variation–1% to 2%	Type-A0: (with SCIG) 250 kW Shriram EPC	Type-A1: (with SCIG) 600 kW RRBenergy	Type-A2: (with SCIG) 1650 kW Vestas
Type-B: Narrow Range Variable Speed–0% to 16%	Type-B0: (with WRIG) 1 MW Nordic Wind (two-bladed)	Type-B1: (with WRIG) 3 MW Vestas 'Optislip®' 2.1 MW Suzlon 'Flexi-slip'	Type-B2: (with WRIG) 750/180 kW NEPC-Norwin

7.5 EQUIVALENT CIRCUIT OF WRIG OF TYPE-B WPP

Only when the speed is above synchronous speed of the WRIG, does it begin to supply power to the electric grid. When the maximum possible power limit (or torque limit) of the WPP is reached, the speed of the WPP is limited by the pitch regulation. At high wind speeds, the total resistance of the rotor can be increased to keep the current flowing in the rotor constant (and therefore also in the stator) and also the power put into the grid at the grid voltage and frequency. The excess of mechanical energy generated by the rotor windings is dissipated as heat in the external resistors.

In the equivalent circuit of WRIG (see Figure 7.16) with constant frequency, the resistive component ($R'_{ex}/s\omega$) has been added to the common T equivalent circuit of the SCIG (refer Figure 7.7). The output power at the stator side is always inductive (lagging or under excited), as there is no compensation in the rotor circuit. Ideally, the resistances and leakage reactances are zero and the magnetising reactance is infinite.



R_s = Stator resistance	L_s = Stator inductance
L'_m = Magnetising inductance	L'_s = Rotor inductance
R'_s = Rotor resistance	$s\omega$ = Slip frequency
s = Slip	I_s = Stator current
V_s = Stator voltage	I_r = Rotor current
I_m = Magnetising current	R'_{ex} = Variable rotor external resistance

Figure 7.16 Equivalent Circuit of Constant Frequency WRIG Referred to Stator Side.

The range of the dynamic speed control depends on the size of the variable rotor resistance. Through this resistor, it is possible to achieve a variation in the speed exceeding the synchronism speed even upto 16% in some WPPs.

7.6 REACTIVE POWER IN CONSTANT SPEED WPP

Whether it is a Type-A or a Type-B constant speed WPP, the major drawback is the reactive power consumption required for its excitation (i.e., it needs reactive

power to build up its magnetic field), which is drawn from the electric grid in order to generate active power. This is an apparent power which does not contribute to direct energy conversion.

The induction generators in these constant speed WPPs consume large amount of VArs from the grid especially during start-up. The magnetising currents drawn by step-up transformer near the WPPs also add up to the reactive power consumption to some extent. The current associated with it (which means reactive current) causes losses in the grid supply and in the generator as well. If uncompensated, these fluctuating VAr flow can cause severe voltage fluctuations, thereby affecting overall power quality and the reliability of the local transmission grid. For weaker networks, these effects are more acute.

The active power P and reactive power Q from these WPPs affect voltages on the network as the current flows through the network impedances. Higher the reactive current content in the overall current, lower will be the power factor (cos φ). This reactive power consumption leads to increased transmission and distribution (T and D) losses, poor voltage profile (and hence reduced voltage stability margins), overloading and reduction in T and D equipment. From no load (idling) to full load, the consumption of reactive power by these WPPs may increase even up to 60%. WPPs, in earlier years, were of smaller capacities and hence, did not affect the strong grids mainly fed by conventional power plants; but they did affect the weaker distribution systems.

To compensate the reactive power, shunt capacitor banks have been used with the WPPs for years. According to the need, they are switched in and out in steps in accordance with the VAr requirements by the command from the on-board microcomputer inside the electronic controller. These shunt capacitors are switched in three to four steps with a time delay of around one second. Shunt capacitor banks have proved to be useful as they:

- Effectively improve the power factor of the WPP
- Can be switched in and out in blocks
- Are relatively inexpensive.

The voltage change at the terminal voltage of the constant speed WPP can be divided into two parts (see Figure 7.17). Due to the reactive power consumption in the initial stage, a voltage drop can be seen in the first part. This reactive power is to be compensated by the shunt capacitors. This voltage level is restored when the capacitors are switched on due to which reactive power consumption is reduced. In some Type-A0 WPPs, the soft starter and the capacitor bank are used only when they are acutely needed, i.e., during starting and whenever there is a reactive power requirement; rest of the time, they remain bypassed. This strategy helps in reducing the losses and thereby harnessing the maximum wind power.

7.6.1 Shunt Compensation

The networks with large number of constant speed WPPs require switched capacitor banks and shunt reactors as well as the transformers with tap changers for greater

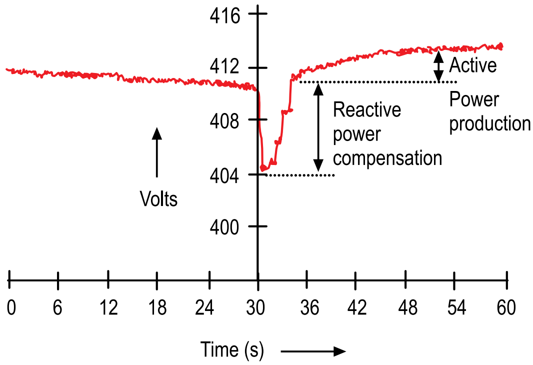


Figure 7.17 Typical Characteristics of Reactive Power Compensation of a Constant Speed WPP at Start-up: The reactive power demand is only for a short duration during start-up after which the WPP operates normally.

control of voltage stability. These can be provided at each WPP or at PCC. In any given local area with these WPPs, the total reactive power demand is the sum of the demand of the loads and the demand of each WPP.

As the shunt capacitors are switched in and out, the output characteristic becomes discontinuous and depends on the rating and number of capacitors and hence, the voltage support provided also becomes discontinuous. The switch-out occurs at zero current after an integral number of half cycles. The switching operation excites transients which have to be kept at a minimum. However, during lower voltages, the reactive power capability of the capacitors significantly falls and is less effective.

If frequent overvoltages occur, chances of capacitor overloading and damage may occur whereby maintenance cost may increase. During switching-in operations, the surge currents tend to reduce the lifetime of the capacitors. Since the reactive power varies continuously, the limited variability of the capacitance values becomes a limitation.

But shunt capacitor banks have their drawbacks as well:

- Switching a big block of capacitance in and out can swing the voltage up or down and this variation is felt as an abrupt change in torque on the WPP gearboxes.
- They are not good at addressing transient events.
- As the power factor and the output power fluctuate, ideal compensation requires variable reactive compensators such as the FACTS devices (SVC, STATCOM or DVR).

A typical wind farm with constant speed WPPs can experience 50–100 capacitor switching events on a given day. Such frequent switching can cause stresses, effectively reducing lifetime of the capacitors. As these capacitors are slow and not able to provide fine and continuous control, they are unable to react to the sudden momentary voltage dips commonly seen in weak grids or during gusty windy conditions. This can add stresses to the utility grid. In addition, some WPP gearboxes are sensitive

to large step changes in voltages associated with normal capacitor switching which can overstress the gearbox—one of the most expensive and maintenance intensive components of a WPP. Therefore, FACTS devices are better alternatives, but they come at a higher price with additional complexities.

7.6.2 FACTS Devices for Constant Speed WPPs

Depending on proximity to the local load and the distribution network configuration, WPPs can cause voltage transients or flicker on a local distribution grid. This occurs due to the inrush associated with the energisation of the induction generator stators. Depending on the strength of the local grid, an undesirable voltage dip can result every time when the WPPs are started. For this reason, local utilities often require those WPPs to limit the magnitude of their voltage disturbances to a maximum of 1%–2%. For minimising these voltage disturbances, a dynamic reactive compensation (such as a FACTS device) is required that can instantaneously and infinitely vary their output to precisely counteract the reactive current being drawn by the stators.

Presently, various types of reactive power compensating devices called flexible AC transmission systems (FACTS) devices are adapted by the wind industry either at each WPP or at PCC. These FACTS devices are basically power electronics and transistor-based switches classified as:

- Series device, e.g. dynamic voltage restorer (DVR)
- Shunt device, e.g. static VAr compensator (SVC) and static compensator (STATCOM)
- Series–shunt device (combination of series and shunt FACTS devices), e.g. unified power quality conditioner (UPQC).

(a) Static VAr Compensators (SVC)

Static voltage compensator is a shunt connected VAr generator or absorber whose output is adjusted to exchange capacitive or inductive current. Some of the SVC technologies (see Figure 7.18) such as thyristor switched reactor (TSR) and thyristor switched capacitors (TSC) are used with constant speed WPPs. The capacitor banks in TSC are connected in series with a bidirectional thyristor pair and a small inductor (to limit the switching transients and inrush currents). These devices use electronic switches as thyristor which can open or close in few milliseconds. It is usually connected between the utility and the generator.

The TSR consists of an inductance in series with a two parallel bidirectional reverse connected thyristor pair. It mimics the working principles of a variable shunt capacitor and uses fast thyristor controllers with settling times of only a few fundamental frequencies periods. It uses naturally commutated standard thyristors to switch inductors onto the network, thereby obtaining a controllable reactance. The TSR produces higher harmonic currents in the phase control mode. By connecting the TSR components in delta, the third harmonic can be cancelled in three-phase systems. More harmonics can be taken off by connecting additional filter elements.

TSC shares similar composition and same operational mode as TSR but the reactor is replaced by a capacitor.

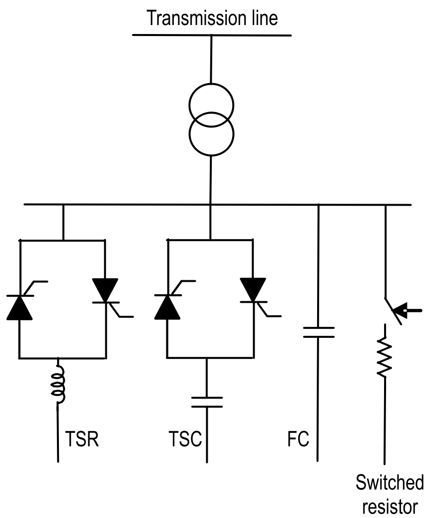


Figure 7.18 **Different Topologies of SVC:** Anyone or combinations of these FACTS devices are used for reactive power compensation in WPP connected networks.

Fixed capacitors (FC) bias the TSR compensator so that its overall power factor can be rendered either leading or lagging. The fixed capacitors are switched on or off in packets as required and these are signalled by the microcomputer. The reactance can only be either fully connected or fully disconnected (zero) due to the characteristic of capacitor.

A reasonably-sized SVC is able to reduce the undamped voltage oscillations and prevent voltage collapse. However, it does not prevent the violation of a certain voltage limit (say 0.7 p.u.) immediately following the fault recovery, once the WPP size becomes too large. This is at least partially due to the fact that the voltage is quite low and the SVC can only produce a reduced VAr output during low voltage. SVCs typically operate poorly at lower than nominal voltages. But the problem with SVC is the undesirable harmonics associated with it. SVC can provide reactive power from 0 p.u. to 1 p.u. depending on the voltage (see Figure 7.19).

The SVC differs from the STATCOM in its way of implementation. SVC is based on thyristors *without gate turn-off capability*. The current flow is controlled by adjusting the firing angle (from 90° to 180°) of the thyristors. SVC outputs are continuous (infinitely variable). They do not cause sudden voltage changes in the system and are highly effective in regulating voltage. For the same rating, system and contingency, the SVC is relatively larger, consumes more space and hence, more expensive than a STATCOM or DVR.

(b) Static Compensator (STATCOMs)

The name STATCOM arises as it is the electronic version of the synchronous condenser (rotating synchronous machine with variable field excitation control). A synchronous

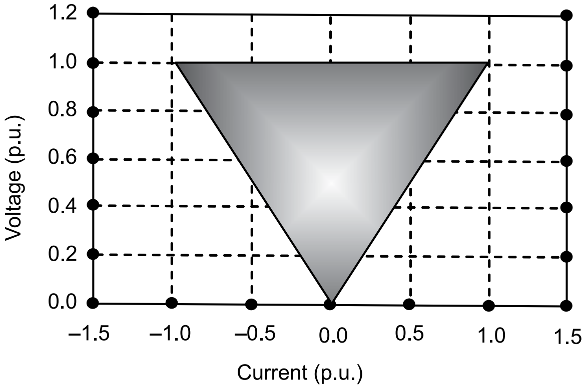


Figure 7.19 ***V–I* Characteristics of SVC.**

condenser can provide the needed reactive compensation, as it also increases the short circuit power at the bus. However, they are expensive and require considerable amount of maintenance. STATCOM is a voltage source converter which can inject or absorb reactive current in an AC system, thus modifying the power flow. It is usually connected between the utility and the generator (see Figure 7.20).

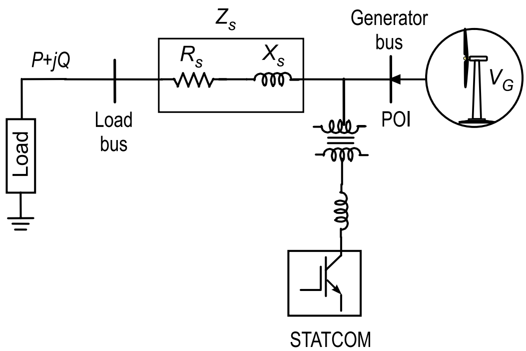


Figure 7.20 **STATCOM:** Static compensator (STATCOM) is a shunt connected VSI-based power electronic device.

The STATCOMs belong to a family of PECs that base their operation on the voltage source inverter (VSI) principle. It is a *forced commutated PWM-based shunt connected power electronic device* that is able to emulate reactive loads, both inductive and capacitive. The most basic configuration of the STATCOM consists of a two-level VSI with a DC energy storage device, a coupling transformer connected in shunt with the AC system and associated control circuits.

The reactive and real power exchange between the STATCOM and the AC system can be controlled independently of each other. STATCOM is the evolution of SVC, but it has continuous control and can compensate both power factor and voltage simultaneously (see Figure 7.21). Other advantage of STATCOM is its dynamic capacity of getting smaller response times.

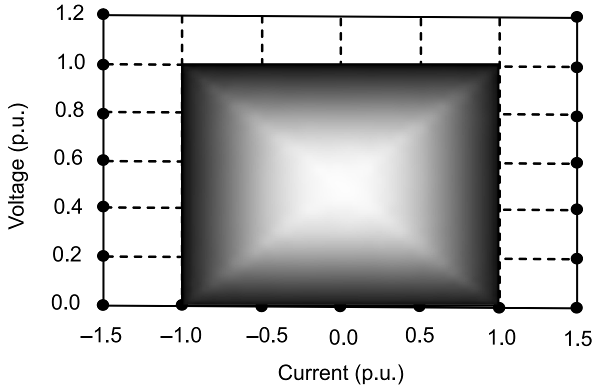


Figure 7.21 ***V–I* Characteristics of STATCOM.**

It can supply some reactive power to the wind farm under normal operation and also operate as reactive power source when the wind speed is below cut-in speed of the WPP. It has much better transient performance as compared to the rotating systems and it is better in terms of cost, weight and size. When it injects reactive current into the electric grid, it behaves as an overexcited synchronous generator (or capacitor) supporting the grid voltage and when it absorbs reactive current, it behaves like an underexcited synchronous generator (or inductor) tending to decrease the grid voltage. During a fault, the reactive power supplied by the STATCOM is decreased due to the voltage drop. After the fault, the STATCOM supplies an amount of reactive power to the wind farm and compensates its requirements for reactive power in order to ride through the fault. The DC energy storage device may be a battery the output voltage of which remains constant or it may be a capacitor whose terminal voltage can be raised or lowered by means of suitable converter control.

A STATCOM provides extra benefit for the post-disturbance under voltage criteria, but it does not damp out the oscillations as good as a similar-sized SVC. A similar-sized SVC does not meet the under voltage criteria; however, it provides better damping.

(c) Dynamic Voltage Restorer (DVR)

DVR is a power electronic device (see Figure 7.22) that is similar in function to the STATCOM to control the WPP reactive power, but it is connected in series in the system. A DVR can inject or absorb real and reactive power independently by an external storage system without reactors and capacitors. It consists of medium voltage switchgear, a coupling transformer, filters, rectifier, inverter and energy source (e.g. storage capacitor bank) and a control and protection system.

The DVR, also referred to as series voltage booster (SVB) or static series compensator (SSC), is connected in series to the utility primary distribution circuit to provide three-phase controllable voltage. During a voltage sag, the DVR injects a voltage to restore the load supply voltages.

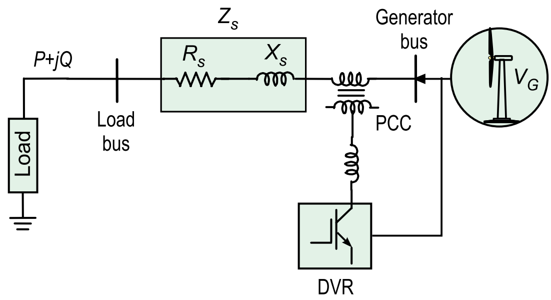


Figure 7.22 **DVR:** Dynamic voltage restorer (DVR) is a series connected VSI-based power electronic device.

(d) Unified Power Quality Conditioner (UPQC)

UPQC is a combination of a series and a shunt FACTS devices (see Figure 7.23). It comprises of two voltage source inverters connected back-to-back and sharing a DC link. Its main aim is to improve the voltage flicker, unbalance, negative sequence current and harmonics. The shunt inverter helps in compensating the load harmonic current and maintains DC voltage at constant level. The second inverter is connected in series by using a series transformer and helps in maintaining the load voltage sinusoidal and compensates voltage dips and swells.

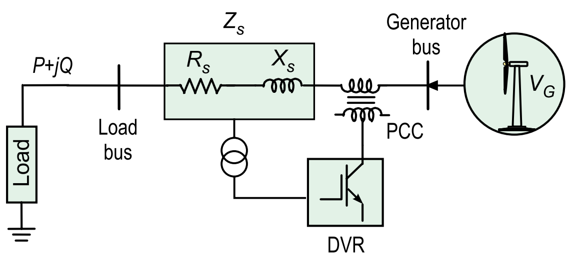


Figure 7.23 **UPQC:** The main aim is to improve the voltage flicker, unbalance, negative sequence current and harmonics.

7.7 FEATURES AND LIMITATIONS OF CONSTANT SPEED WPPs

The constant speed WPPs have following positive features:

(i) The excellent mechanical and electrical properties, i.e., slip provides a damping action that helps in arresting electromechanical oscillations of the WPP.
(ii) They cost only about one-tenth of a synchronous generator of same rating.
(iii) There is no hunting problem.
(iv) They reduce the short circuit risk of the power station.
(v) They contribute to the power system inertia similarly as a standard industrial induction motor.

(vi) Gusts can be partially transferred into the acceleration of the rotor and hence, in pitch controlled WPPs, there is no need to reduce the blade pitch angle immediately. Wind gusts are not only buffered in the mechanical inertia, but also in the energy storage of the intermediate capacitors.
(vii) There is a reduction in power peaks. As they are less sensitive to the grid abnormalities, they can sustain grid abnormalities with greater ease.
(viii) As the torque of WRIG in Type-B WPPs is directly proportional to the slip (varied upto 16%) by the external resistors, speed control is possible that is otherwise difficult to achieve in a SCIG with better power factor.
(ix) Due to the greater slip that is possible in Type-B WPPs, grid coupling is a little more elastic in comparison to Type-A WPPs. Further, with the use of WRIGs, damping of rotor dynamics is also improved.
(x) They have a simpler control because the magnetising current is practically constant, regardless of the rotor frequency, whereas the rotor current in the DFIG (of a Type-C WPP) has to be synchronised to the stator reference.
(xi) During wind gusts, if the induction generator has high slips, the energy in the WRIG is a more economic and less complex design to achieve load reductions as compared to the other variable speed WPPs.
(xii) Standard off-the-shelf WRIGs can be used for Type-B WPPs.

Constant speed WPPs have their share of limitations as well:

(i) These SCIGs and WRIGs consume reactive power due to the magnetising current supplied by the grid (VArs) to the stator winding which results in low power factor, thereby requiring compensation devices to be used.
(ii) These WPPs are more successful only in strong grids.
(iii) Generally, these WPPs do not have fault-ride-through (FRT) property.
(iv) They cannot provide voltage or frequency control due to narrow range of speed control.
(v) Optimisation of the aerodynamic efficiency cannot be achieved continuously with a single speed SCIG.
(vi) Wind speed fluctuations or wind gusts and the back pressure of the tower cause generator shaft power fluctuations that are directly passed onto the grid network modified by the internal impedance of the generator itself. This is not acceptable to the distribution network.
(vii) There is a lack of both fine active and reactive power control.
(viii) Due to the gusts, high mechanical and fatigue stresses also adversely affect the gearbox, electric generator and blades.
(ix) The electrical power fluctuations from the grid-side get translated into torque pulsations which may lead to early gearbox failure.
(x) In the absence of energy buffer in the form of rotating mass, varying rotational speed causes large output power fluctuations which lead to swing oscillations between the wind turbine rotor and generator shaft resulting in light flicker in the electrical distribution network.
(xi) The slip power in the rotor is dissipated in variable resistance as heat losses in Type-B WPPs which also leads to reduction in the output power yield.

(xii) Insulated winding on the rotor may be subjected to stresses arising from the rotation and vibration and this is likely to reduce the technical lifetime of the generator.

SUMMARY

The success of the wind industry began with use of SCIGs as the trusted workhorse of the constant speed WPPs in the early years followed by the adaptation of WRIGs in constant speed WPPs. They are cheaper than variable speed WPPs but not as grid- friendly as variable speed WPPs. Using relevant software simulation is a good way of studying the behaviour of WPPs equipped with the induction generators. Software such as MATLAB® version-11 and DIgSILENT® PowerFactory are sufficiently good to study the behaviour of WPPs. The latter is optimised to handle very large systems with ample buses/machines, appropriate initialisation of models, etc. Finally, the choice of which type of electric generator should be used in WPPs depends upon the performance and economics.

EXERCISES

7.1 Describe the working of a Type-A WPP.

7.2 Justify the need of a soft starter for Type-A WPP.

7.3 With a sketch of the SCIG torque, speed and power characteristics, explain the various phenomena with respect to Type-A WPP.

7.4 Distinguish the features of Type-A0, Type-A1, and Type-A2 WPPs.

7.5 Describe the starting of (i) Type-A0 WPP, and (ii) Type-A1 WPP.

7.6 With sketches of the characteristics, justify the need for two-speed operation of Type-A WPP.

7.7 With the sketch of the generic model of Type-A WPP, list the stator equations, rotor equations and flux linkage equations.

7.8 Compare the major features in the working principle of a Type-A and Type-B WPPs.

7.9 Compare the torque-speed characteristics of Type-A and Type-B WPPs with sketches.

7.10 Discriminate the features of Type-B0, Type-B1, and Type-B2 WPPs.

7.11 Compare the VAr compensators used in WPPs.

7.12 Justify the role of FACTS devices with regard to WPPs.

7.13 Compare the features of three FACTS-based reactive power compensation devices in PECs.

7.14 Describe the working of a (i) STATCOM, (ii) SVC, and (iii) DVR.

7.15 With sketches, differentiate between a STATCOM and a DVR.

7.16 With sketches explain the generalised equivalent circuit of WRIG.

8

Variable Speed Wind Power Plants

LORD made an east wind blow across the land all that day and all that night.
—Exodus 10:13

Learning Outcome

On studying this chapter, you will be able to distinguish the technologies adapted in different types of variable speed wind power plants.

CHAPTER HIGHLIGHTS

8.1 INTRODUCTION

For increasing the annual energy yield from any WPP, it is essential that they WPPs operate over a wide range of wind speeds. The wind industry demands those WPPs that can operate over a wide range of wind speeds so that more electrical power can be harnessed. WPPs with greater control of the active and reactive power, lesser acoustic noise, reduced stresses on the drive train and mechanical components was also desired. This has become possible, to a great extent, by the invention of various types of variable speed WPPs using different types of electric generators controlled by power electronic converters (PEC).

Based on the speed variability, two major categories of variable speed WPPs are as follows:

- Type-C WPP for limited range variable speed
- Type-D WPP for wide range variable speed.

To allow variable speed operation, the mechanical rotor speed and the electrical frequency of the grid need to be decoupled. Various topologies incorporated in variable speed WPPs are discussed in this chapter with the assumption that the reader has a basic understanding of electrical engineering principles.

8.2 TYPE-C WPP

Type-C WPP operates within a range of –30% to +40% of its rated speed and hence, is considered as a *limited range variable speed WPP*. The doubly-fed induction generator (DFIG) in type-C WPPs combines the advantages (e.g. robustness) of an induction generator as well as the variable speed feature of the synchronous generator. It is basically an induction generator with three-phase stator winding that is directly connected to the electrical grid (see Figure 8.1).

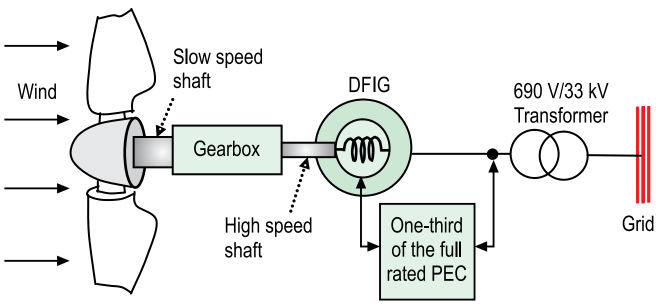


Figure 8.1 Type-C WPP: The stator of the DFIG is directly connected to the grid while the rotor is also connected to the grid through a power electronic control circuit.

Rapid fluctuations in mechanical power can be temporarily stored as kinetic energy by this WPP. Within limits, DFIG control can hold the electrical power constant, even during fluctuating wind speed, storing temporarily the rapid power

fluctuations as kinetic energy in the drive train. During high wind speeds, the speed of the WPP is limited to its rated speed by the coordinated aerodynamic pitching action and PEC operation.

The three-phase wound rotor is connected to the grid through a PEC with the help of slip rings and brushes. This is a back-to-back partially rated (30%) PEC that feeds the grid so that the mechanical rotor speed and the electrical rotor frequency are decoupled and the stator and rotor frequencies can be matched, independent of the mechanical rotor speed. Almost all the Type-C WPPs are of Type-C1 category, as they have blades which can be fully feathered. Type-C WPPs fulfil the grid code requirements and DFIG is one of the control technologies for WPPs that minimises the peak voltage values, flicker and harmonics, thus easing the connection licensing issues for grid connection.

The back-to-back PEC usually consists of a pulse with modulated (PWM) converter. Due to the bidirectional power flow ability of the PEC, the DFIG may operate as a generator or motor both subsynchronously ($0 < \text{slip} < 1$) and supersynchronously ($\text{slip} < 0$). By directing the slip power of the rotor circuit through the PEC, the WPP can be operated with limited range variable speed.

Type-C WPP has to prevent overspeeding which is done by the coordinated action of the pitch control and PEC. The use of the partial scale PEC for the Type-C WPP is an attractive concept from an economical point of view.

8.2.1 Working Principle

The DFIG is still characteristically an induction generator. However, since both the stator and rotor windings are connected to the grid and participate in the energy conversion process, they are termed as *doubly-fed*. Unlike the WRIG in Type-B WPP where the rotor power is dissipated as heat energy in the passive resistors, in Type-C WPP, the slip power in the DFIG rotor circuit is recovered, treated, transformed and sent onwards to the grid through a partial scale (one-third of the rated power) back-to-back PEC. The DFIG supplies the grid with two-third of the rated power through the stator directly connected and one-third through the rotor connected to the PEC. It is possible to control the reactive power production and allow voltage regulation and magnetisation of the machine by the rotor, regardless of the grid voltage.

The aerodynamic torque T_{aero} from the wind turbine rotor acts on the front end of the gearbox while the generation torque T_{gen} (see Figure 8.2) from the DFIG side acts on the rear end of the gearbox resulting in the torsion of the high speed shaft. The DFIG usually has a synchronism which can speed upto 2000 RPM and it is connected to the rotor axis through a gearbox. However, due to the torsion–spring characteristics of the drive train, the generator torque T_{gen}, T_{aero} and the generator speed start to oscillate with the so called free-free frequency (f_{osc}).

$$f_{osc} = \frac{1}{2\pi}\sqrt{\frac{k}{J_{eq}}} \tag{8.1}$$

where,

J_{eq} = Equivalent polar moment of inertia of the drive train.

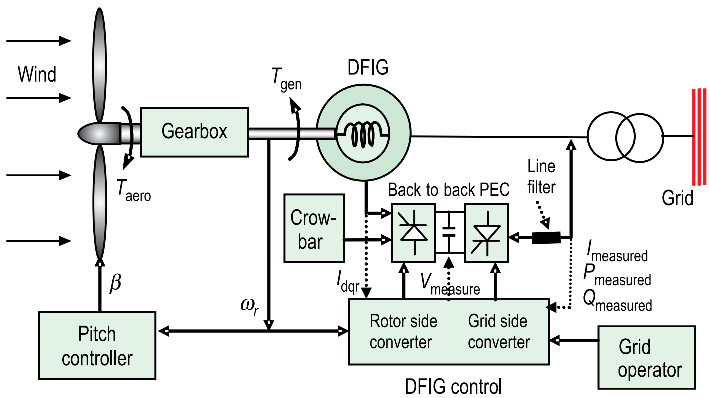


Figure 8.2 **Type-C WPP Working Principle:** The DFIG is controlled by a back-to-back PEC. The coordinated operation of the pitch controller and the DFIG variable speed operation is possible and the active and reactive power can be controlled.

Leading and lagging power factors can be achieved by overexciting or underexciting the rotor of the DFIG. When overexcited, the DFIG rotor provides VArs to the utility similar to a synchronous generator. Underexcitation causes the absorption of VArs. By control of the PEC output voltage with respect to the grid voltage, the PEC appears as a generator or absorber of reactive power. Since the frequencies keep on changing, for every change in wind speed, there is a separate torque–speed characteristic of the DFIG (see Figure 8.3). The stator carries the grid frequency current.

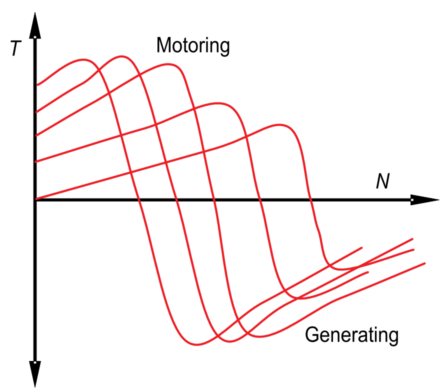


Figure 8.3 **Torque–Speed Characteristics of DFIG:** For every change in frequency, there will be a separate torque–speed characteristic.

In the event of a grid disturbance, since there is a direct connection of the DFIG stator to the grid, undesirable stator dynamics may arise leading to excessive torque

transients on the gearbox and slow speed shaft. The rotor windings carry the slip frequency currents. Only the power flow from the rotor windings of the DFIG is converted by a PEC and fed to the grid.

The active power P always goes out from the stator and is put into the grid, independent of the operation state either supersynchronous or subsynchronous, whereas the rotor absorbs power when operating as motor (at subsynchronism) and delivers it when operating as a generator (at supersynchronism).

The reactive power operational point of rotor-side converter (RSC) and grid-side converter (GSC) of the PEC are fully decoupled so that the reactive power Q (which is finally provided to the grid) can be independently controlled by the GSC. The PEC uses vector control techniques for decoupling the mechanical and electrical rotor frequencies from the grid network so that the electrical stator and rotor frequencies can be matched, independent of the mechanical rotor speed, thereby controlling both active and reactive power.

In case of a weak grid, where the voltage may fluctuate, the DFIG may be commanded to produce or absorb an amount of reactive power to or from the grid. This has important consequences for power system stability and allows the machine to remain connected to the electrical grid during severe voltage disturbances also.

The basic aim of Type-C WPP control system is to:

- Control the WPP speed (refer Figure 6.12) for maximum power point tracking (MPPT).
- Limit the power in case of high wind speeds.
- Control the reactive power interchanged between the WPP generator and the grid.

8.2.2 Subsynchronous Operation

The PEC enables the DFIG to generate power because it has a bidirectional power flow. At positive slips, during lower than rated wind speeds, the DFIG is said to operate at subsynchronous speeds (see Figure 8.4). It behaves as if a negative resistance is inserted into the rotor circuit to fulfil the energy deficit, i.e., the PEC borrows power from the grid for the under speed rotor, which it passes onto the stator, still allowing the stator to feed the network at the same frequency. The borrowed power along with the slow speed shaft energy passes into the stator that is connected to the grid, as if the stator appears to be supplying 130% of the power to the grid. It is seen that the generator rotor has borrowed 30%, leaving the line with 100% for the theoretical lossless DFIG. When the power flow is in the reverse direction, the grid side PEC acts as a converter and the rotor side PEC acts as an inverter.

8.2.3 Supersynchronous Operation

When the wind speeds up the rotor beyond the rated speed, the DFIG is said to operate at supersynchronous speeds. The extra power is then spilled away by pitching the rotor blades out of the wind. Simultaneously, the PEC in the rotor

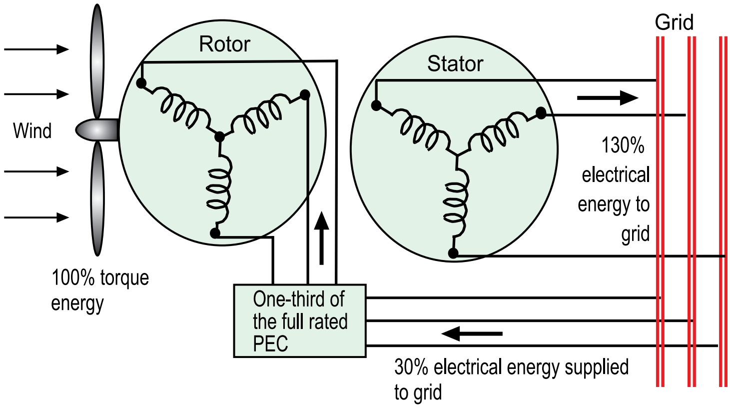


Figure 8.4 Type-C WPP Subsynchronous Speed Operation: Here the stator appears to be supplying 130% of power to the grid. Note that the generator rotor has borrowed 30%, leaving the line with 100% for the theoretical lossless DFIG.

circuit compensates the difference between the mechanical and electrical frequency of the WPP by injecting a current into the rotor circuit with a variable frequency. In this mode, the stator of the DFIG delivers the power directly to the grid (see Figure 8.5).

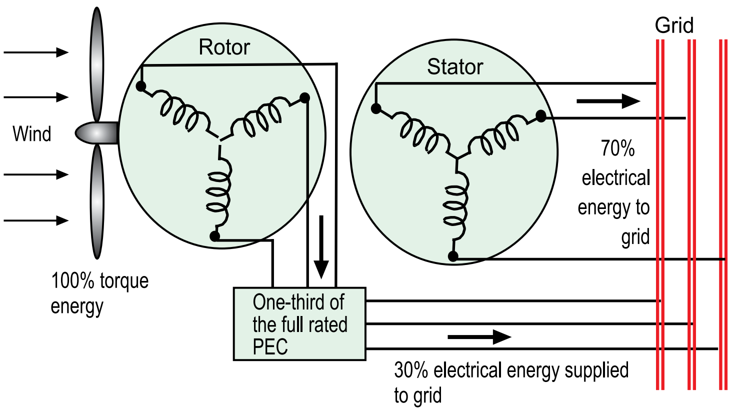


Figure 8.5 Type-C WPP Supersynchronous Speed Operation: Unlike the WRIG where 30% of the energy is wasted as heat in the rotor circuit, in DFIG, this slip power is fed to the grid through the PEC.

At the same time, power also flows from the DFIG rotor to the grid through PEC, i.e., behaves as if positive resistance is inserted. In this condition, the grid side controller works as a converter (refer Figure 8.2) recovering the slip power from the rotor side controller which works as an inverter supplying power to the grid. At supersynchronous mode, both the stator and rotor powers add up to convert the mechanical power to the electrical power.

Neglecting losses, the rotor power handled by the PEC can be represented as:

$$P_{\text{rotor}} \approx -sP_{\text{stator}} \text{ (negative sign is for supersynchronous speed)} \quad (8.2)$$

If P_{grid} is the total power from the DFIG to the grid, then:

$$P_{\text{grid}} = P_{\text{rotor}} + P_{\text{stator}} = P_{\text{stator}} - sP_{\text{stator}} = P_{\text{stator}}(1 - s) \quad (8.3)$$

Mechanical power is represented as:

$$P_{\text{mech}} \approx -P_{\text{rotor}}(1 - s)/s = P_{\text{stator}} + P_{\text{rotor}} \quad (8.4)$$

Higher the slip, larger will be the electrical power that is either absorbed or delivered through the DFIG rotor. The operation modes and power signs of a DFIG at subsynchronous and supersynchronous speed are given in Table 8.1.

Table 8.1 DFIG Operation Modes and Power Signs

Slip	Operation Mode	P_{mech}	P_{stator}	P_{rotor}
$0 < s < 1$ Subsynchronous	Motor	< 0	< 0	> 0
	Generator	> 0	> 0	< 0
$s < 0$ Supersynchronous	Motor	< 0	< 0	< 0
	Generator	> 0	> 0	> 0

8.2.4 Back-to-Back PEC in Type-C WPP

The DFIG rotor connected to the grid through a three-phase, variable frequency, bidirectional, back-to-back, four-quadrant PEC, discussed in Section 6.6 (refer Figure 8.2) is controlled by vector controlled techniques. To include a limited operating range between the subsynchronous and supersynchronous speeds for DFIG, PEC operates in all four quadrants, as the rotor power flows bidirectionally depending upon the operating speed. The DFIG stator current is regulated by controlling the output current from the rotor PEC. The DFIG stator side voltage V_s and frequency f_s match with the grid voltage V_g and grid frequency f_g. It is assumed that the voltage drop across the stator resistance and leakage reactance is negligible.

The frequency fed to the rotor winding is proportional to the slip times the stator frequency and the voltage across the rotor windings is determined by the stator voltage, slip and the turns ratio of the rotor to stator winding. The variable rotor voltage V_r at variable rotor frequency f_r on the rotor side is converted by the partial rated PEC to electric power compatible to the grid voltage of V_g at constant frequency f_g.

The reactive power in the rotor circuit is controlled to zero so that any reactive power exchange is done only through the stator. Since rotor flux tracks the stator flux, air gap torque provides no damping of shaft oscillations and an additional modulating signal needs to be added. With the RSC, it is possible to control the speed of the generator, the stator-side reactive power and hence, the power factor at the stator terminals. In normal operation, the RSC independently controls the active and reactive power on the grid.

The PEC in the rotor circuit of the DFIG has a four-quadrant operation. So, it can control the reactive power in either capacitive or inductive quadrant. This can be achieved by changing the firing angle of the RSC relative to the stator field and hence, the device has the ability to dynamically generate and absorb reactive power.

The RSC consists of active elements such as IGBTs. The firing angle delay of the RSC controls the phase difference between the injected rotor phase voltage and the rotor current. The voltage phasor is so controlled that the electric frequency of the rotor circuit corresponds to the desired RPM of the rotor. The manipulations of the magnitude and phase of the injected rotor currents provide power factor control. By controlling the frequency delivered to the rotor circuit, it is possible to keep the frequency of DFIG on a stable level, independent of the generator's speed.

The GSC generates or absorbs reactive power. The route of the reactive power from the generator to the grid is only through the stator. The stator power factor is typically set at unity. This is accomplished by controlling the magnetising component of the rotor current through PEC. The firing angle delay of the GSC dictates the injected voltage into the rotor circuit.

8.2.5 Type-C WPP and Grid Faults

Since stator of a DFIG is directly connected to the grid, large grid disturbances can lead to large fault currents in the stator. The present grid codes require the DFIG to remain grid connected during grid faults so that they can contribute to the stability of the power system.

When a fault occurs in a type-C WPP, the flux of the DFIG stator cannot follow the sudden stator voltage variation. The integral term is reduced and the stator flux becomes nearly stationary and cannot follow the sudden change in stator voltage and a DC component in the stator flux appears. Transients in the voltage on the stator side cause flux oscillations resulting in torque pulsations, if large, can result in mechanical stresses in the drive train. The rotor torque oscillations also cause power oscillations through the DC link of PEC.

Due to the magnetic coupling between the stator and the rotor and because of the laws of flux conservation, the stator disturbance is further transmitted to the rotor inducing high voltages in the rotor windings causing high currents in the rotor circuits which can damage the highly current sensitive PEC. Moreover, following a fault, there is sudden inrush of power from the rotor terminals towards the PEC and it might not be possible to achieve the desired rotor voltage (for which it is designed). This means that the PEC reaches its limits quite quickly and as a result, it loses the control of the DFIG during the grid fault.

Since the PEC in the rotor circuit is designed for a particular rating, adequate protection is provided to limit the rotor side current to a predetermined value. If the current rises above set value, the protective crowbar circuit in the rotor is activated to short circuit the rotor winding at the slip rings with a static switch and then, the DFIG operates as an ordinary induction generator. In case, the voltage at the DFIG terminals decreases rapidly may be during a grid fault, then to avoid overspeeding of WPP, the speed reference for the pitch control is reduced simultaneously so that the

pitch angle is increased and the mechanical power input to the generator is reduced considerably. Another technique of rotor speed protection is to disconnect WPP from the grid if rotor speed is higher or lower than set levels for a predefined time.

As the PEC is very sensitive to overcurrents, it is difficult to ride through voltage dips, as the higher voltage and current in the rotor circuit may damage the PEC if not rated slightly higher than the rated power. Therefore, after a certain designed limit, crowbar protection circuits are used to bypass the PEC during voltage dips; but then considerable mechanical stresses are experienced by the drive train. When the PEC is bypassed, it behaves same as a WRIG.

8.3 EQUIVALENT CIRCUIT OF DFIG IN TYPE-C WPP

It is important to note that the three-phase asynchronous machine equations are often transformed into direct and quadrature (d–q) axis as well, in order to develop nth order models for specific applications whereby higher order models are used for studies requiring high degree of accuracy. Lower order models are used for simplicity and are achieved after certain conditions and assumptions. The transformation into two-phase components and subsequently rotating all variables into a synchronous (d–q) reference frame enables linking of the synchronous frame to the stator or rotor flux of an induction machine and is also used in vector control.

Some form of modelling needs to be done to ascertain these torsional oscillations, as they may influence the PEC operations both during grid faults and for a short while after the grid faults have been removed. Figure 8.6 illustrates the generic model of a type-C WPP. The choice of software is often driven by the appropriateness of the application, its availability and past experience with the software. For studying effects of power generation by a WPP connected to the grid, the most widely used simulation software are the DIgSILENT® PowerFactory, PSCAD®, PSS/E®, MiPower and MATLAB® with SimPower Systems.

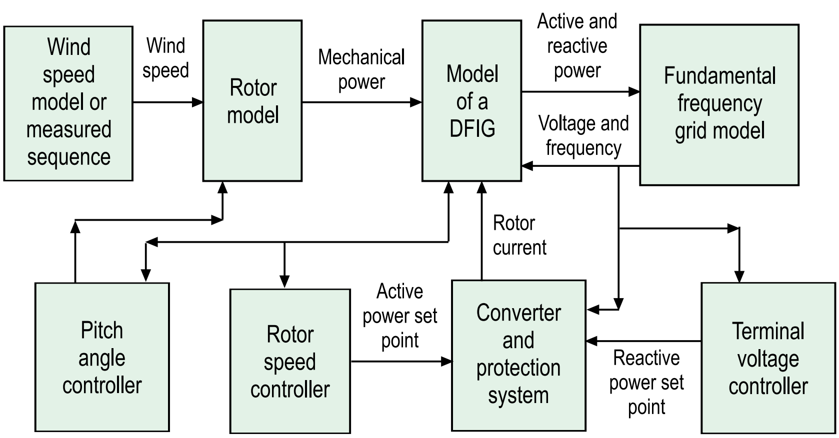


Figure 8.6 Generic Model of Type-C WPP.

Based on the concept of a rotating reference frame and projecting currents on such a reference, such projections are referred to as d-axis and q-axis components. In flux-based rotating frames, changes in the:

- d-axis component of current lead to the changing of reactive power
- q-axis component vary the active power.

This allows independent control of active and reactive power of the stator implemented through RSC control, an important aspect of the DFIG concept.

DFIG can be represented electrically by an equivalent circuit (see Figure 8.7). The PEC influence represented by the varying rotor voltage ($V'_r/s\omega$) which is a function of slip s, is added to the common T circuit of the SCIG. This equivalent circuit includes the magnetisation losses and is valid for one equivalent star (Y) phase and for steady state calculations. In case of a delta (Δ) connected DFIG, it can be represented by an equivalent star (Y) representation.

The slip$s$ of the DFIG is given by:

$$s = \frac{\omega_1 - \omega_r}{\omega_1} = \frac{\omega_2}{\omega_1} \tag{8.5}$$

where,

ω_1 = Stator frequency
ω_r = Rotor speed
ω_2 = Slip frequency.

Applying Kirchhoff's voltage law in Figure 8.7 and using $X_s = j\omega_1 L_{s\lambda}$ and $X_r = j\omega_1 L_{r\lambda}$, give the following equations:

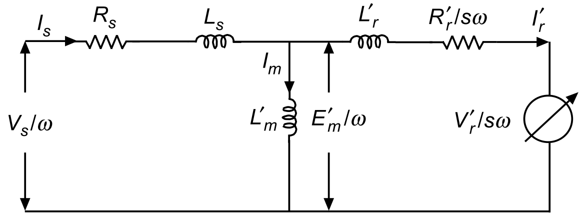
$$V_s = R_s I_s + j\omega_1 L_{s\lambda} I_s + j\omega_1 L_m(I_s + I_r + I_{rm}) \tag{8.6}$$

$$\frac{V_r}{s} = \frac{R_r}{s} I_r + j\omega_1 L_{\mathrm{r}\lambda} I_{\mathrm{r}} + j\omega_1 L_m(I_s + I_{\mathrm{r}} + I_{\mathrm{m}}) \tag{8.7}$$

$$0 = R_m I_{rm} + j\omega_1 L_m(I_s + I_r + I_{rm}) \tag{8.8}$$

where,

V_s = Stator voltage
I_s = Stator current
R_s = Stator resistance
ω_1 = Stator frequency
V_r = Rotor voltage
I_r = Rotor current
R_r = Rotor resistance
R_m = Magnetising resistance
s = Slip
$L_{s\lambda}$ = Stator leakage inductance
$L_{r\lambda}$ = Rotor leakage inductance
I_{rm} = Magnetising resistance current
L_m = Magnetising inductance.



R_s = Stator resistance
L'_m = Magnetising inductance
R'_r = Rotor resistance
s = Slip
V_s = Stator voltage
$V'_r/s\omega$ = Varying rotor voltage
I_m = Magnetising current

L_s = Stator inductance
L'_r = Rotor inductance
$s\omega$ = Slip frequency
I_s = Stator current
I'_r = Rotor current
$E'_m/s\omega$ = Varying generated voltage

Figure 8.7 Equivalent Circuit of DFIG Referred to Stator Side.

Furthermore, if the air gap, stator and rotor fluxes are defined as:

$$\psi_m = L_m(I_s + I_r + I_{rm}) \tag{8.9}$$

$$\psi_s = L_{s\lambda}I_s + L_m(I_s + I_r + I_{rm}) = L_{s\lambda}I_s + \psi_m \tag{8.10}$$

$$\psi_r = L_{r\lambda}I_r + L_m(I_s + I_r + I_{rm}) = L_{r\lambda}I_r + \psi_m \tag{8.11}$$

where,

ψ_m = Air gap flux
ψ_s = Stator flux
ψ_r = Rotor flux.

Then, Eqs. (8.6) to (8.8) become:

$$V_s = R_sI_s + j\omega_1\psi_s \tag{8.12}$$

$$\frac{V_r}{s} = \frac{R_r}{s}I_r + j\omega_1\psi_r \tag{8.13}$$

$$0 = R_mI_{rm} + j\omega_1\psi_m \tag{8.14}$$

The stator flux of the DFIG can also be determined by the following expression:

$$\psi_s = \psi_{s0} + \int_0^t (V_s - R_sI_s)dt \tag{8.15}$$

After determining the apparent and active power that is fed to the DFIG through the stator and rotor circuit, the mechanical power produced by the DFIG can be determined.

8.4 SALIENT FEATURES AND LIMITATIONS OF TYPE-C WPP

The positive features of type-C WPP are substantial, as compared to the constant speed WPPs. These are as follows:

(i) While the WPP varies in speed due to the varying wind speed, the control of the rotor voltage enables the DFIG to remain synchronised with the grid.
(ii) The DFIG must not necessarily be magnetised from the electrical grid; it can be magnetised from the rotor circuit too.
(iii) The DFIG with a four-quadrant converter in the rotor circuit enables decoupled control of active and reactive power of the generator.
(iv) As the rotor voltage is controlled by a PEC, the DFIG is able to import and export the reactive power, thus providing the necessary reactive power compensation for smoother grid connection.
(v) The PWM-based PEC also contributes to frequency regulation.
(vi) DFIGs are increasingly equipped with grid fault-ride-through capabilities and have the ability or potential to contribute passively and actively to manage under frequency events on the grid.
(vii) It contributes to the overall power system inertia, as the machine stator windings are still grid connected.
(viii) Flicker problems are limited to a great extent, as there is smoothing of power output.
(ix) System efficiency is improved due to the low rating of the PEC and the losses are also less.
(x) There is a lesser acoustical noise.
(xi) When compared to synchronous generators, more or less standard off-the-shelf WRIGs can be used to convert them to DFIGs.
(xii) PEC cost is quite low, as it is typically rated at 0.35 p.u. only while the speed range is around ±40% of the synchronous speed.

Type-C WPP has its share of demerits too which are given below:

(i) It still requires a gearbox in the drive train which is often a weak link of any geared WPP as far as maintenance is concerned.
(ii) The grid fault issue remains compounded by the fact that a fault would induce a large voltage in the rotor which could potentially damage it.
(iii) The dynamic behaviour of the WPP in case of grid disturbances (especially with crowbar in rotor circuit) is still complex and difficult to predict exactly (although dynamic modelling is done) the torques, speed and grid impact for every situation.
(iv) Electrical losses in the PECs are also not quite less.
(v) It requires high power slip rings and brushes which can get damaged by stray currents induced in the rotor shaft. Brushless doubly-fed induction generator (BDIG) avoids the use of slip rings.

8.5 TYPE-D WPP

The greatest asset of type-D WPPs is that they can operate over a wide range of wind speeds, about 2.5 times the rated wind speed. Their output power from the stator terminals of the electric generators are either grid compatible due to the hydrodynamic gearbox arrangement (see Figure 8.8 and refer Figures 8.18 and

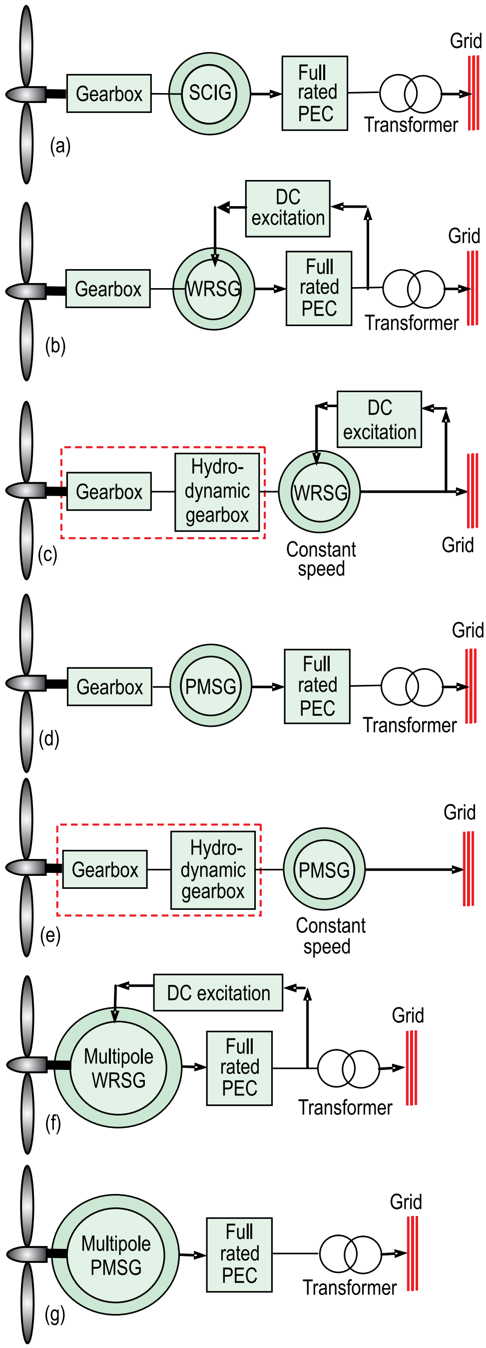


Figure 8.8 Comparison of Type-D WPP Topologies.

8.21) or they are made grid compatible by transforming all the power generated in the full rated PEC into sinusoidal output power of constant voltage and constant frequency, as required by the grid operators. Such generators provide the requisite reactive power compensation as and when required along with voltage and frequency regulation. These electric generators have inherent high power factor, as it does not draw any magnetising emf from the electric grid.

In type-D category also, there are different topologies (see Figure 8.8), each having a different working principle with their merits and demerits. These are as follows:

(i) Type-D geared WPP with variable speed SCIG and full rated PEC.
(ii) Type-D geared WPP with variable speed WRSG and full rated PEC.
(iii) Type-D hydrodynamically geared WPP with constant speed WRSG.
(iv) Type-D geared WPP with variable speed PMSG and full rated PEC.
(v) Type-D hydrodynamically geared WPP and constant speed PMSG.
(vi) Type-D direct-drive WPP with variable speed WRSG and full rated PEC.
(vii) Type-D direct-drive WPP with variable speed PMSG and full rated PEC.
(viii) Type-D hybrid (semi-geared) WPP with variable speed PMSG and full rated PEC.

Typically, in a full calendar year, for most of the time, the WPPs operate under partial load conditions due to the varying wind speeds. It is also observed that in a full rated WPP, the combined generator and PEC losses are higher in type-D WPP as compared to a DFIG having a one-third rated PEC. Hence, the choice of any particular type of WPP is a question of actual grid conditions and wind farm conditions coupled with economics.

Since the variable speed full rated PEC is common with many topologies, its working principle is first discussed.

8.5.1 Full Rated PEC in Type-D WPP

Unlike the one-third of the full power rated PEC of DFIG, the full power from the stator of the generator of a type-D WPP is fed into the full power rated VSI-based back-to-back PEC operating in the four-quadrant mode, allowing maximum speed variability and grid compatibility. The PEC in type-D WPPs that carry the full power has following three primary functions:

- PEC, as an energy buffer for the WPP rotor side, prevents the power fluctuations caused by the gusty wind energy from reaching the electric generator.
- It prevents disturbances from the grid side from reaching the generator.
- It controls the magnetisation of the generator and to avoid problems keeps it synchronous with the grid frequency.

At higher wind speeds, the speed controller permits a dynamic variation of the generator speed in order to avoid mechanical stresses in the drive train while the PEC keeps adjusting the power to the rated level. The PECs generally use *vector control techniques* for decoupling and controlling both active and reactive power as

the entire power harnessed by the WPP passes from the stator of the synchronous generator into the PEC.

Due to the presence of fully rated PEC, whenever there is an abrupt reduced power demand resulting in the sudden frequency increase, the WPP reacts by withdrawing the power feed to adjust to the reduced power absorbing capacity of the grid. This has a stabilising effect which is especially conspicuous on weak grids.

The GSC ensures decoupling of stator side active and reactive power. The GSC controls the rotor speed and thus, the power too by means of the generator current. It also controls the amplitude and frequency of the generated voltage, independent of the grid characteristics and are therefore, not necessarily the same as the grid frequency. The PEC regulates the electromagnetic torque to optimise the aerodynamic efficiency C_p of the wind turbine rotor enabling MPPT by varying pitch settings for maximising energy capture and thus, increasing the electric power quantity and reliability of the generator with wide speed range operation.

The DC-link capacitor serves as a buffer between the generator and the grid and contributes to the damping process. If small variations of the DC voltage are allowed, speed and torque oscillations can be absorbed by charging and discharging of the capacitor. Thus, the damping provides a reference signal for the DC-link voltage controller of the GSC.

The GSC controls the grid current. The function of the GSC is to keep the DC-link voltage constant and to maintain a unity power factor for the power flow between the generator and the grid, thus allowing for the control of real and reactive power transferred to the grid. In case of a grid fault, the excess power produced by the generator can be controlled by means of a chopper circuit that maintains the DC-link voltage constant. As this field current is increased, the generator passes from the consuming (VArs) status to the producing (VArs) status.

8.6 TYPE-D GEARED WPP WITH VARIABLE SPEED SCIG

In early 1990s, for the first time, *Kenetech* demonstrated how SCIGs in WPPs can be operated to harness energy from a wide range of variable wind speeds. When the SCIG is adapted for wide range variable speed operation, the stator winding is not connected directly to the grid (see Figure 8.9) but indirectly through VSI-based PECs. Another feature is that this wind turbine rotor rotated in anticlockwise direction, i.e., against the standard clockwise rotation of WPPs. The other features of this topology are as follows:

(i) The SCIG is quite rugged requiring less maintenance.
(ii) The power factor can be controlled over a wide range.
(iii) Wind gusts can, not only be buffered due to the mechanical inertia, but also in the energy storage of the intermediate PEC.
(iv) The PEC is of a more complex design with relatively higher costs.

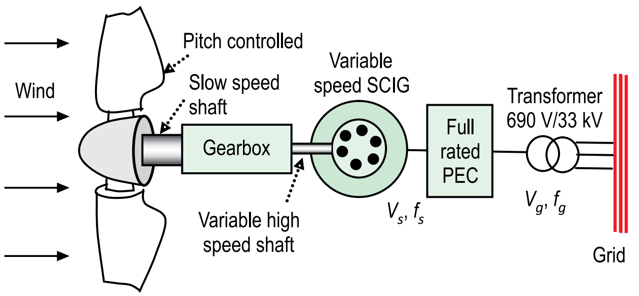


Figure 8.9 **Type-D Geared WPP with Variable Speed SCIG:** Since this WPP has SCIG, it is more rugged. The full rated PEC treats the variable voltage and variable frequency output power to render it grid compatible.

Presently, there are some manufacturers adapting the variable speed SCIG in WPPs like RRBEnergy PS-1800 kW (see Figure 8.10).

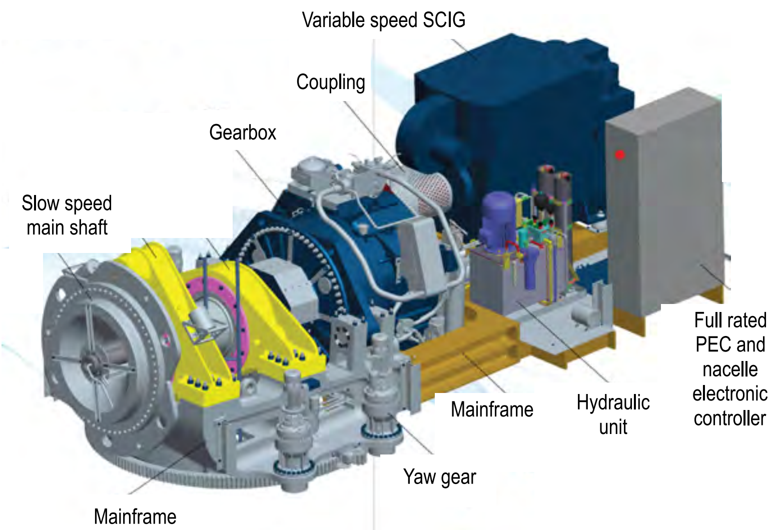


Figure 8.10 **Type-D Geared WPP with Wide Range Variable Speed SCIG–1800 kW.** *Courtesy:* www.rrbenergy.com

8.6.1 Working Principle

The slow speed shaft of the wind turbine rotor connects the planetary gearbox. The high speed shaft connects the gearbox and the SCIG. A back-to-back PEC (working principle already discussed in Section 8.2.4) in the stator circuit is employed to manipulate the rotating magnetic field and change the frequency, rendering the power to be grid compatible at constant voltage and frequency.

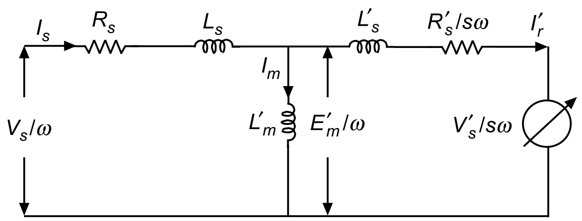
Decreasing the frequency of the current fed to the SCIG decreases the reactance X_L, thereby increasing the stator current. This may cause the stator magnetic circuit to saturate with disastrous results. For speed control, the supply voltage must increase in step with the frequency, otherwise the flux in the machine deviates from the desired optimum operating point. In other words, if the flux density B is to be constant, the volts/hertz (V/f) must also be constant. In practice, the voltage across SCIG needs to be decreased when the frequency is decreased. This is also called the *flux weakening region*. However, the voltage also needs to be increased to overcome increasing reactance X_L to keep the current upto a normal value and maintain the torque. This is known as *V/f control,* the principle on which wide range variable speed SCIGs are designed to operate.

The speed control of SCIG can be achieved through *scalar control* (which generally adapts relatively simpler and lower cost methods to control only voltage and frequency without feedback) or the *vector control* where the flux and torque producing components of the stator current are measured or estimated on a real-time basis to enhance the torque–speed curve. This control also allows the power factor of the grid to be controlled independently.

The significant benefit of this topology is that the PEC decouples the SCIG and releases the frequency of the rotating magnetic field from the grid frequency and then, the frequency of the rotating magnetic field is modulated to control the rotating speed of the rotor.

8.7 EQUIVALENT CIRCUIT OF VARIABLE SPEED SCIG OF TYPE-D WPP

The equivalent circuit of a constant speed SCIG referred to the stator side has been discussed in Section 7.3 Figure 7.7. Over here, the voltage source and the parameters of the SCIG are divided by the electrical angular frequency ω and an equivalent circuit (see Figure 8.11) is obtained, for a variable speed SCIG.



R_s = Stator resistance
L'_m = Magnetising inductance
$E'_m/s\omega$ = Varying generated voltage
s = Slip
V_s = Stator voltage
I_m = Magnetising current
R'_s = Rotor resistance

L_s = Stator inductance
L'_S = Rotor inductance
$s\omega$ = Slip frequency
I_s = Stator current
I'_r = Rotor current
ω = Rotor resistance
$V'_S/s\omega$ = Varying rotor voltage

Figure 8.11 Equivalent Circuit of Variable Speed SCIG Referred to Stator Side.

Figure 8.12 depicts the performance characteristics of a variable speed SCIG. At high frequencies, ω is large enough that the R_s/ω is negligible. Thus, the torque–speed characteristics can be drawn as a set of curves shifted with frequency. In the lower frequency region, R_s/ω cannot be neglected because as it increases, ω decreases. V_s/ω is constant to get the desired torque–speed characteristic of the SCIG. But, in the lower frequency region, V_s/ω is boosted a little to compensate for the changes in R_s/ω.

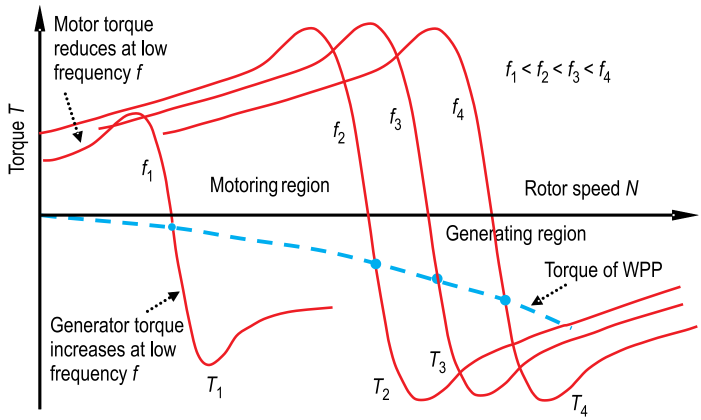


Figure 8.12 **Typical Variable SCIG Torque–Speed Characteristics for Constant *V/f* Operation:** By keeping the *V/f* constant in a SCIG, the machine can be run at wide range variable speed, even if the RPM keeps on changing (hence the frequency) due to the changing wind speeds.

8.8 TYPE-D GEARED WPP WITH VARIABLE SPEED WRSG

If the WPPs operate in a wider range of wind speeds, then greater electrical power can be harnessed and therefore, type-D WPPs with wound rotor synchronous generators (WRSG), pioneered by *Enercon* (Germany) in early 1990s became popular. The synchronous generator consists of a stationary stator and a magnetic field on the rotor. The stator carries three separate (three-phase) armature windings physically distributed around the stator and electrically displaced from each other by 120° for producing an AC voltage output. The rotor's magnetic field system (excitation) is created by the rotor windings energised electromagnetically by the external DC flowing through them. Geared type-D WPP with WRSG can have following different configurations:

(i) Type-D geared variable speed WPP with variable speed four-pole WRSG, e.g. 2.5 MW Kenersys K100 model (see Figure 8.13).
(ii) Type-D hydrodynamically geared variable speed WPP with constant speed four-pole WRSG, e.g. 500 kW Windflow 500 model (refer Figure 8.17).

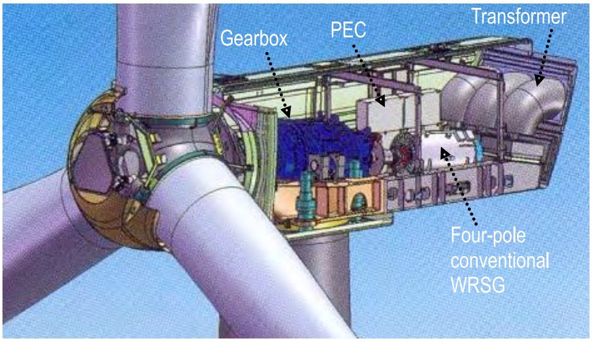


Figure 8.13 **Type-D Geared WPP Variable Speed with WRSG:** Four-pole variable speed WRSG with full rated PEC and a step up transformer is used for grid compatibility.
Courtesy: www.kenersys.com

8.8.1 Working Principle

Type-D WPP is mounted with a gearbox and a wide range variable speed WRSG (see Figure 8.13) to operate in a very large range of wind speeds. The advantage of this configuration is that the conventional planetary gearbox used in WPPs can be connected to a relatively much smaller high speed conventional off-the-shelf available four-pole WRSG. The WRSG in Type-D WPP is separately excited and fully decoupled from the grid by a full rated PEC.

The control of a typical Type-D1 (see Figure 8.14) WPP is achieved by the coordinated action of two controllers simultaneously—the aerodynamic power controller for pitching the blades and an electric generator speed controller, i.e., the PEC to control the electric generator speed.

Due to the stochastic nature of the wind, the power output from the WRSG (or alternator) is a variable voltage V_s, variable frequency f_s that is treated by the full power rated PEC for grid compatible voltage V_g and frequency f_g. The working of the PEC in this type of WPP has been discussed earlier in section 8.5.1.

The active power is given by:

$$P = |V|\,|I|\,\cos\theta \tag{8.16}$$

where,

θ = Angle between voltage and current, i.e., $\theta = \angle V - \angle I$. The word *lead* means θ is negative and current is leading the voltage.

The reactive power is given by:

$$Q = |V|\,|I|\,\sin\theta \tag{8.17}$$

A WRSG consists of a rotor windings, slip rings and brushes which creates the magnetic field and a stator comprising of three-phase windings. The electromagnets of the rotor winding are excited by an external DC supply through slip rings and brushes or by a brushless exciter (with rotating diode bridge mounted on the shaft) that generates the necessary excitation field. When the wind rotates the wind turbine rotor, the DC excited electromagnets also rotate and sweep past the stationary

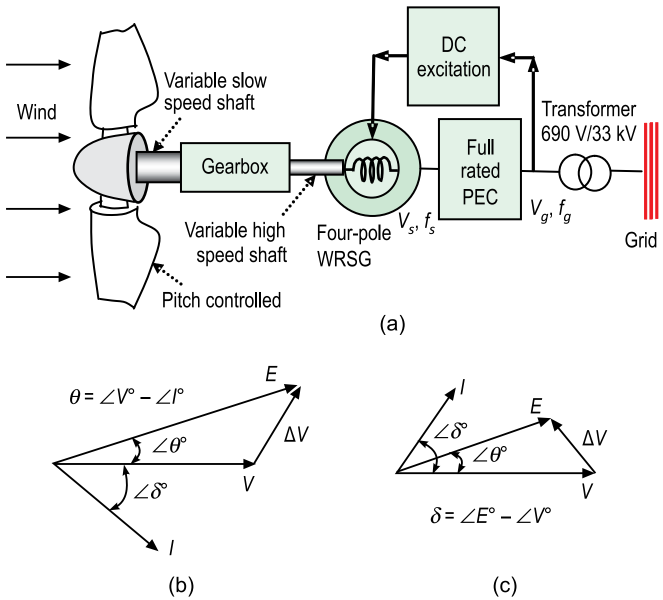


Figure 8.14 Type-D Geared WPP with WRSG and Phasor Diagram: (a) Due to the gearbox, a conventional topology four-pole WRSG with a separately excited field winding operating in wide range of wind speeds is used. The variable output power is fed into a full rated PEC connected to a step-up transformer, (b) Phasor diagram when overexcited, (c) Phasor diagram when under excited.

stator conductors to induce a triad of alternating voltages in the stator windings with the RMS value proportional to the magnetic flux of the rotor and the RPM.

The generated voltage $|E|$ is produced due to the continuous current I_r flowing in the rotor field winding and the rotor magnetic field ($\phi = k_r I_r$) which is controlled by the control system.

$$E \propto \phi N$$

$$E = k_s \phi f \qquad \text{(since } N = 120f/p\text{)} \qquad (8.18)$$

where,

ϕ = Flux density
f = Frequency (50 Hz)
p = Number of poles
N = RPM
k_s = Constant.

Alternatively, by keeping the active power P fixed when N and consequently, the frequency f and the generated voltage E vary, the delivered current changes (see Figure 8.15). If the induced voltage E exceeds the grid voltage V, the synchronous generator (alternator) provides the reactive power and if the induced voltage is lower than the grid voltage, then the alternator absorbs reactive power.

If the field current is increased, then $|E|$ must also increase. If the active power P is fixed by the prime mover (here, the wind), then sin δ (refer Figures 8.14 and

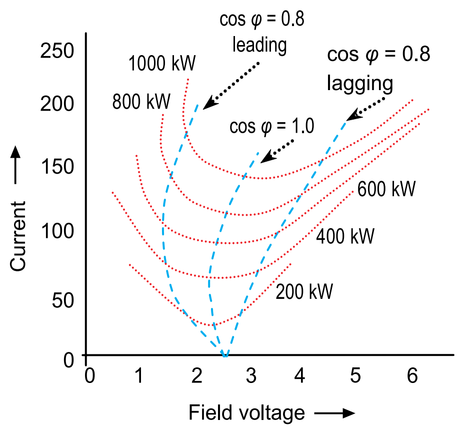


Figure 8.15 Currents in Synchronous Generator.

Eq. 8.19) will cause the reactive power Q to increase. A decrease in $|E|$ causes Q to decrease, eventually becoming negative. This shows that a synchronous generator can work in an independent mode as well as inter-tied with the grid network. The stator current is limited by the cooling provided to overcome the stator winding losses.

The interaction of the rotor's magnetic field with the stator's magnetic field generates a torque on the shaft. Torque is determined by the air gap field B and the stator current. The load angle δ of the generator is the angle between the rotating magnetic field of the stator and the magnetic field of the rotor. The torque of the generator is a function of load angle. At no load, this load angle is generally zero. If the two magnetic fields are aligned ($\delta = 0$), there is no resistive torque and consequently, the active power provided to the grid is zero. Changes in the load cause the load angle δ to advance or drop back a few degrees from the rotating magnetic field of the stator supplied by the grid.

If there is a displacement due to an external motive torque (the wind in this case), a resistive electrical torque is generated balancing the active power supplied to the grid (then, $\delta > 0$). The greater the deviation in δ from zero, the more will be the active power supplied to the grid. The saliency of the rotor poles provides an added torque and a stiffer machine operation. By keeping the angle δ fixed, the active power supplied to the grid increases linearly with the RMS value of the induced voltage and therefore, proportionally to the RPM of the WPP as well as to the voltage and frequency. The active power P and reactive power Q supplied are also given by:

$$P = \frac{|E||V|}{X_s} \sin \delta \text{ W/phase} \tag{8.19}$$

$$Q = \frac{|E||V| \cos \delta - |V|^2}{X_s} \text{ VAr/phase} \tag{8.20}$$

where,

E = Generated voltage

V = Grid voltage

δ = Load angle.

For the plot of P versus δ (see Figure 8.16), the AC generator shows that if the mechanical input power increases, the output electrical power also increases, reaching a maximum at $\delta = 90°$, i.e., at $\sin \delta = 1$, and this is called the *pullout power*. If the mechanical input power is further increased from this point, the output power begins to droop causing a rapid increase in δ and a loss of synchronism. If a WPP operates near rated power and a sudden gust of wind causes the input power to exceed the pullout power from the generator, then the rotor accelerates above the rated speed by which large generator currents start flowing which may damage the generator but to avoid this, it is disconnected from the network. The rotor is then slowed down by pitching of the blades and the generator re-synchronised with the grid.

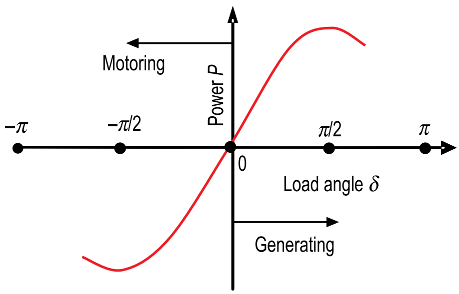


Figure 8.16 AC Generator Power Curve.

Another point to be noted in the curve is that the power becomes negative for negative δ, i.e., the machine starts behaving as a motor drawing current from the grid which speeds up the air passing through the rotor blades. Hence, when the wind speed drops below a critical value, the WPP is disconnected from the grid.

In type-D WPPs, load changes can excite oscillations which can be amplified and may require an external damping of the WPP. A damping controller is implemented which is necessary to damp torsional oscillations of the drive train system. Different damping methods are possible like blade pitching, damping by means of a compliant mounting of the generator or by electrical system, i.e., by means of back-to-back PEC.

The WRSGs are not intrinsically self-starting. They reach the synchronous speed by means of the prime mover (the wind in this case) and then, it is connected in parallel by a speed control system used for the synchronisation procedure. In applications, for which self-starting of the alternator is required, the rotor is equipped with dampening copper bars which start the alternator as an induction machine and during operation, dampen the dynamic oscillations of the machine.

EXAMPLE 8.1

A 1 MW type-D geared WPP with four-pole WRSG is rated at 1250 kVA, 0.8 power factor and 440 V line-to-line. The generator parameters are $R_s = 0.004$ Ω/phase and $X_s = 5.01$ Ω/phase. The generator delivers 900 kW at rated voltage and 0.9 power factor lagging. Find the rated current, phasor operating current, total reactive power, line to neutral phasor generated voltage E, load angle δ, three-phase ohmic losses in the stator and the pullout power.

Solution:

The per phase value of terminal voltage is:

$$|V| = \frac{440}{\sqrt{3}} = 254.04 \text{ V/phase}$$

Rated apparent power per phase is:

$$P_R = \frac{1250}{3} = 416.667 \text{ kVA/phase} = 41667 \text{ VA/phase}$$

The rated current is:

$$I_R = \frac{P_R}{V_R} = \frac{41667}{254.04} = 164.01 \text{ A}$$

Actual power being supplied to the grid per phase is:

$$P = \frac{900}{3} = 300 \text{ kW/phase} = 300 \times 10^3 \text{ W/phase}$$

Real power is defined as:

$$P = |V|\,|I| \cos\theta$$

So, the magnitude of the phasor operating current is:

$$|I| = \frac{P}{|V| \cos\theta} = \frac{300 \times 10^3}{254.04(0.9)} = 1312 \text{ A}$$

The angle θ is:

$$\theta = \cos^{-1} 0.9 = 25.84°$$

The phasor operating current is then:

$$I = |I| \angle{-\theta} = 1312\angle{-25.84°} = 1180.82 - j571.85$$

The reactive power supplied to the grid per phase is:

$$Q = |V|\,|I| \sin\theta$$

$$Q = 254.04 \times 1312 \times \sin 25.84°$$

$$= 254.04 \times 1312 \times 0.436 = 145319 \text{ VAr/phase}$$

The generator then supplies a total reactive power of 145.319 kVAr to the grid in addition to the total of 900 kW.

The total E is given by Kirchhoff's voltage law, i.e.,

$$E = V + IZ_s = 254.04\angle 0° + 1312\angle{-25.84°}(0.004 + j5.01)$$

$$= 254.04 + \{(1180.82 - j571.85)(0.004 + j5.01)\}$$

$$= 254.04 + 2869.69 - j5913.03$$

$$= 3123.73 - j5913.03$$

$$= 6687\angle 62.153°$$

Since the terminal voltage V is taken as the reference ($V = |V| \angle 0°$), the power angle is just the angle of E or 62.153°. The total stator loss is:

$$P_{\text{loss}} = 3I^2R_s = 3 \times (1312)^2 \times 0.004 = 20656.128 \text{ W} = 20.656 \text{ kW}.$$

Though this is a small fraction of the total power delivered to the grid, but still represents a significant amount of heat which must be transferred to the atmosphere by generator cooling system.

The pullout power (when $\sin \delta = 1$) is given by:

$$P = \frac{|E|\,|V|}{X_s} = \frac{6687 \times 254.04}{5.01}$$

$$= 339074.95 \text{ W/phase}$$

$$= 339.074 \text{ kW/phase.}$$

The total generator pullout torque will be 1017 kW (339.074 × 3).

If the input shaft power will rise above this pullout power due to a wind gust, the generator will lose synchronism with the grid network. However, in most of the systems, the pullout power is twice the rated power of the generator to prevent this possibility.

8.9 TYPE-D HYDRODYNAMIC GEARED WPP WITH CONSTANT SPEED WRSG

In this type of WPP, a special type of hydrodynamic gearbox (see Figure 8.17) is superimposed onto a planetary gearbox of a fixed gear ratio of 20–30. The hydrodynamic gearbox converts the slow moving variable speed of the wind turbine rotor to a constant high speed output connected to the conventional constant speed four-pole WRSG to provide grid compatible power. A main feature of this type of WPP is that the output power from the generator can be directly fed into the grid without a PEC.

8.9.1 Working Principle

This WPP consists of a hydrodynamic gearbox placed in the driveline of the wind turbine between the planetary gearbox and the generator. The wind turbine rotor is connected to a normal planetary gearbox which is superimposed by a hydrodynamic (fluid coupling) gearbox. This converts the varying input wind speed to a constant output speed. In this topology, the voltage V_g and frequency f_g (see Figure 8.18) of the generated electric power are grid compatible of constant voltage and constant frequency. Therefore, neither a PEC nor a step up transformer is required.

The planetary gearbox consists of a sun gear, planet gears and a ring gear. The planet gears are mounted on the rotating planet carrier. The wind rotor drives the rotating planet carrier through the main gearbox. The planet gears drive the sun gear, which in turn, drives the generator and the pump wheel of the torque converter

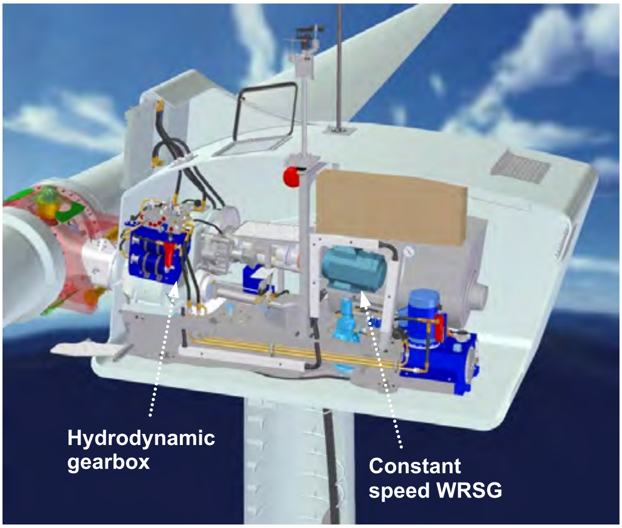


Figure 8.17 **Type-D Hydrodynamic Geared Variable Speed WPP:** The constant speed conventional WRSG produces a grid compatible electric power that can be directly fed into the grid due to the hydrodynamic gearbox.
Courtesy: www.windflow.co.nz

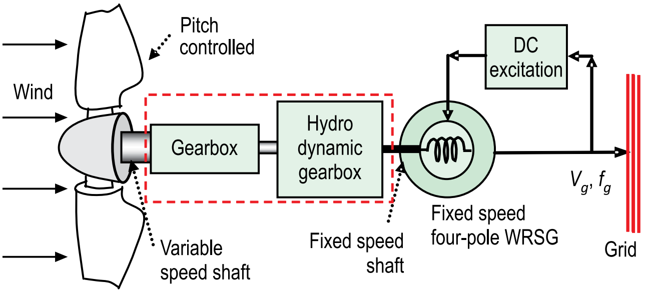


Figure 8.18 **Type-D Hydrodynamic Geared Variable Speed WPP with Fixed Speed WRSG:** The main gearbox is superimposed by a hydrodynamic gearbox which provides constant speed output to conventional four-pole WRSG directly connected to the grid, eliminating the need of an expensive PEC and transformer.

to get a constant RPM on the output shaft. The hydrodynamic subsystem stabilises the speed of the output shaft driving the generator. Control is effected with an adjustable guide vane within the hydrodynamic (fluidic) unit which amounts to a continuously controlling the variable speed gearbox.

Relying on fluid coupling, the subsystem is continuously variable and offers smooth speed regulation. Hence, the expensive full rated PEC and the transformer are not needed and the generator can be connected directly to the grid. The excellent damping characteristics of a hydrodynamic drive train prevent the system from damages. The modular assembly allows to adapt the system to a wide power range. A good efficiency can be achieved even at low wind speeds.

This combination of hydrodynamic gearbox and pitch control allows the WPP to be operated at rated power of around 12 m/s to 25 m/s with a constant power output. With this topology, relatively smaller off-the-shelf, conventional four-pole separately excited WRSG can be used. This results in a relatively lighter nacelle and tower, thereby lowering the cost. This variable ratio hydrodynamic gear drive comes in various designs and is called by various names by different manufacturers such as *Torque Limiting Gearbox* by Windflow of New Zealand, *Windrive* by DeWind and others.

8.10 EQUIVALENT CIRCUIT OF WRSG IN TYPE-D WPP

In type-D WPP with WRSG, the AC power is generated when the alternator rotates at synchronous speed which is represented by an equivalent circuit (see Figure 8.19). The speed of the wind turbine rotor is also regulated by the pitching mechanism of the blades depending on the wind speeds. The RPM of the synchronous generator depends on the frequency of the rotating magnetic field and the number of pole-pairs of the wound rotor.

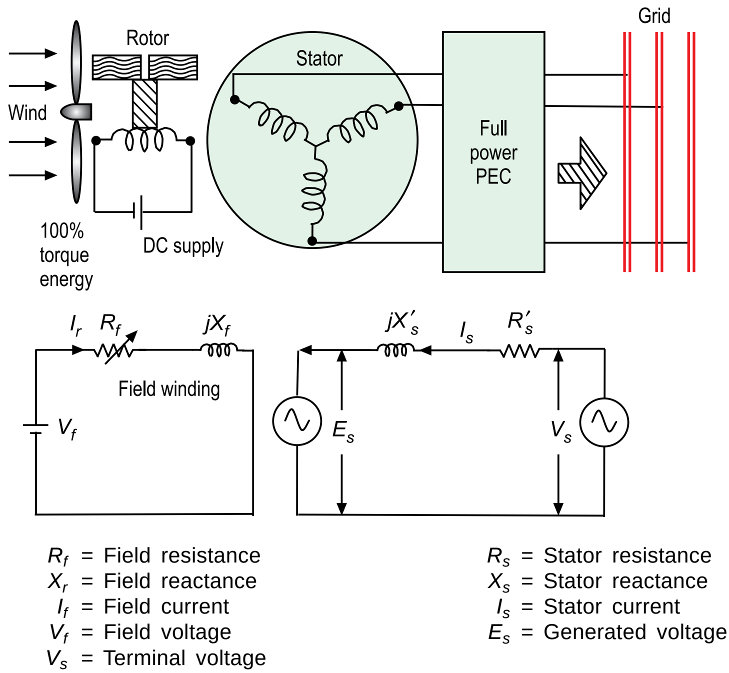


Figure 8.19 Type-D WPP Schematic and WRSG Equivalent Circuit.

By the use of appropriate software, the performance of this Type-D WPP with WRSG could be modelled.

8.10.1 Modelling of a WRSG in Type-D WPP

A three-phase WRSG has three identical armature windings (refer Figure 8.19) symmetrically distributed around the air gap and one field winding. One or more damper windings can also be present in the axis of each machine. Normally, the armature windings are placed on the stator whereas the field and damper windings are placed on the rotor. By using Eqs. (8.21), (8.22), (8.23) and (8.24), the WRSG could be modelled.

Basic stator equations are as follows:

$$v_a(t) = -R_a i_a(t) - d/dt\ \psi_a \tag{8.21}$$

$$v_b(t) = -R_a i_b(t) - d/dt\ \psi_b \tag{8.22}$$

$$v_{ca}(t) = -R_a i_c(t) - d/dt\ \psi_c \tag{8.23}$$

where,

v_a, v_b, v_c = Stator voltages of phase a, b and c
R_a, R_b, R_c = Resistance of stator windings of phase a, b and c
ψ_a, ψ_b, ψ_c = Stator fluxes of phase a, b and c
i_a, i_b, i_c = Stator currents in phase a, b and c

Basic rotor equations are given below:

$$v_f(t) = -R_f i_f(t) - d/dt\ \psi_f \tag{8.24}$$

$$0 = R_{d1}\ i_{d1}(t) + d/dt\ \psi_{d1} \tag{8.25}$$

$$0 = R_{q1}\ i_{q1}(t) + d/dt\ \psi_{q1} \tag{8.26}$$

$$0 = R_{q2}\ i_{q2}(t) + d/dt\ \psi_{q2} \tag{8.27}$$

where,

v_f = Rotor voltage
R_f = Rotor resistance
i_f = Rotor current
ψ_f = Rotor flux
d_1; q_1 = Damper (or amortisseur) windings
q_2 = Equivalent circuit to account for eddy currents in round-rotor machine no q_2 winding in the model of a salient-pole machine
ψ_d = d-axis flux
ψ_q = q-axis flux
R_d = d-axis resistance
R_q = q-axis resistance
i_d = d-axis current is constant during steady-state balanced operating conditions
i_q = q-axis currents is constant during steady-state balanced operating conditions.

8.10.2 Salient Features of Type-D Geared WPP with WRSG

The following are some of the positive features of geared type-D WPP with WRSG:

(i) Since they are designed for variable speed operation, the rotors of these WPPs can be operated for optimum TSR even at widely varying wind speeds, resulting in increased overall efficiency of WPP of more than one per cent.

(ii) Separately excited four-pole WRSG is a proven technology in conventional power plants.
(iii) Using a gearbox drastically reduces the size and mass of a generator.
(iv) The generator is fully decoupled from the grid by the full rated PEC.
(v) The four-pole synchronous generator may be dynamically controlled to run in one of the following three modes:
   (a) Voltage control mode (keeping terminal voltage constant at a fixed level)
   (b) Power factor (PF) control mode (usually set to near unity)
   (c) VAr control mode (allowing export/import of VArs).
(vi) The hydrodynamic torque converter (refer Figure 8.18) functionally decouples the mechanical gearbox output shaft from the electric generator input shaft and hence, minimises torsional vibrations and mis-alignment, if any.
(vii) In the hydrodynamic gearbox, the fluid coupling absorbs the shocks arising from wind gusts and the grid faults are dampened, thereby reducing fatigue on the drive train.
(viii) The absence of PEC and transformer provides initial capital cost savings with hydrodynamic gearbox.
(ix) The reliability of hydrodynamic gearbox topology is better due to the absence of PECs and transformer. Moreover, their absence also eliminates the problems due to generator side harmonics and fault condition transient torques.

However, the losses in the PEC are almost 2% of the produced power which is not quite less. The maintenance of the brushes and slip rings still remains. For hydrodynamically geared type-D WPPs with WRSGs, the planetary gearbox maintenance persists as in other types of geared WPPs.

8.11 TYPE-D WPP WITH VARIABLE SPEED PMSG

Of late, type-D geared WPPs with wide range variable speed PMSGs have also been commercialised, even in the megawatt category. A PMSG is one in which the rotor windings of the WRSG have been replaced by permanent magnets. This could happen only due to the continuous development of high efficiency rare earth metal-based Nd-Fe-B (i.e., neodymium-iron-boron) permanent magnets. These rare earth magnets developed now are substantially stronger than earlier ferrite or ALNICO magnets of 1970s and 1980s. These new magnetic materials which a high coercive force and a high performance/cost ratio are high energy producers and made it having possible to manufacture high efficiency, high power factor permanent magnets for megawatt WPP applications.

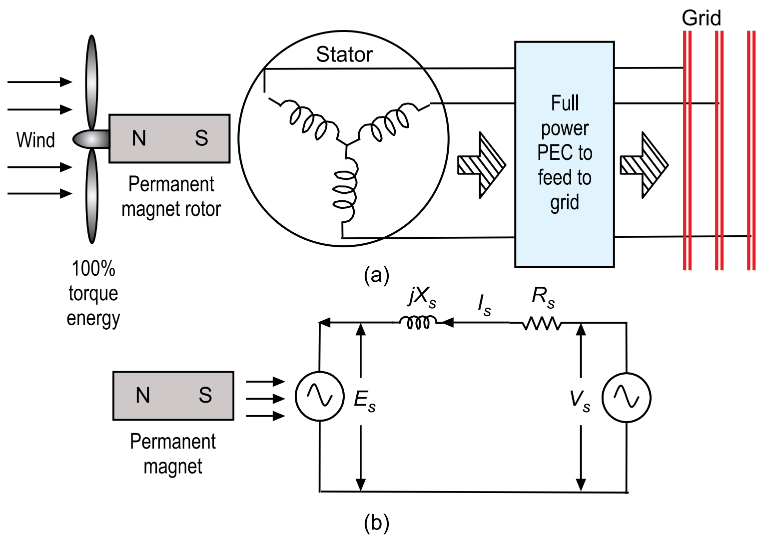
The permanent magnet enables high power density leading to a smaller size, high power factor and high efficiency at all speeds, thereby offering the maximum annual production of kilowatt hours with the lowest lifetime cost. The magnetic field typically produced by rare earth magnets can be in excess of 1.4 Tesla, whereas ferrite or ceramic magnets typically exhibit fields of only 0.5 Tesla to 1 Tesla. They are capable of producing a large air gap flux density even in generators with bigger air gap winding. It has a high power-to-weight ratio and a very short axial length

that makes it possible to integrate the PMSG with the WPP rotor to form quite compact units. However, the design of heat dissipation circuit is still crucial, as the permanent magnets are quite vulnerable to high temperatures.

In type-D wide range variable speed WPPs with PMSGs, there can be different design variations which are as follows:

(i) Type-D geared WPP variable speed PMSG, e.g. 3 MW (Vestas 112) model.
(ii) Type-D hydrodynamically geared WPP with constant speed PMSG, e.g. 2 MW DeWind (D8.2 model).
(iii) Type-D hybrid (semi-geared) WPP with variable speed PMSG, e.g. 3 MW WinWinD (WWD-3 model).

The equivalent circuit of the PMSG in type-D WPP is depicted in Figure 8.20. The speed of the synchronous generator in the WPP is dictated by the wind. So, the output voltage and frequency of the stator also vary. The AC power generated by the PMSG is then rectified by the PEC and fed to the grid.



R_s = Stator resistance E_s = Generated voltage

Figure 8.20 (a) WPP Circuit Diagram, (b) PMSG Equivalent Circuit.

By the use of appropriate software, the performance of this WPP could be modelled.

8.11.1 PMSG Equivalent Magnetic Circuit of Type-D WPP

The PMSG magnetic circuit can be described by Figure 8.21 which shows a flux source in parallel with the magnet's self-permeance and in series with the external magnetic circuit which can be represented by the armature reaction magnetomotive force (mmf) in series with the permeance of the external magnetic circuit. φ_m denotes the total flux generated by the magnets. It includes two parts—the leakage flux φ_σ and the main flux φ_δ. All symbols in the equivalent magnetic circuit are represented in per units. The flux leakage of the magnet is taken into account using a leakage permeance that is in parallel with the external magnetic circuit.

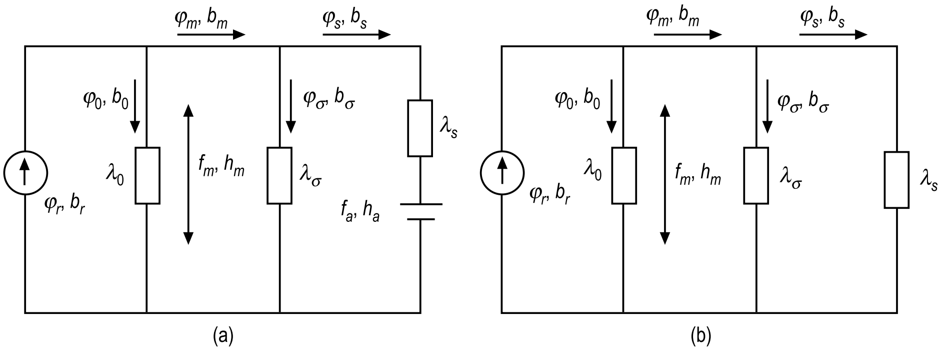


Figure 8.21 **PMSG Equivalent Magnetic Circuits:** (a) PMEM with load, (b) PMEM under no-load condition.

The symbols shown in Figure 8.21 are defined as follows:

$$\varphi_r = \frac{\Phi_r}{\Phi_r} = 1 = B_r \tag{8.28}$$

$$f_c = \frac{F_c}{F_c} = 1 = h_c$$

$$\lambda_\delta = \frac{\Lambda_\delta}{\Lambda_b} \tag{8.29}$$

$$\lambda_0 = \frac{\Lambda_0}{\Lambda_b} = 1 \tag{8.30}$$

$$\lambda_\sigma = \frac{\Lambda_\sigma}{\Lambda_b} \tag{8.31}$$

$$\varphi_m = \frac{\Phi_m}{\Phi_r} = \frac{B_m}{B_r} = B_m \tag{8.32}$$

$$f_m = \frac{F_m}{F_c} = \frac{H_m}{H_c} = h_m \tag{8.33}$$

$$f'_m = \frac{F'_a}{F_c} = \frac{H_a}{\sigma_0 F_c} = h'_s \tag{8.34}$$

The values of flux Φ_b, mmf F_b and permeance Λ_b can be calculated using:

$$\left.\begin{aligned} \Phi_b &= \Phi_r = B_r A_m \\ F_b &= F_c = H_c h_m \\ \Lambda_b &= \frac{\Phi_b}{F_b} = \frac{\Phi_r}{F_c} = \frac{B_r A_m}{H_c h_m} = \Lambda_0 \end{aligned}\right\} \tag{8.35}$$

where,

B_r = Magnetic remanence of the permanent magnet
H_c = Coercive force A_m is the area of the magnet per pole
h_m = Length (in the magnetisation direction) of the magnet
B_m = Flux density

H_m = Magnetic force seen from the external magnetic circuit of the magnet
Λ_σ = Permeance of the flux leakage circuit
Λ_δ = Permeance of the external magnetic circuit
Λ_0 = Self-permeance of the magnet
F_a = Armature reaction mmf.

8.11.2 Three-phase PMSG d–q model

The voltage of a three-phase PMSG in the phase coordinate frame can be expressed as:

$$\left.\begin{aligned} V_A &= V_m \sin \omega t \\ V_B &= V_m \sin\left(\omega t - \frac{2\pi}{3}\right) \\ V_C &= V_m \sin\left(\omega t + \frac{2\pi}{3}\right) \end{aligned}\right\} \tag{8.36}$$

where,
V_m = Magnitude of the phase voltage
V_A, V_B, V_C = Stator phase voltages
ω = Angular frequency of the voltage in the phase coordinate frame.

Equation 8.36 can be transformed to the d–q axis through the following transformation matrix:

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos \theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ -\sin \theta_r & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \\ V_C \end{bmatrix} \tag{8.37}$$

where,
θ_r = Rotor position
$\theta_r = \theta_0 + f\omega dt$
θ_0 = Initial position of the rotor

After the transformation, the performance of a PMSG can be described by the parameters given in the following paragraphs:

$$\begin{bmatrix} v_d = \dfrac{d\psi_d}{dt} - \omega\psi_q - R_d i_d \\ v_q = \dfrac{d\psi_q}{dt} - \omega\psi_d - R_q i_q \end{bmatrix} \tag{8.38}$$

where,
ψ_d = d-axis flux
ψ_q = q-axis flux

i_d = d-axis current
i_q = q-axis currents
R_d = d-axis resistance
R_q = q-axis resistance.

For a typical PMSG, $R_d = R_q = R_1$ (R_1 is phase resistance of the PMSG)
The PMSG flux is described by:

$$\left.\begin{aligned}\psi_d &= L_d i_d + L_{ad} i_{fm} \\ \psi_q &= -L_q i_q\end{aligned}\right\} \tag{8.39}$$

where,
L_{ad} = d-axis armature reaction inductance
L_1 = Leakage inductance
L_d = d-axis synchronous inductance
L_q = q-axis synchronous inductance.

$$\begin{aligned}L_d &= L_{\text{ad}} + L_1 \\ L_q &= L_{\text{aq}} + L_1\end{aligned} \tag{8.40}$$

where,
L_{aq} = q-axis armature reaction inductance
i_{fm} = Equivalent current of the magnet.

The electromagnetic torque is described by:

$$\begin{aligned}T_{\text{em}} &= p(\psi_d i_q - \psi_q i_d) \\ &= p[L_{ad} i_{fm} i_q - (L_q - L_q) i_d i_q]\end{aligned} \tag{8.41}$$

where,
p = Number of pole-pairs

The mechanical equation of PMSG is described by:

$$J = \frac{d\Omega}{dt} = T_{\text{mec}} - T_{em} - R_\Omega \Omega \tag{8.42}$$

where,
J = Rotational moment of inertia
Ω = Mechanical angular speed
T_{mec} = Turbine mechanical drive torque
T_{em} = PMSG electromagnetic torque
R_Ω = Damping coefficient.

The damping coefficient can be calculated from:

$$R_\Omega = \begin{cases}\dfrac{P_{fw}}{\Omega^2} & \Omega \le \Omega_N \\[2ex] \dfrac{P_{fw}}{\Omega^2} & \Omega > \Omega_N\end{cases} \tag{8.43}$$

where,
Ω_N = rated PMSG angular mechanical speed
P_{fw} = mechanical loss under rated load conditions.

8.11.3 Two-phase PMSG d–q Model

The phase voltage of a two-phase PMSG can be expressed as:

$$\left.\begin{aligned} v_A &= V_m \sin \omega t \\ v_B &= V_m \sin\left(\omega t - \frac{\pi}{2}\right) \end{aligned}\right\} \tag{8.44}$$

The phase voltage can be transformed to the d–q axis through the following transformation matrix.

$$\begin{bmatrix} v_d \\ v_q \\ v_0 \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\ \theta_r & \cos\left(\theta_r - \frac{\pi}{2}\right) \\ -\sin\ \theta_r & -\sin\left(\theta_r - \frac{\pi}{2}\right) \\ \sqrt{\frac{1}{2}} & \sqrt{\frac{1}{2}} \end{bmatrix} \begin{bmatrix} V_A \\ V_B \end{bmatrix} \tag{8.45}$$

After this transformation, performance calculations of the two-phase PMSG are identical to that of the three-phase PMSG.

Eq. 8.38 through Eq. 8.43 can also be used to calculate and analyse the performance of a two-phase PMSG.

8.12 TYPE-D GEARED WPP WITH VARIABLE SPEED PMSG

This Type-D design, such as adapted by 3 MW Vestas 112 Model, enables the WPP to operate across the full speed range, theoretically from 0% to 100% of its speed operation while maintaining grid compatible synchronous output. To render them grid-friendly, all the generated power from the generator stator is sent to the grid through the full rated PEC converter. The presence of gearbox (see Figure 8.22) renders the PMSG to be smaller such as the conventional synchronous generators as against the large diameter of direct-drive WPPs with multiple pole PMSGs.

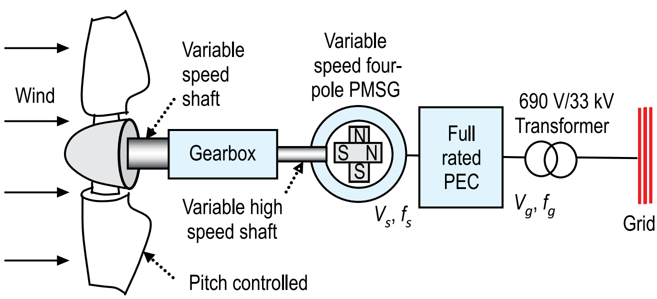


Figure 8.22 Type-D Geared WPP with Variable Speed PMSG: Since this WPP has permanent magnets instead of the coil winding, it is self-excited. The full rated PEC and a step up transformer treat the variable voltage and variable frequency output power to render it grid compatible.

8.12.1 Working Principle

The working of a type-D WPP with variable speed radial flux PMSG is similar to a type-D WPP with WRSG in several ways. The major difference is that the excitation magnetic field is generated by the permanent magnets built into the rotor rather than a separate DC supply fed into the excitation circuit through slip rings and brushes. The PM rotor generally has surface mounted permanent magnets rendering the magnetic flux distribution in the rotor to be approximately sinusoidal. As this rotor rotates, the field due to the self-excited permanent magnets interacts with the stator field and electric power is produced at the designed voltage level.

As no separate excitation is required, the excitation losses of the rotor (which normally account for about 20% to 30% of the total generator losses) are eliminated and thus, the efficiency is improved. The PMSG is normally not equipped with damper windings. The only issue in PMSG is that the voltage induced into the stator windings cannot be adjusted through the excitation current. Therefore, the voltage at the generator terminals is only a function of the RPM of the rotor.

The power from the stator is fed to the full rated PEC to render it grid-friendly. The working of the back-to-back PEC is similar, as discussed in earlier sections. The PEC's DC link totally decouples the generator and the mechanical drive train from the grid. Therefore, the changes in the grid do not affect the WPP generator dynamics. This decoupling also enables the maximum drive train damping, leading to simpler WPP design which results in lower weight.

8.13 TYPE-D HYDRODYNAMIC GEARED WPP WITH CONSTANT SPEED PMSG

In this type-D WPP topology (see Figure 8.23), the PMSG is adapted along with a relatively smaller planetary gearbox due to the superimposed hydrodynamic gearbox. This hydrodynamic adaptation facilitates a constant speed output torque to the generator shaft as in the 2 MW DeWind WPP, eliminating the need of PEC and transformer.

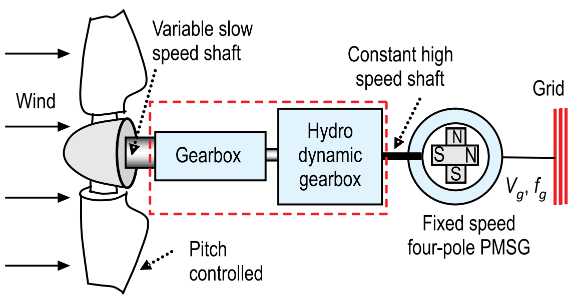


Figure 8.23 Type-D Hydrodynamic Variable Speed Geared WPP with Constant Speed Four-pole PMSG: The planetary gearbox is superimposed on a hydrodynamic gearbox which provides constant speed output to the four-pole PMSG, directly connected to the grid eliminating the need of a PEC and transformer.

8.13.1 Working Principle

The hydrodynamic variable ratio gear drive (refer Figure 8.24) automatically converts the wide range variable input speed of the wind turbine rotor to a constant output high speed shaft connected to the shaft of a four-pole radial flux PMSG.

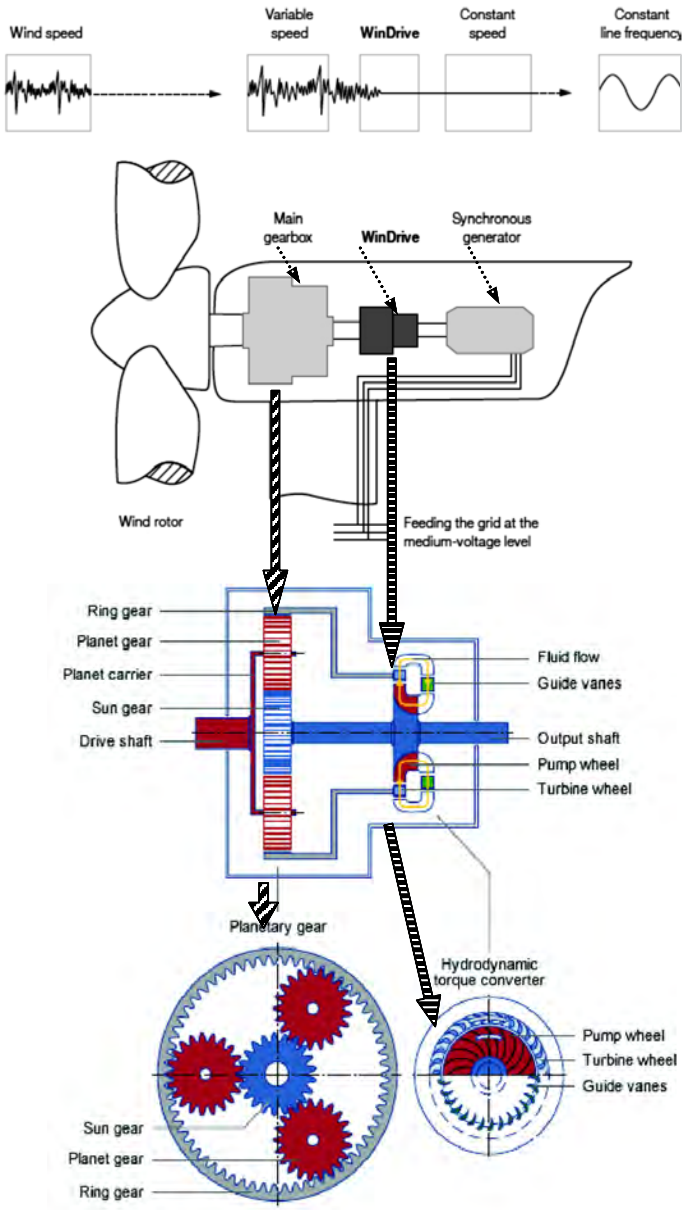


Figure 8.24 Type-D Hydrodynamic Geared WPP Constant Speed PMSG: Rotor is operated at its greatest efficiency for a wide range of wind speeds because of the WinDrive hydrodynamic gearbox.
Courtesy: www.voith.com

Since the speed is constant, it generates an electric power of constant voltage and frequency directly feeding to the grid. Therefore, the use of expensive PECs and transformer can be avoided. The fluid coupling element dampens shocks arising from wind gusts, thus reducing fatigue on the drive train. Constant speed control of the hydrodynamic gearbox is achieved by adjusting guide vanes within the gearbox.

In addition, this topology enables a reduction in weight and the space required in the nacelles of the WPPs. From grid side, the grid faults are also prevented from reaching the planetary gearbox, thereby reducing the unnecessary stresses and overall fatigue. Further, in this design, dynamically loaded components can be made lighter and cheaper for the same life period. This advantage translates to longer lives for the WPP.

8.14 TYPE-D GEARED WPP WITH MULTIPLE VARIABLE SPEED PMSGs

There are several examples of multiple generator-based designs in the wind industry such as the early Kenetech's KVS-33M, 410 kW with two equal-sized generators, Nedwind's 1 MW 50 series fitted with four-gearbox driven, each of 250 kW generator and the two-belt driven 150 kW units, and the first version of the Nordtank 1.5 MW NTK 60/1500 with two 750 kW generators.

The Type-D topology from Clipperwind consists of a single gearbox and widely variable speed but relatively smaller multiple PMSGs mounted on it (see Figure 8.25). The basic advantage of this design is that even if one of the PMSGs are under repair or being replaced, the rest of the three generators continue to produce electric power. The use of multiple PMSGs is an approach that may have some advantages over a single large PM generator as the individual permanent magnets are small enough to be removed, shipped and re-assembled.

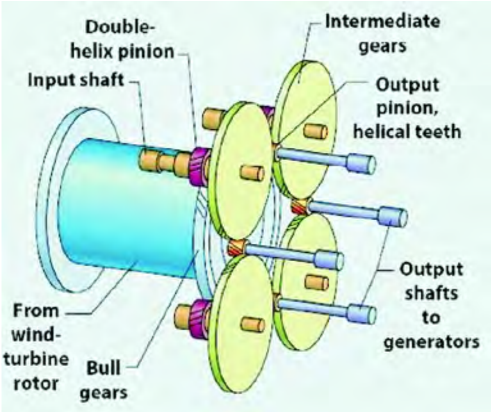


Figure 8.25 Single Gearbox with Variable Speed Four-PMSG WPP: The 2.5 MW divides the performance flow in the gears, thereby reducing the loads on the shafts.
Courtesy: www.clipperwind.com

8.14.1 Working Principle

The Clipperwind WPP gearbox is not the conventional planetary one, but a patented design. Its multiple drive path design radically decreases individual gearbox component loads which reduce the gearbox size and weight. It is a light weight, two-stage, helical design that uses four variable speed PMSGs instead of usual single generator. This contrasts with planetary systems where torque typically gets transmitted in three stages to three planetary gears, each with two teeth simultaneously engaged, one with the sun gear and the other with the ring gear.

The principal advantage of this gearbox is said to be the high level of torque splitting that occurs which claims for the benefit of reducing stress on the gear teeth as compared to that which needs to be catered for in more conventional designs. The design also promises high tooth contact ratios for reduced noise emissions. The gear ratio is 1:72.4 and the mechanical power rating is 2674 kW.

The gearbox has four individual output shafts driving the four PMSGs. The PMSGs mount directly on the gearbox housing in such a way that the need for couplings and field alignment is avoided. There are eight load paths in the first stage of the gearbox and the load is split twice in the second stage.

The high speed gearsets can also be replaced without removing the entire gearbox. Many modern gearboxes of megawatt scale WPPs weigh 50 tons to 70 tons. By comparison, this gearbox weighs only 36 tons, including gearbox, brakes and housing. The direct linkage of the two-stage gearbox and the permanent magnet driven generator shortens the drive train by about 35%. Moreover, this WPP has a 30 year lifetime as against 20 years for the usual WPPs.

The electronic controller (turbine control) monitors the output parameters of the PMSGs (see Figure 8.26) and coordinates the servo mechanism that controls the pitch of the turbine blades. Its overarching goal is to optimise the generator torque and blade pitch to capture the most amount of energy while minimising the mechanical loads.

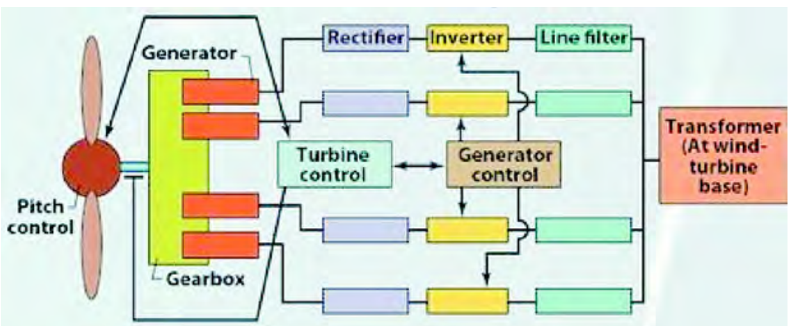


Figure 8.26 Control Scheme of Multiple Generator Variable Speed WPP: To capture the maximum energy, the control of all four generators and blade pitch is optimised by the 2.5 MW turbine control.
Courtesy: www.clipperwind.com

The varying voltage and varying frequency electric power from the radial flux PMSGs are converted to fixed voltage and fixed frequency grid compatible electric power by the full rated PEC, as discussed in earlier sections. In this way, the PEC completely decouples the generator from the grid, eliminating grid induced and wind gust drive train torque excursions.

8.15 PMSG TOPOLOGIES

There are several topologies of type-D large WPPs with PMSGs and many are still being researched for commercialisation. Based on the permanent magnet mounting and direction of flux linkages, following three major PMSG topologies (see Table 8.2) are possible:

- Radial flux permanent magnet synchronous generator (RF-PMSG) WPPs
- Axial flux permanent magnet synchronous generator (AF-PMSG) WPPs
- Transversal flux permanent magnet synchronous generator (TF-PMSG) WPPs.

Table 8.2 PMSG Topologies for WPP Applications

S.No.	Mounting	Type of PMSG	Rotor Type	Stator Type
1	Surface magnet Surface magnet	Radial flux Radial flux	Internal rotor External rotor	External stator Internal stator
2	Surface mounted Surface mounted	Axial flux Axial flux	Single disc Single disc	Single disc stator Dual disc stator
3	Surface mounted Buried in rotor	Transversal flux Transversal flux	Single disc Single disc	Dual disc stator Dual disc stator

For large WPP applications, the first two have become commercially viable while the third (i.e., transversal flux generators) is yet to catch up the commercial market for large WPPs, although it is being adapted in some small wind turbines.

8.15.1 Salient Features of Type-D WPPs with PMSGs

The self-excited PMSG solution offers a number of economic and technical advantages. The features of type-D WPPs with PMSGs are as follows:

(i) PMSGs provide high partial load efficiency. It is important for the WPPs which spend approximately 50% or more of their lifetime operating below the rated power.
(ii) Incorporating permanent magnets in rotor circuit reduces the size, weight and electrical/thermal losses.
(iii) Absence of the DC excitation system also does away with the slip rings and brushes leading to higher reliability.

(iv) Excitation losses, typically 20%–30% of overall generator losses are eliminated due to the permanent magnets in the field circuit.
(v) High performance/cost ratio and a high coercive force permit high pole number designs, complementing the low speed, direct drive wind turbine generator application.
(vi) The WPPs with PMSG solution is especially suitable to weak grids and also for stand-alone operation.
(vii) As permanent magnets are rare earth materials, using powder technology, it is more easier to design complicated designs.

However, there are certain limitations of type-D WPP with PMSG as well, which are as follows:

(i) The one major disadvantage of PMSG in the WPP is that with no control of the rotor flux, they attain their peak efficiency only at one predefined wind speed.
(ii) Permanent magnets made of rare earth tend to become demagnetised when working in the powerful magnetic fields inside the nacelles. There is always a danger of demagnetisation of the magnets due to stator magnetic overload.
(iii) The magnetic materials are also sensitive to high temperature. Therefore, elaborate cooling arrangements are to be provided.
(iv) The synchronous operation also causes a very stiff performance in the case of an external short circuit and if the wind speed is unsteady.
(v) PMSG-based WPPs may cause problems during start-ups, synchronisation and voltage regulation.
(vi) The extraction of rare earth material of which the permanent magnets are made, is difficult and hence, quite expensive. According to Siemens, about 650 kg of permanent magnets are needed for every megawatt of WPP capacity, out of which 25%–30% is rare earth magnet material. Most of the rare earth material (almost 97%) comes from China and hence, is short in supply.

8.16 NEED FOR DIRECT-DRIVE WPP

The topologies discussed so far were related to geared WPPs with their perennial gearbox maintenance problems. Even now, more than 85% of grid integrated WPPs currently sold worldwide, still use a gearbox (see Figure 8.27). According to WPP aerodynamics, efficiency will be better if the rotor blades operate at its optimal tip speed ratio (TSR) discussed in the earlier chapters and which is around 6 to 8 depending on the aerofoil design.

The very first Type-D WPP topology that was used to harness the energy over a wide range of wind speeds was not the variable speed geared ones discussed so far, but it was the direct-drive (also called gearless) WPPs pioneered by *Enercon* (Germany) in early 1990s, followed by other manufacturers such as MTorres (Spain), EWT (Netherlands), Vensys (Germany) and others.

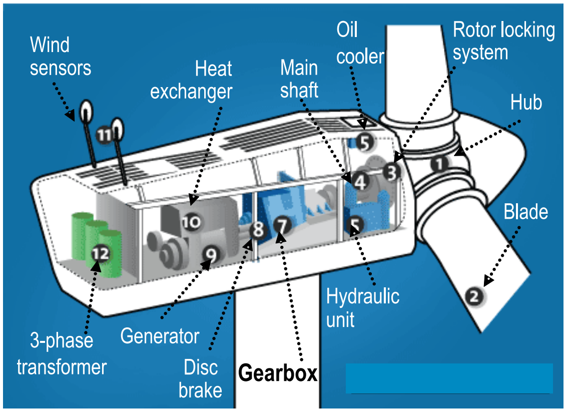


Figure 8.27 **Type-D Geared WPP:** Conspicuous by its gearbox, smaller generator and no PEC losses. *Courtesy:* www.lec.ethz.ch/research/wind_energy/wind_energy_glossary.

To obtain the optimal TSR, the angular velocity of the blades has to be low which necessitates a low speed electrical generator to achieve a high torque which means a large diameter and high pole count ($N = f/p$) machine, i.e., a multipole electrical generator, where f is the frequency and p is the number of poles.

A large diameter with a high pole count is not desirable for induction generators, as the magnetising current becomes too high. Moreover, induction generators cannot be built for low speeds, as a smaller pole pitch together with a large air gap yields a too large reactive power demand for multipole induction generator. In this backdrop, a multipole large diameter direct-drive synchronous generator is the option for low speed WPP applications. But, too high pole count leads to quite small rotor poles resulting in quite small stator slots, thereby making it quite expensive and unwieldy.

The direct-drive generator (see Figure 8.28) in WPPs has a large diameter and small pole pitch to increase the efficiency, reduce the active material and keep the end winding losses small. However, a large diameter requires a larger torque T because the torque is proportional to the square of the air gap diameter. Higher torque demands larger air gap diameter of the generator and high tangential force f_d. Larger air gap helps to achieve higher overloading capacity.

In a direct-drive configuration, the wind turbine rotor is directly connected to a low speed multipole synchronous generator (WRSG or PMSG) that rotates at the same RPM as the wind turbine rotor. As the capacity of a WPP increases, the RPM is decreased due to the tip speed limitation of 120 m/s. The torque T increases inverse proportionately to the decrease of the mechanical angular speed ω_m.

$$P = T\omega_m \tag{8.46}$$

where,

P = Generated power

T = Torque

ω_m = Angular speed determined by the RPM. It is given by the equation:

$$\omega_m = \frac{2\pi N}{60}$$

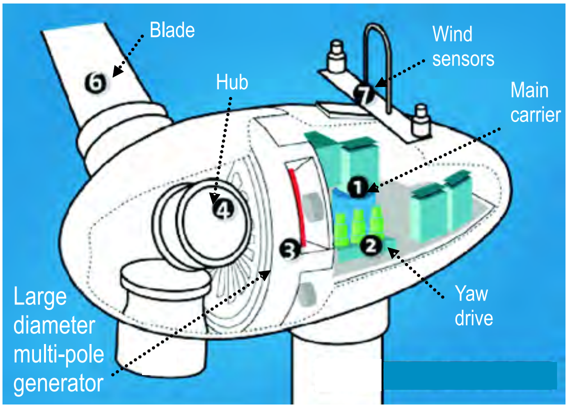


Figure 8.28 **Type-D Direct Drive WPP:** Conspicuous by its large diameter multipole annular generator with no gearbox issues.
Courtesy: www.lec.ethz.ch/research/wind_energy/wind_energy_glossary.

P is also defined as a function of the tangential force density f_d:

$$P = \frac{\pi}{2} f_d D_g^2 l_s \omega_m \tag{8.47}$$

where,

D_g = Rotor air gap diameter of electrical generator
l_s = Axial length of generator stator.

It can be seen that torque T is proportional to the square of the air gap diameter. A large air gap helps in proper deflection against the normal stress between the rotor and stator.

Large direct-drive WPPs also impose mechanical constraints. To maintain the air gap against the powerful force of attraction between the rotor and the stator, the mechanical construction has to be very rigid. This stiffness applies to the load path through the rotor, shaft, bearings and the stator, thus placing practical and economical limits on the diameter. For a large direct-drive synchronous generator with a diameter of several metres, the air gap should not exceed a few millimetres to avoid excessive magnetisation requirements. This results in the increase of materials to maintain the air gap in proper deflection against the normal stress between the rotor and stator.

Due to continuous research and development in wind power, the capacity of the WPPs keeps on going higher. As the direct-drive WPPs with multipole generator grows rapidly larger, air gap design becomes crucial to handle flux density requirements and prevent rotor stator rubbing under all operating conditions. The dynamic short circuit forces should also be accommodated within the limits of the minimum air gap. Some of these factors can become too dominant and affect generator choice in WPPs. Due to high torque requirements, the weight and size of the multipole generator need to be limited to avoid upgrading of the tower structure to handle the increased top head mass (THM).

The advantages of direct-drive WPPs are simplified nacelle systems, increased reliability, efficiency and no gearbox issues. Type-D direct-drive wide range variable speed range WPPs have following two different topologies:

(i) Type-D direct-drive WPP with variable speed WRSG, e.g. Enercon, MTorres and others.
(ii) Type-D direct-drive WPP with variable speed PMSG, e.g. Leitwind, Regenpowertech and others.

A main issue with the grid-friendly, low speed, direct-drive type-D WPP is its relatively large size resulting in relatively heavy top head mass which leads to greater mechanical stresses on the tower and foundations and transportation problems. Direct-drive multipole generators require a large diameter and need to be built with very small pole pitches (which cannot be less than 150 mm) and large number of poles (>120).

The aerodynamic noise generated by a WPP is approximately proportional to the 5th power of the tip speed. Since the RPM of direct-drive variable speed WPPs is much lower, the audible aerodynamic noise is also considerably less.

Due to large variable speed, the WPP can be operated at optimal power coefficient C_p leading to high overall WPP efficiency, thus raising the annual energy production ranging from 8% to 15% in comparison to constant speed WPPs.

Although gearbox has some problems, it enables a much smaller, lighter generator and also offers some of the advantages as a direct-drive WPP. Therefore, electric generator designers and wind turbine designers need to work together to optimise the entire range of WPP designs.

8.17 DIRECT-DRIVE WPP WITH VARIABLE SPEED WRSG

This topology was the first in Type-D WPP with variable speed WRSG category and pioneered by *Enercon* who harnessed the widely variable wind speeds (see Figure 8.29) in early 1990s. The WRSG in this WPP has a separately excited salient pole rotor directly connected to the wind turbine rotor hub by a slow moving shaft. The large multipole stator in the shape of a ring is fastened onto the yoke ring whereby the WRSG is also called as *ring generator* (or *annular generator*).

8.17.1 Working Principle

In this topology, the RPM of a multipole generator is same as the wind turbine rotor. The basic characteristic of the WRSG is that its rotor speed is always locked and in synchronism with the stator rotating magnetic field. With varying wind speeds, the voltage and frequency at the generator terminals are also not constant and they vary. As these do not match with that of the grid voltage and frequency, the WRSG is fully decoupled by the fully rated PEC and the varying electric power from the stator is connected to the electric grid after being treated in the four-quadrant operating PEC, as discussed in earlier sections.

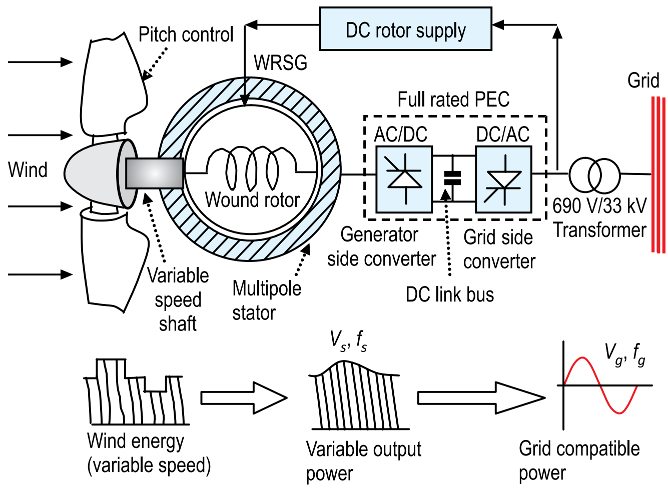


Figure 8.29 **Type-D Direct Drive WPP with Variable Speed WRSG:** The generator rotor has field coils that are separately excited, by a separate DC supply through slip rings and brushes. The full power from stator is fed to the full rated PEC.

Voltage control is affected by controlling the magnetising level of WRSG, i.e., high magnetising level results in high voltage and production of reactive power. In other words, it can be said that an ideal WPP has the ability to export and import net reactive power at full load over a range of grid voltages.

The electronic controller of the direct-drive WPP continuously monitors the grid parameters and if the grid power factor becomes low, without use of any capacitors, the PEC will automatically feed reactive power to the grid to improve the power factor.

Direct-drive WPPs can continue to operate at lower power capacities (see Figure 8.30) if the grids do not have temporary or long term overcapacities. Setting a power gradient in direct-drive WPPs (a salient feature of this type of WPP) helps in adjusting the power gradient regulation (see Figure 8.31) and in optimally suppressing the flicker and voltage fluctuations even in very weak grids.

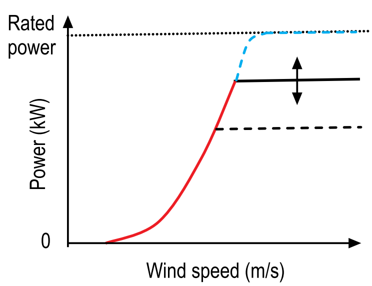


Figure 8.30 **WRSG Power Regulation:** Possible direct-drive WPP operation when grids do not have temporary or long term overcapacities.
Courtesy: www.thewindpowerindia.com

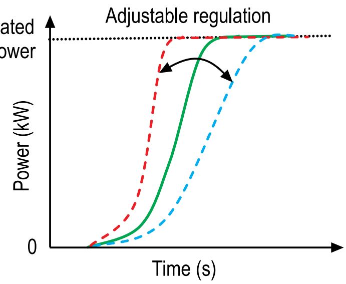


Figure 8.31 **WRSG Power Gradient Regulation *dp/dt*:** Possible in direct- drive WPPs to minimise the flicker and voltage fluctuations.

With recent developments, fault-ride-through capability (that means it remains connected to the grid even during grid faults) to a limited extent is provided with WRSGs, a feature which is very much required by the grid operators. Power ramp regulation is also being provided with WRSGs. However, owing to the presence of PECs in the stator connections to the grid, this type of generator cannot contribute much to system inertia.

8.18 DIRECT-DRIVE WPP WITH VARIABLE SPEED PMSG

One of the main drawbacks of Type-D direct-drive WPP with WRSG is the high maintenance of slip rings and brushes. This problem is solved by low speed direct-drive WPP with PMSG (see Figure 8.32). Its inherent self-excitation characteristic lowers the maintenance problem to a great extent. Since the modern rare earth

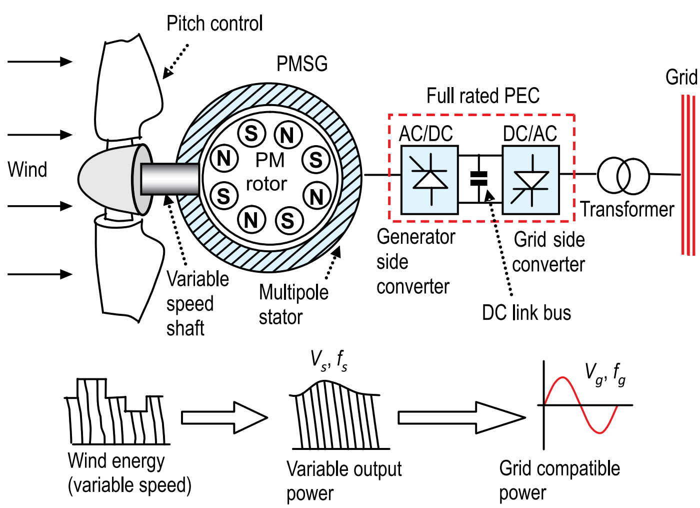


Figure 8.32 **Type-D Direct-drive WPP with PMSG:** Since the generator rotor has permanent magnets, it is self-excited and therefore, does not require separate field coils and separate DC supply to excite them, thereby eliminating the need for slip rings and brushes.

permanent magnets have the ability to produce large quantities of magnetic flux within a very small volume and geometry, they permit high pole count designs and complement the low speed direct-drive WPP application. For the same rating, a PMSG has a relatively smaller volume than a WRSG due to the absence of windings in the generator rotor, leading to slightly lower weight which results in a lower THM.

8.18.1 Working Principle

This PMSG topology is more competitive because it can have higher pole count of 60 or more poles as compared to a conventional WRSG. The permanent magnet rotor of the radial flux PMSG is directly connected to the varying speed, WPP rotor (between 7 RPM–20 RPM, depending on the rotor diameter size). Larger the diameter, the slower will be the speed of rotation. Direct-drive WPP with PMSG can have following two different constructions:

- Outer stator coils and inner rotor mounted with permanent magnets (see Figure 8.32).
- Inner stator coils and outer rotor mounted with permanent magnets (see Figure 8.34).

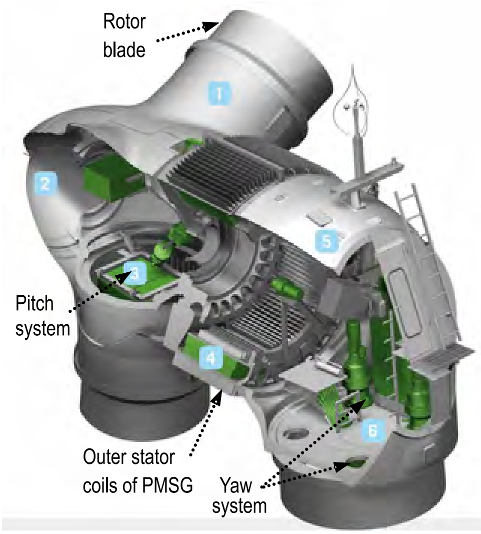


Figure 8.33 Type-D Direct-drive WPP with Inner PMSG Rotor: Nacelle length is shorter due to absence of gearbox in direct-drive WPPs and the multipole generator rotates at the same slow speed as the rotors.
Courtesy: www.leitwind.com

Figure 8.33 depicts the typical external stator coils and internal permanent magnet rotor constructional design of 1.5 MW Leitwind Type-D direct-drive WPP with PMSG. Whereas, Figure 8.34 depicts the typical outer rotor and inner stator constructional design of 1.5 MW Vensys design (licensed to Regen Powertech, India) type-D direct-drive WPP with PMSG.

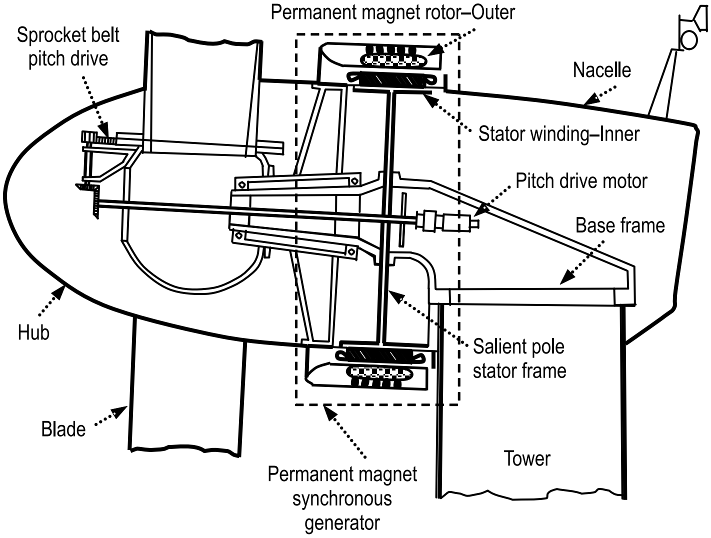


Figure 8.34 **Type-D Direct Drive WPP with Outer PMSG Rotor:** The radial flux strategy forms the externally rotating rotor frame of this PMSG. This helps to increase the torque due to the increase in bore diameter.

Irrespective of the type of permanent magnet rotor construction (inner or outer), the stator of the radial flux PMSG has a three-phase symmetrically distributed stator winding wound around a large number of poles (multipole) to adjust the speed of slow moving rotor. During normal operation of the WPP, the rotor speed of the PMSG is always locked to the stator exactly proportional to the frequency of the electrical grid. Changes in load cause the PMSG rotor to advance or drop back a few degrees (called the load angle δ) from the rotating magnetic field of the stator supplied by the grid. If the torques or currents necessary to accomplish this speed exceed the rated PMSG rating, then the circuit breakers will open, thereby disconnecting it from the grid in order to protect the generator from getting damaged.

The power from the multipole generator is fed to the back-to-back PEC, as discussed in earlier sections. There is no significant starting current when the PMSG is supplied by a PEC and also the relation between the starting and the nominal currents is very low. This is one of the greatest asset of the PMSG that the output power is sinusoidal which is the requirement of a grid operator. There is no exchange of reactive power between the PMSG and GSC during normal operation; it only absorbs electric power.

The control of reactive power and the voltage in the WPP equipped with PMSG is defined by the control system of GSC. Transfer of electric power is through the DC link bus of the PEC. However, the permanent magnet excitation cannot be controlled as in WRSG electromagnets and so, the output voltage falls, as load is increased. Therefore, a voltage regulator is needed in most applications. However, the PEC between PMSG stator and grid solves this problem to a certain extent.

In the case of a WRSG, the reactive power is not a problem, since it is produced internally using the electromagnetic field winding.

One issue for the PMSG regarding the PECs in the stator connections to the grid is that it cannot contribute much to the system inertia. Another issue is cogging. It is an inherent characteristic peculiar to slotted PMSGs which is not much of an issue in WRSG, and hence, needs to be taken care during design. Modern WPPs with PMSG fault-ride-through capability (to remain connected to the grid during system faults), exists to a limited extent, subject to their rating.

Therefore, PMSG solution yields a higher efficiency throughout the whole variable speed operation range that results in smaller power fluctuations and lower rotor noise even during partial power operation.

8.19 MODELLING OF TYPE-D DIRECT-DRIVE WPP

Modelling helps to simulate the working of WPP to understand its performance under various conditions. Figure 8.35 illustrates the generic model of a type-D variable speed direct-drive WPP with WRSG or PMSG. Simulations using appropriate software can be undertaken to assess the behaviour of this type of WPP under various wind and grid conditions.

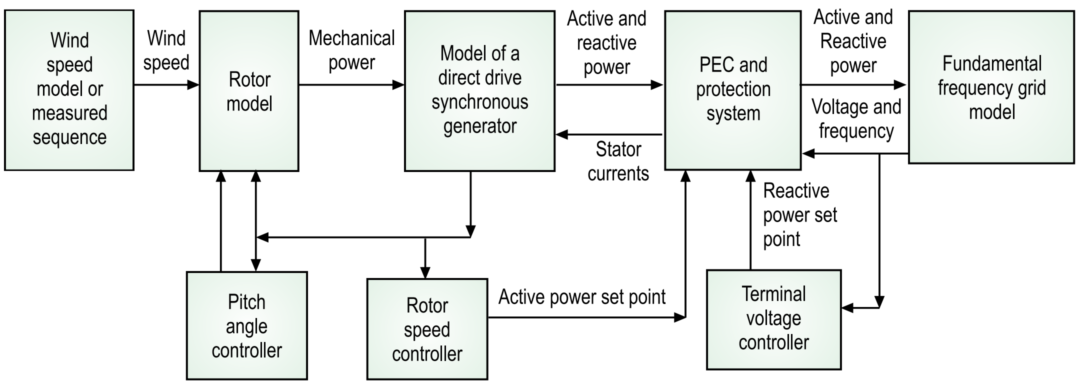


Figure 8.35 Generic Model of Type-D Direct-drive WPP.

8.19.1 Salient Features of Type-D Direct-Drive WPP

Following are some of the positive features of type-D direct-drive WPP with synchronous generator:

(i) Absence of gearbox maintenance and failures.

(ii) The rotor blades and the large size generator have considerable inertia that functions as a flywheel (absorbing and storing the energy temporarily as a buffer) smoothing out the aerodynamic torque fluctuations that results in

less mechanical stress on the drive train, especially during the blade passing frequency.

(iii) There is a reduced loading on mechanical components. Lesser fatigue loads on blades, tower and different parts of the WPP, as wind gusts can be absorbed by the inertia of the WPP creating an elasticity which reduces torque pulsations that results in lesser electric power fluctuations as well.

(iv) These WPPs have lesser number of bearings and couplings.

(v) Net energy capture at partial load (which is quite common, as the wind does not always blow at rated speed conditions for full load operations) is maximised by optimal TSR operation by Type-D WPPs, thereby maximising the aerodynamic efficiency of the WPP rotor.

(vi) The pitch control can be simpler because the time constant can be longer for variable speed operations.

(vii) These WPPs can easily comply with the requirements of grid operators, as the active and reactive power can be controlled and large wind farms can even act as a source of reactive power to compensate poor power factor of other consumers on the electrical network particularly in remote locations and offshore WPPs.

(viii) These slow rotating WPPs produce lesser tip noise at low wind speeds.

(ix) Due to the full rated PEC (in contrast to one-third rated PEC of type-C WPP), it can deliver more reactive power (100%) to support a stable voltage level.

(x) Voltage flicker problems are reduced.

(xi) Although the electrical efficiency decreases due to the losses in the PECs that are essential for Type-D WPPs, the increase in rotor efficiency outweighs the losses of the PEC.

(xii) Fault-ride-through (FRT) is possible.

However, type-D direct-drive WPPs have some limitations as well which are given below:

(i) Type-D WPPs can only be connected to the grid when frequency, phase position and voltage of the power produced are in synchronism with the grid.

(ii) Absence of gearbox is offset by a larger PEC (requiring greater cooling arrangements) with more complicated circuits for which expert maintenance personnel is difficult to get on time, as many of the wind farms are in remote and rural locations.

(iii) Type-D WPPs due to commutation losses, continuously lose 1% to 2% of the nominal power in generating and maintaining the magnetic field. Additional maintenance and heat dissipation is required.

(iv) The PECs are sensitive to voltage dips caused by faults and/or switching. IGBT switches in the PECs are very sensitive to thermal overloads, overcurrents and overvoltages. In such cases, to prevent their damage, the PEC may block, i.e., stop switching. Converter blocking may lead to disconnection of the WPPs which is not acceptable to most of the TSOs.

(v) As the power of the WPPs increase in the megawatt range, direct-drive WPPs become heavier and more expensive generator. Their top head mass is relatively much more than that of geared WPPs.

(vi) As compared to a SCIG of similar size, the WRSG is mechanically and electrically more complicated.

(vii) There is a substantial cost difference between the constant speed WPPs and variable speed WPPs.

(viii) If proper cable shielding is not done, the electrical noise can create problems for control signals within the WPP. With the use of optical fibre cables, this problem is being minimised.

8.20 TYPE-D HYBRID WPP WITH VARIABLE SPEED PMSG

The Type-D hybrid (semi-geared) WPP with variable speed PMSG (see Figure 8.36) combines the advantages of geared and direct-drive WPPs. It was pioneered and commercialised in large WPPs by WinWinD and Areva Multibrid. The main feature is that it is a medium speed gear unit with variable speed PMSG as a single integrated product that eliminates the use of a high speed shaft system and hence, shortens the drive train by about 35% length, creating more space for a transformer in the nacelle. Since the transformer can be in the nacelle, the low voltage cable losses are also avoided, thereby increasing the efficiency. The medium speed makes it possible to use a two-stage gearbox rather than the three stages commonly used conventional geared WPPs.

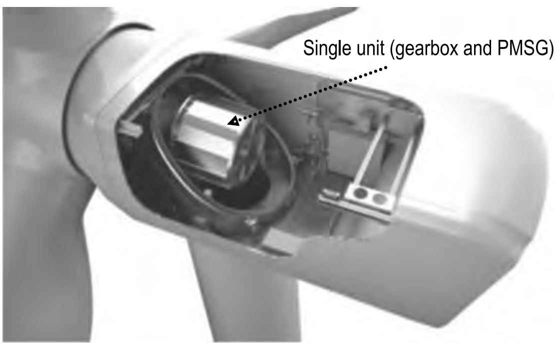


Figure 8.36 Type-D Hybrid Variable Speed WPP with PMSG: Medium speed WPP with integrated gearbox and PMSG, reduces the nacelle length by about 35%. *Courtesy:* www.winwind.com

A typical hybrid WPP has a medium speed range of approximately 40 RPM to 150 RPM. Due to the two-stage gearbox, medium speed PMSG can be used. As only 80% less rare earth magnets are required as compared to a direct-drive PMSG, the cost is lesser. Less material means less weight which leads to reduction in cost

as well. Being one integrated unit, one cooling system will also suffice. Two-stage systems are claimed to offer superior CoE performance as compared to direct-drive, single stage, low speed PMSG systems. As a rule of thumb, with fewer stages, there are fewer reliability issues and the efficiency is higher.

8.20.1 Working Principle

The drive train of the hybrid WPP consists of a gearbox that runs with the wind turbine rotor integrated with a radial flux PMSG (see Figure 8.37) and eliminating the high speed shaft. The drive train generally consists of a two-stage compound planetary helical gearbox with medium speed PMSG. The planetary carrier runs the planet gears which pass the power to the sun gear with the rotating speed ratio around 6:1.

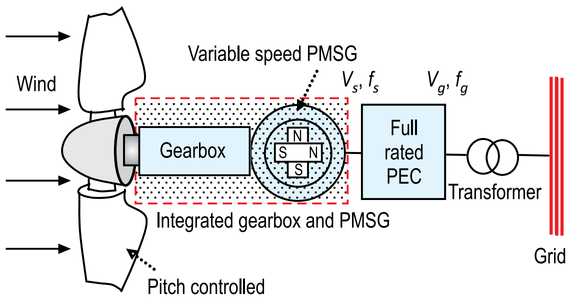


Figure 8.37 Type-D Hybrid (Semi-geared) Type-D WPP with Variable Speed PMSG.

The PMSG is flange mounted on the gearbox to minimise the weight and vibration and thereby doing away with the high speed shaft, i.e., the PMSG rotor is mounted on the output shaft of the gearbox and therefore needs no further bearings. The stator of the PMSG is directly mounted on the mainframe using gear case flanges on the gearbox and generator housings. This arrangement protects the gearbox safely from any shock loads which might otherwise occur due to short circuits from the generator side.

The drive train drives the radial flux PMSG rotor at medium speed that can absorb fault torques without causing damage to the gearbox. The permanent magnets are mounted directly on the rotor. No separate excitation system is necessary because of the self-excitation feature of the permanent magnets. The output of the PMSG stator is connected to the full power four-quadrant operating PEC that treats and transfers the grid compatible power to the grid. Located on the back of the generator, the mechanical brake system is composed of a brake disc, calipers and hydraulic system.

Table 8.3 provides a comparison of various types of variable speed WPPs that has been commercialised.

Table 8.3 Comparison of Variable Speed WPPs

WPP Type	Aerodynamics and Electrical Generator (with examples)		
	Stall	**Pitch**	**Active-stall**
Type-C: Limited range variable speed: –30% to +40%	Type-C0 Nil	Type-C1: Geared with DFIG • 5 MW Repower • 850 kW Gamesa	Type-C2 Nil
Type-D: Wide range variable speed: (upto 2.5 times the rated speed)	Type-D0 Nil	Type-D1: Geared with variable speed SCIG • 1800 kW RRBEnergy • 410 kW Kenetech	Type-D2 Nil
	—	Type-D1: Geared with smaller four-pole WRSG • 2.5 MW Kenersys	—
	—	Type-D1: Direct-drive with larger diameter multipole WRSG • 1.65 MW Mtorres • 7.5 MW Enercon	—
	Type-D0: Direct drive with axial flux PMSG • 750 kW Jeumont	Type-D1: Direct-drive with larger diameter multipole radial flux PMSG • 6 MW Siemens • 4.1 MW GE	—
	—	Type-D1: Geared with radial flux with smaller four-pole PMSG • 3 MW Vestas • 2.5 MW Clipper	—
	—	Type-D1: With smaller four-pole WRSG and hydro-dynamic gearbox • 500 kW (two-bladed) Windflow	—
	—	Type-D1: With smaller radial flux four-pole PMSG and hydrodynamic gearbox • 2.1 MW DeWind	—
	—	Type-D1: Hybrid (Semi-geared) with radial flux with smaller four-pole PMSG • 3 MW WinWinD • 5 MW Areva	—

SUMMARY

By variable speed operation of WPPs, not only the extraction of electrical power is enhanced but also the stresses on the mechanical structure are reduced. The energy from the wind gusts is partially transferred into the acceleration of the wind turbine rotor and therefore, there is no need to reduce the blade pitch angle instantaneously. Moreover, there is a greater control of active and reactive power and lesser acoustic noise. Therefore, various types of variable speed WPPs in the category of type-C and type-D WPPs got evolved over the years that have been discussed over here.

EXERCISES

8.1 Describe the working of a Type-C WPP.

8.2 With sketches, describe the operation modes of Type-C limited range variable speed WPP.

8.3 Explain the process of compensating reactive power in Type-C WPP.

8.4 Explain the generic model and the equivalent circuit of Type-C WPP.

8.5 Describe the impact of grid faults in Type-C WPP.

8.6 Explain the working of Type-D geared WPP with squirrel cage induction generator for wide range variable speed operation.

8.7 Explain the SCIG torque–speed characteristics for constant *V/f* operation.

8.8 Explain the working of Type-D geared WPP with wound rotor synchronous generator.

8.9 Differentiate the three primary functions of a PEC in a WPP.

8.10 Describe the working of Type-D hydrodynamically geared WPP with wound rotor synchronous generator.

8.11 Explain the working of Type-D geared WPP with permanent magnet synchronous generator.

8.12 Describe the working of Type-D hydrodynamically geared WPP with permanent magnet synchronous generator.

8.13 With a sketch, explain the magnetic circuit of a WPP with PMSG.

8.14 Justify the need for a large diameter electrical generator in WPPs.

8.15 Using a sketch, explain the generic model of Type-D variable speed direct-drive WPP with synchronous generator.

8.16 Explain the working of Type-D direct-drive WPP with wound rotor synchronous generator.

8.17 Justify the need for fault-ride-through facility in WPPs.

8.18 Describe the working of Type-D direct-drive WPP with permanent magnet synchronous generator.

8.19 Justify the need of a hybrid (semi-geared) WPP.

8.20 Explain the benefits of using multiple PMSGs with single gearbox.

8.21 Explain the significance of specific power of WPPs.

9

Quality Issues of Wind Power

HE who forms the mountains, creates the wind.
—Amos 4:13

Learning Outcome

On studying this chapter, you will able to diagnose the various factors that affect the power quality in an electric grid due to the connection of wind power plants.

CHAPTER HIGHLIGHTS

9.1 *Introduction*
9.2 *Wind power impact*
9.3 *Local impacts of wind power*
9.4 *Systemwide impacts of wind power*
9.5 *Wind power variability*
9.6 *Islanding*
9.7 *WPP electrical safety and grid*
9.8 *WPP inertia*
9.9 *Plant load factor (or capacity factor)*
9.10 *Capacity credit*

9.1 INTRODUCTION

Power quality relates to different characteristics of the electric power system to which the wind power plants (WPPs) are connected. The first question that arises is why wind power is different from the conventional power. There are three main reasons—the very first reason is that wind speed is often varying. The variations occur on all time scales (i.e., seconds, minutes, hours, days, months, seasons and years) resulting in varying power supplied to the grid, leading to operational problems. Moreover, windy sites are distributed over different locations and not centralised as conventional power stations. This situation is more acute especially if the wind power penetration crosses 15%–20% or the grids are weak. Secondly, WPPs/wind farms are usually connected to distribution networks or low and medium voltage networks such as 33 kV/66 kV sub-transmission lines different from the conventional power stations. Thirdly, the electric generator technologies on which WPPs are based are different from the conventional synchronous generators and WPPs respond differently to different fault conditions.

The second question that arises in one's mind is what are the other equipment that affect the grid power quality other than the WPPs and how they are addressed. Proliferation of non-linear loads, power electronic devices, flicker, voltage sags and harmonics affect the power quality. The wind power quality depends on the interaction between the WPP and grid. In most of the WPPs, the output is the standard 690 V AC. The WPPs have step-up transformers either in the nacelle or at the tower bottom that are connected by a medium voltage (MV) electrical network in the range 11 kV–33 kV. This network consists of underground cables and/or overhead lines in some locations. Overhead lines, though cheaper, creates greater visual influence and can also restrict the movement and use of cranes.

The point of common coupling (PCC) is the grid point (see Figure 9.1) at which the WPP/wind farm is connected to the grid. In fact, it is the point where a judicious interaction of the grid operator and WPP operator begins for stable supply network. Other WPPs in the wind farm are usually connected in parallel to the radial feeders. At the point of interconnection (POI) or PCC, the voltage level

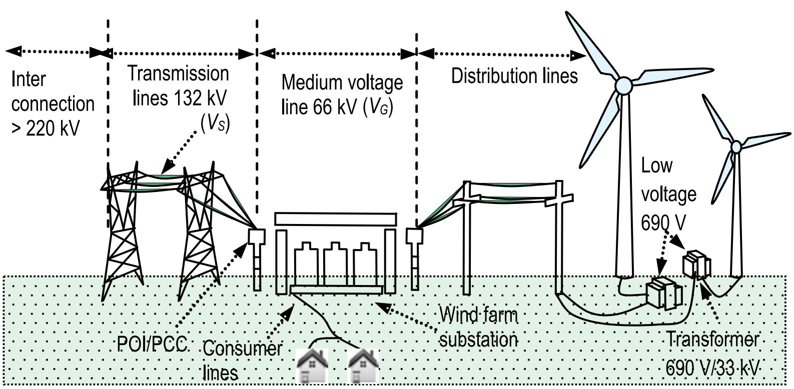


Figure 9.1 Wind Power and Electrical Power System: When smaller and fewer number of WPPs are connected to the grid where the major stable feed is from conventional power plants, the electrically stiff grid is capable to absorb shocks.

is further increased which is suitable for onward transmission. The way in which WPPs respond to the various phenomena on the grid is, many times, different from the conventional synchronous generators. Hence the power quality of the grid gets affected, that is discussed in this chapter.

9.2 WIND POWER IMPACT

The impact of wind power in the electric power system depends, to a large extent, on the following:

- Wind power penetration level
- Grid size
- Generation mix in the power system.

Wind penetration of 5% is not an issue to the grid operators. Above 5%, the effect of wind power is felt. When the wind power penetration crosses 10% of the total load, some form of grid adaptation and remedial measures need to be undertaken in some parts of the grid. But when WPP penetration crosses 20%, strengthening of existing grid becomes essential.

Wind capacity penetration looks at how the total installed wind power capacity in a certain region is related to the peak load in this region over a certain time period.

$$\text{Wind capacity penetration (percent)} = \frac{\text{Installed wind power capacity (MW)}}{\text{Peak load (MW)}} \times 100 \tag{9.1}$$

Wind energy penetration looks at the percentage of demand covered by wind energy in a certain region on an annual basis.

$$\text{Wind energy penetration (percent)} = \frac{\text{Annual production of wind energy (TWh)}}{\text{Gross annual electricity demand (TWh)}} \times 100 \tag{9.2}$$

Maximum share of wind power looks at the power balance in a certain region, taking into account the minimum demand, the maximum wind power generated and the exchange with neighbouring regions or countries. This figure must remain below 100% to ensure the correct power balance in the region. The nearer to 100%, the closer will be the system to its limits (when wind power would need to be curtailed).

$$\text{Maximum share of wind power (percent)} = \frac{\text{Maximum wind power generated (MW)}}{\text{Minimum load (MW)} + \text{Power exchange capacity (MW)}} \times 100 \tag{9.3}$$

The variable nature of the wind speed often creates small imbalances, unless taken due care which is likely to degrade the power quality especially in weak grids where WPPs are connected. But large imbalances due to faults, loss of generation, etc. can threaten the stability of the power system but generally, these are not due to the WPPs.

Normally, single WPPs have fast, autonomous self-protecting regulation of their terminal voltages and they respond rapidly and correctly for grid voltage events while

the Wind Farm Management System (WFMS) and wind power management software SCADA provide wind farm level controls to meet the performance requirements (e.g. voltage regulation) at the PCC by:

- Sending reactive power commands to single WPPs to trim up initial single WPP response.
- Coordinating other substation equipment (e.g. switching shunt capacitors).
- Interfacing with utility SCADA.
- Accepting utility system operator commands (e.g. voltage reference set point).

The quality of the power produced by constant speed WPPs has cyclic variations approximately which get passed onto the grid network that needs to be controlled if it goes beyond the specified limit. Since the speed of constant speed WPPs directly connected to the grid is fixed, it is not possible to store the wind gusts in the form of rotational energy, but they result in power variations affecting the power quality of the grid.

However, the quality of the power produced by a variable speed WPP is steadier. Many of the faster power variations are not transmitted to the network but are smoothened out by the flywheel action of the wind turbine rotor. In these WPPs where the generator speed is controlled by the PECs, the power fluctuations caused by the wind variations can more or less be absorbed by changing the rotor speed, rendering the power quality steadier.

Due to the spread of the operating point and averaging effect, the variations in power supply at the PCC are less than that of a single WPP. Another alternative is to configure the WPPs as an integrated energy system for operation in conjunction with other renewable energy sources, traditional energy sources and/or storage elements (like the wind-diesel, wind-SPV-diesel and wind powered pumped hydro systems). By proper sizing of the various elements and selection of control logic, a near constant output power can be achieved. Another strategy is to operate this integrated energy system either in a grid connected mode or stand-alone mode.

Generally, connecting loads to an electric grid reduces the voltage, while connecting power producing units (like WPPs) increases the voltage level. In both cases, there are two kinds of impacts on the network:

- Impact of WPPs on the grid (see Figure 9.2).
- Impact of grid disturbances on the WPPs (see Figure 9.3).

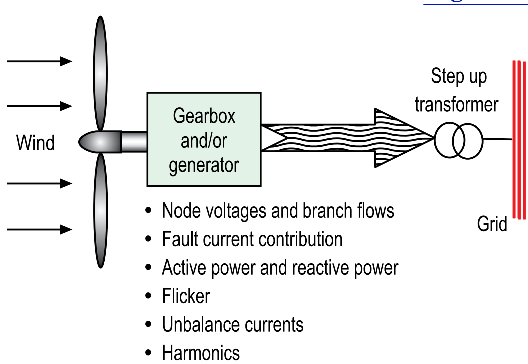


Figure 9.2 WPP Impact on Electric Grid.

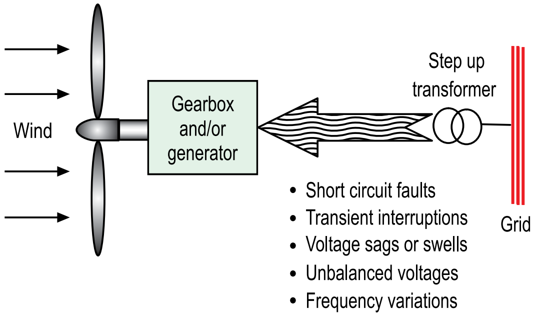


Figure 9.3 Electric Grid Impact on WPP.

Then, there is the local impact and systemwide impact due to the grid connection of the WPPs/wind farms (see Figure 9.4) that affect the electrical power quality within the ambit of the above two situations.

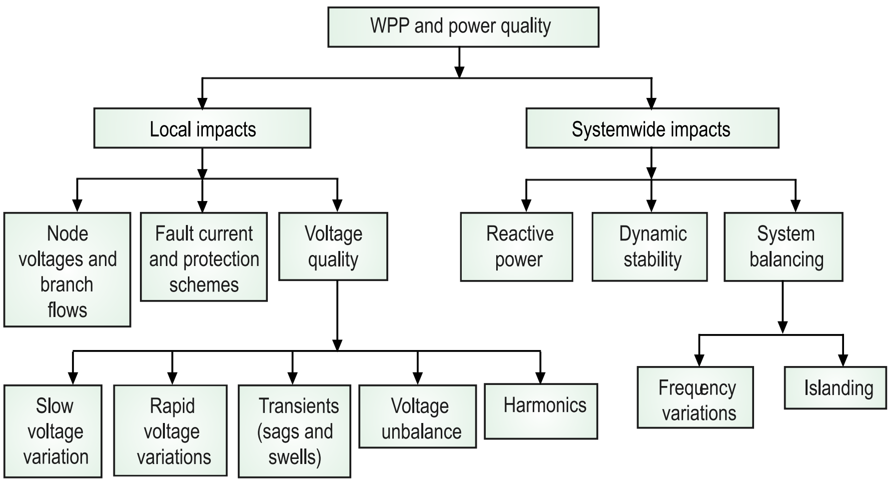


Figure 9.4 Overview of Grid Power Quality due to WPPs.

(a) Local Impacts

These are electrical impacts that can occur in the immediate vicinity (i.e., localised) due to the connection of a large capacity WPP/wind farm or due to the electric grid disturbance or both. These are largely independent of the overall wind power penetration in the grid but depend on the capacity of the constant speed and variable speed WPPs/wind farms in the vicinity.

(b) Systemwide Impacts

Unlike the local impact seen above, this global effect may lead to loss of synchronism of synchronous generators attributed to individual WPPs or wind farms anywhere on the grid network, not necessarily in the immediate vicinity.

Each of these aspects and their implications thereof in relation to the performance of the WPPs are discussed in the following sections.

9.3 LOCAL IMPACTS OF WIND POWER

Since the WPPs are generally located in rural areas in the electric distribution networks of the grid, power fed by them into the network could lead to some local impacts which need to be addressed. On the local level, wind power has an impact on the following aspects of a power system:

(i) Node voltages and branch flows.
(ii) Fault currents and grid connected WPP.
(iii) Voltage quality
The voltage quality is affected by different distortion causes given in Table 9.1. All these causes are common to any electric generator but are of particular interest when WPPs are connected to the grid. Different types of voltage quality are given below:
  (a) Slow voltage variations (or steady state voltage)
  (b) Rapid voltage variations (leading to flicker)
  (c) Voltage transients
  (d) Voltage dips
  (e) Voltage sags
  (f) Voltage swells
  (g) Voltage unbalance (i.e., negative phase sequence voltage)
  (h) Waveform distortion (i.e., harmonics).

9.3.1 Node Voltages and Branch Flows

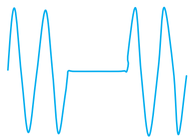
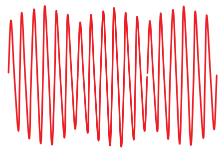
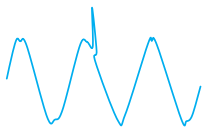
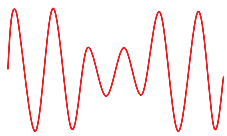
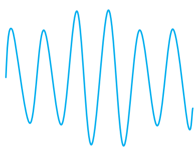
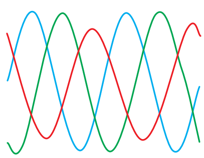
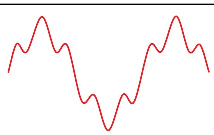
A *node* is defined as a point where:

- Electric power is taken from the grid
- Electric power generation is injected into the grid or
- Two or more lines connect to each other.

Voltage is a local quantity which can be affected at or in the direct vicinity of a node. Node voltage is a local quantity as opposed to system frequency which is a global quantity. Node voltages are affected by reactive power, although they depend on active power. Even though, there is a voltage difference between the two ends of the line, the node voltage should not be allowed to deviate from the nominal value of the voltage in excess of a certain value (normally 5% to 10%). Appropriate measures must be taken to prevent such deviation.

Distribution networks consisting of overhead lines and/or underground cables have high resistance as compared with its inductance (i.e., high R/X ratios). Therefore, these remote node voltages in distribution grids are controlled mainly by changing the turns ratio of the transformer that connect the distribution grid to higher voltage level and also by devices that generate or consume reactive power such as shunt reactors and capacitors.

Table 9.1 WPPs and Typical Power Quality Disturbances

Voltage Quality	Disturbance	Origin of Disturbance	Consequence
Slow voltage variations (or steady state voltage)		• Load variations • Variation in power production • False tripping • Short duration interruptions	Disconnection of equipment
Rapid voltage variations (Flicker)		• WPP blade pitch error • WPP yaw error • WPP wind shear • Tower shadow effect • Wind speed changes • Turbulence intensity	• Flickering of lamps • Aging of insulation • Fail functions
Voltage transients		• Lightning strike • Switching events in Type-A and Type-B WPPs	• Insulation failure • Reduced lifetime of transformers and motors
Voltage dip (or sag)		• Start up of large capacity Type-A WPP • Grid short circuit • Start-up of large motors	• Disconnection of sensitive loads • Fail functions
Voltage swell		• Shut down of large capacity Type-A WPP • Grid lightning strikes • Earth fault on another phase • Incorrect setting in sub-stations	• Disconnection of equipment • Aging of insulation • Harm equipment with inadequate design margins
Unbalanced voltages		• Single phase loads • Weak connections in network	• Overload of three-phase equipment • Noise in three-phase equipment
Harmonic distortion		• Type-C and Type-D WPPs • Non-linear loads • Resonance phenomenon • Transformer saturation	• Extended heating • Failure of electronic equipment

Transmission networks have lower resistance (i.e., low *R*/*X* ratios) and the node voltages are controlled by changing the reactive power generation and consumption of large scale centralised generators connected to the transmission lines. It is, therefore, not possible to control the voltage of a certain node from any point in the grid as compared to the frequency that can be controlled from anywhere in the grid. Instead, the voltage of a certain node can only be controlled from that

particular node or in its direct vicinity. In other words, voltage control depends on the way in which WPPs affect the voltages at nearby nodes as well as on whether they are constant speed or variable speed WPPs.

Regardless of the type of WPP (stall, pitch or active-stall), the power produced by it fluctuates due to the varying wind and tower shadow. If the WPP has three blades, the power produced will fluctuate three times per revolution. The constant speed WPPs (Type-A and Type-B) have a fixed relation between rotor speed, active power, reactive power and terminal voltage. Therefore, they cannot control node voltages. While the generator speeds of the variable speed WPPs (Type-C and Type-D) can control the node voltage better because they are capable of varying the reactive power for a given active power and terminal voltage. In DFIG, this is done by changing the direct component of the rotor current. In WRSG, it is done by changing the current on the grid side of the PEC that couples the generator to the grid.

9.3.2 Fault Currents and Grid Connected WPP

The voltage at the WPP generator (refer Figure 9.1) is given by:

$$V_G^4 + V_G^2[2(QX - PR) - V_S^2] + (QX - PR)^2 + (PX - QR)^2 = 0 \quad (9.4)$$

where,

V_G = Generator voltage
V_S = Transmission voltage (line-to-neutral)
P = Generated power
Q = Reactive power requirement
R = Distribution system resistance
X = Distribution system impedance.

Whenever there is a short circuit (fault), the power system is disturbed (see Figure 9.5). The ability of the grid to absorb disturbances is directly related to the short circuit power level at the point under consideration. In this case, it is the PCC of the WPP/wind farm. The minimum acceptable network strength is the minimum short circuit level at the PCC of a single WPP/wind farm that can be connected without producing unsatisfactory effects (poor power quality) for other consumers. Therefore, the first step when implementing a WPP project is to determine the effect of the connection on the steady state voltage level.

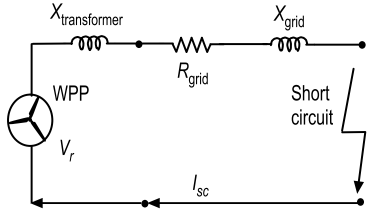


Figure 9.5 Single Phase Diagram for Short Circuit Power.

The responses of each of the WPP types during faults, in terms of contribution of fault currents, are different:

- Constant speed WPPs Type-A and Type-B equipped with directly grid coupled SCIG or WRIG rely on conventional protection schemes (overcurrent, overspeed, overvoltage and undervoltage, overfrequency and underfrequency) and contribute to the fault current to some extent.
- Variable speed Type-C WPPs contribute to the fault current differently. The control system of the PEC measures the grid voltage at a very high sampling rate (several kHz) and regulates the rotor current. A fault is, therefore, detected very quickly. Due to the sensitivity of PECs to overcurrents, this type of WPP is, at present, quickly disconnected when a fault current goes beyond the permissible limit of the PEC. Therefore, the duration of its contribution is rather short to the fault current.
- Variable speed Type-D WPPs hardly contribute to the fault current at all because the PEC through which such a WPP is connected to the grid cannot carry such heavy fault currents and therefore, it is a normal practice for these WPPs to be quickly disconnected, in case of a fault.

The system disturbance increases with increasing nominal apparent power of the WPP/wind farm and decreases with decreasing short circuit power. As a rule of thumb, a steady state voltage deviation cannot be less than 2%, i.e., about 50 times the rated power of the WPP or wind farm.

The fault level M is an indication of the strength of the network. The higher the fault level, the stronger will be the grid:

$$M = I_F V_S \tag{9.5}$$

where,

I_F = Short circuit (or fault) current
V_S = Sending end voltage.

If there is a short circuit in the WPP generator, the fault current I_F is given by:

$$I_F = \frac{V_S}{\sqrt{R^2 + X^2}} \tag{9.6}$$

The short circuit current for the power system (refer Figure 9.5) is calculated from the following voltage equation:

$$V_r = [R_{\text{grid}} + j\omega(L_{\text{trans}} + L_{\text{grid}})]\, I_{sc} \tag{9.7}$$

where,

I_{sc} = Short circuit current
V_r = Rated voltage at the PCC
R_{grid} = Resistance of grid
L_{grid} = Inductance of grid
L_{trans} = Inductance of transformer.

The *short circuit apparent power* S_{sc} is defined by the product of the rated voltage and the short circuit current for a short circuit at the PCC of the WPP/wind farm (refer Figure 9.5):

$$S_{sc} = 3/2\ V_r I_{sc} \tag{9.8}$$

This short circuit power is a measure of the voltage deviation that can happen at the WPP terminals at rated power:

$$\frac{\Delta V}{V} \approx k\frac{S_r}{S_{sc}} \tag{9.9}$$

where,

ΔV = Voltage deviation
S_r = Rated power of WPP
k = Constant depending on system conditions, i.e.,
k = 1 for steady state
k = 2 for transient state with induction generator and soft starter
k = 8 for transient state with only induction generator.

Figure 9.6 represents the simplified phasor diagram for short circuit power. The value of the grid impedance increases with the length of the line or cable and the short circuit current and power generally decrease with the length. Therefore, a longer overhead line or cable decreases the short circuit power and increases the voltage deviation.

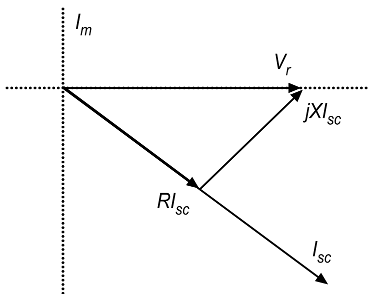


Figure 9.6 Phase Diagram for Short Circuit Power.

(a) Issues Related to Induction Generators

Although Type-A and Type-B WPPs have the advantages of being simple, robust, reliable, the limited quality control on the power fed into the grid consume reactive power and have high mechanical stresses. Every fluctuation of the wind speed causes a change in the mechanical torque which results in a fluctuation of the power fed into the grid. If the grid short circuit power level is low, it will cause voltage fluctuations with negative effects for the loads in parallel and may cause voltage flicker.

The other issue in these constant speed WPPs with grid connected induction generators is the self-excitation. Induction generators alone cannot self-excite. Self-

excitation does not occur during normal grid connected operation, but during off-grid operation. They require reactive power from the grid to operate normally. If a type A/type B WPP operating in normal mode becomes disconnected from the power line due to a sudden fault or disturbance in the line feeder and the capacitors continue to provide the reactive power and no protective schemes are in place, then the induction generator may self-excite, thereby causing overvoltages. The grid dictates the RPM of the induction generator and hence, its voltage and frequency too. The voltage of the system is determined by the flux and frequency of the system. Hence, the level of saturation plays an important role in sustenance or collapse of the self-excitation process.

For steady state conditions, reactive power produced should be equal to the reactive power consumed, i.e., depending on the output and defined margins at the point under consideration, the exchange of reactive power should be more or less zero. For the WPP to operate in isolation, when the conservation of active and reactive power is to be preserved, the total admittance of the induction generator and the rest of the connected load must be zero.

The self-excitation of WPPs gives rise to a danger to the safety of a personnel. As the induction generator still generates voltage after disconnection, it may be dangerous to the personnel inspecting the line or generator. As the generator's operating voltage and frequency are determined by the balance between the system's active and reactive power, sensitive equipment connected can be damaged due to the overvoltage or undervoltage and overfrequency or underfrequency operation that may occur. During grid loss and mechanical brake malfunctions, a judicious design of capacitance and resistor load has to be undertaken so that the energy from the WPP can be dumped to bring it within safe operating speed.

9.3.3 Voltage Quality

Voltage is local variable which means that its value is location specific. A mismatch between the supply and demand of reactive power results in a change in the system voltage, i.e., if the supply of lagging reactive power is less than the demand, a decrease in the system voltage results. Conversely, if the supply of lagging reactive power exceeds the demand, it results in an increase in the system voltage. The power system voltage is regulated by the controllers on the field excitation circuits of the conventional generators. Transformers equipped with automatic voltage regulators (AVR) are used to provide reasonably steady state voltages to the end users.

To analyse the voltage variation caused by a WPP connected to the grid of impedance Z_s, an impedance model (see Figure 9.7) can be used where the active power is P and reactive power is Q. The steady state voltage for this system is given by:

$$\frac{\Delta V}{V_2} = \frac{RP + XQ}{V_1^2} \times 100\% \tag{9.10}$$

where,

V_1 = Grid voltage
V_2 = Voltage at PCC.

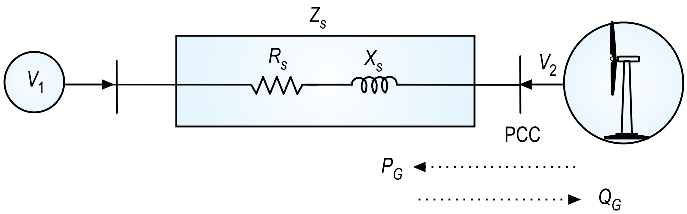


Figure 9.7 **Typical Power System with a WPP:** Equivalent voltage source V_1 is in series with impedance Z_s of a power system. P_G is the active power flow and Q_G is the reactive power consumed in case of induction generators.

R = Resistance of the line
X = Inductive reactance of the line
P = Active power generated by WPP
Q = Reactive power generated by WPP.

IEC 38 recommends 230 V/400 V as the standard voltage for 50 Hz systems. Voltage variations are mainly caused by variations in power production by the WPP/wind farm as well as by the increase/decrease in the connected loads. High consumption and low power production results in low voltages. High production and low consumption leads to the high voltages. Utility and customer equipment is designed for a specific voltage range and quality. Therefore, the voltage at the consumer's terminal should not differ more than ±10% of the rated voltage. The WPP/wind farm must continue to operate between these minimum and maximum voltage limits.

All WPPs cause voltage variations not only due to the variations in the wind, but also due to the emergency stop and start operations. Automatic voltage regulator (AVR) is included in modern WPPs that monitor their terminal voltage magnitude to supply (or absorb) the desired amount of reactive power to the grid network. *Voltage quality* due to a WPP/wind farm could be defined as the change in the RMS value of the voltage in a time span of minute or more, ranging from slow voltage variations to transients. Injection of active or reactive power into the grid by the WPP causes a voltage variation between the PCC and the grid which is expressed by:

$$\Delta V = \frac{PR + QX}{V_r} \tag{9.11}$$

where,

V_r = Grid voltage at the connection point.

Voltage regulation problems arise if wind power dominates the power balance relative to other conventional generators. Generally, the WPPs do not contribute to voltage regulation or frequency in grids, as they are often located in remote areas which aggravate their contribution towards voltage control. Continued and regular voltage variations can damage or shorten the lifetime of the utility of customers' equipment, as they are designed to function at specified voltage range and quality.

Depending on proximity to the local load and the distribution network configuration, WPPs can cause voltage transients or flicker on a local distribution grid.

This occurs also due to the inrush associated with the energisation of the stators of induction generators. Depending on the strength of the local grid, an undesirable voltage dip can result every time when the WPPs are started. For this reason, grid operators often require that WPPs limit the magnitude of their voltage disturbances to a maximum of 1%–2%.

Voltage control problems caused by deficit reactive power (due to induction generators) in the grid can be remedied by installation of fixed, mechanically switched or electronically switched shunt capacitors or FACTS devices. However, these do not help in voltage fluctuations, caused by the varying output of WPPs.

(a) Slow Voltage Variations

Slow voltage variations (almost considered as steady state voltage) can be defined as the changes in the RMS value of the voltage occurring in a time span of many minutes or more. The steady state voltage variations, generally, should not exceed 2.5% for a distribution feeder. If WPPs are connected to it, then the variations should not exceed 5%. Slow voltage variations (refer Table 9.1) are mainly caused by variations in load and power production units. WPPs connected to the grid also create voltage variations as they are not only due to the wind speeds but also depend on the type of WPPs connected to the grid.

Slow voltage variations from the grid are not of much concern to WPPs, as there is sufficient time for the WPPs to respond to the condition and make necessary adjustments. Start-up of Type-A and Type-B WPPs may cause a reduction in the voltage followed by a voltage recovery after a few seconds. However, careful design is required to ensure overspeed (during loss of grid, while the blade pitch control responds), the resulting overvoltage (as the generator produces open circuit voltage proportional to the speed whenever the shaft turns) and also that, it does not damage the PEC of Type-C and Type-D WPPs.

(b) Rapid Voltage Variations (Flicker)

Flicker is an old way of quantifying rapid voltage variations. It is the strobing effect of a blade shadow and people should not be exposed to more than 30 hours per year according to Health Canada. *Voltage flicker* (see Figure 9.8) is a momentary sag in line voltage, either periodic or aperiodic, that results in perceptible (often annoying) fluctuations in the intensity of light from lamps. Flicker is caused by several reasons that are given below:

- Wind turbulence (stochastic, average frequency $f < 0.1$ Hz) and small scale turbulence (disturbances above and below the mean wind speed) over smaller areas than the swept area.
- When constant speed WPPs are first electrically connected to the grid, large changes in active and reactive power could occur that may cause flicker.
- Constant speed WPPs cause power fluctuations due to wind gradient and tower shadow effect caused by the reduction in wind speed by tower blockage (periodic f = 1–2 Hz).
- Wind shear (vertical and/or horizontal gradients in wind speed).

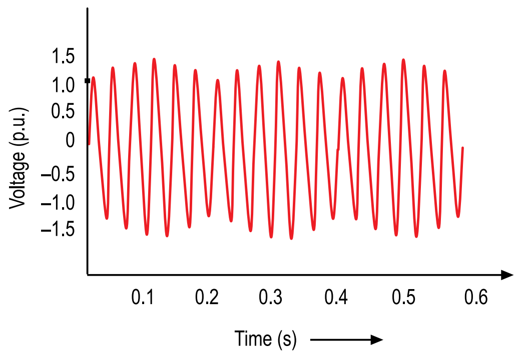


Figure 9.8 **Voltage Flicker:** Short-lived voltage variations in the electric grid which may cause light bulbs to flicker.

- Yaw mis-alignment or yaw error (rotor disc area not perpendicular to the wind direction).
- Switching in and out of WPPs from the grid (single events per hour) or switching of dual-speed generator windings also causes changes in production, leading to pulsations in the output power.

In variable speed WPPs, the starting and stopping is smoother, hence the flicker problem is almost absent.

Flicker coefficient is defined as the fluctuations of the voltage in a frequency range of 0.5 Hz to 35 Hz. According to IEC 61400–21, the flicker coefficient from WPPs can be determined by:

$$c(\psi_k) = P_{st}\frac{S_k}{S_{\text{ref}}} \tag{9.12}$$

where,

$c(\psi_k)$ = Flicker coefficient
P_{st} = Flicker emission from each WPP of a fictitious grid with grid angle ψ_k
S_k = Arbitrary short circuit power of the grid
S_{ref} = Rated apparent power of the WPP.

The grid angle is defined as:

$$\psi_k = \arctan\frac{X_k}{R_k} \tag{9.13}$$

where,

X_k = Reactance of the grid
R_k = Resistance of the grid.

The flicker coefficient must be given for the specified values of network impedance phase angle (30°, 50°, 70°, 85°) and the annual average wind speed (6 m/s, 7.5 m/s, 8.5 m/s, 10 m/s).

When several WPPs are connected to the grid, then:

$$P_{st\Sigma} = \sqrt{\textstyle\sum_i P_{st}^2} \tag{9.14}$$

(c) Voltage Transients

Voltage and *current transients* (usually of very short durations of µs or ms) are undesirable, momentary, but significant deviations from the normal levels (see Figure 9.9). These are usually caused by system faults due to the starting and stopping large constant speed WPPs or lightning discharges.

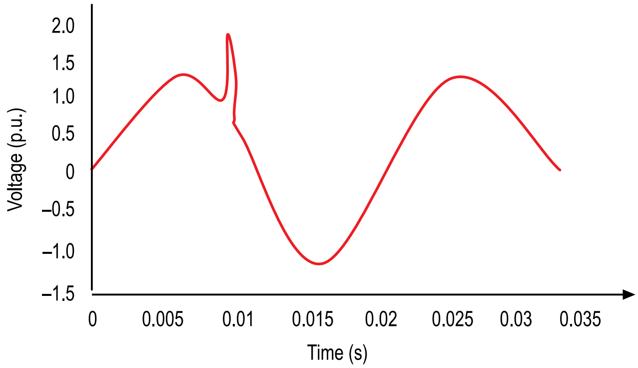


Figure 9.9 Voltage Transient: Transients are sudden and significant deviations from the normal voltage and current levels, usually of very short durations (µs or ms) which, generally, switch in or out loads, lightning or electrostatic discharges.

Transient interruption is a reduction of electric power supply below 0.1 p.u. for duration of <1 minute which is usually caused by system faults, system equipment failures or control and protection malfunctions. Transient voltage events that drop voltage below WPP tolerance levels can cause generators to trip offline.

Voltage collapses (transients) can also appear due to the grid faults or overvoltages associated with sudden islanding of wind power fed parts of distribution grids containing shunt capacitors for reactive power support. Transients caused by autoreclosing of distribution networks can be very damaging due to the possibility of out-of-phase reclosing of the constant speed WPPs with induction generators which are still fluxed and hence, develop a voltage. This situation is taken care by applying fast acting *loss of mains protection* so that the WPP is isolated as soon as the supply is interrupted.

The magnitude of transients may be quite large especially when the capacitor bank switching or back-to-back PEC switching are involved. Such internally generated transients could result in damage to sensitive electronic devices of the WPP control system.

The frequency of occurrences of the transient is determined by:

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC}} \tag{9.15}$$

where,

f = Frequency
L = Inductance
C = Capacitance of the grid.

Outage is an interruption that has a duration of >1 minute. Usually, this is the result of a system failure. Depending on the duration and effect of the outage, power outages can be categorised into following three:

- In *transient fault* (duration of a few seconds), power is automatically restored, once the fault is cleared.
- *Brownout* or *sag* is due to a sudden reduction in the network voltage to a value between 10% to 90% ranging for a period from 1 millisecond to 1 minute.
- *Blackout* (lasting from a few minutes to even weeks) is the most severe form of power outage. It is due to power stations tripping and is particularly difficult to recover quickly.

Large voltage transients could be created (that may reach to even two times the rated WPP current) during switching in operations of the capacitors using mechanical switches that are provided as integral part of some constant speed WPPs.

Other than this, other switching operations also result in switching overvoltages. Lightning hits could cause an induced overvoltage in the electrical system associated with the tower.

Due to repeated exposure to voltage transients the insulation system can become weak, leading to premature failure. The impedance of the grid and the capacitance of the capacitor bank determine the amplitude of the current emanating from the switching of an unloaded capacitor.

(d) Voltage Dip (or Sag)

A *voltage dip* (or sag or collapse) is a sudden reduction in voltage in the electric grid followed by a rapid return to its normal value. It is a sudden reduction in RMS voltage (see Figure 9.10) within the range of 0.1 p.u. to 0.9 p.u. for more than a half cycle and less than 1 minute (a value between 10% and 90% may be for a period from 1 ms to 1 min). This drop in voltage happens in a matter of milliseconds. Keeping WPPs online under low voltage conditions is also a potential trouble spot that WPP operators and grid operators need to consider.

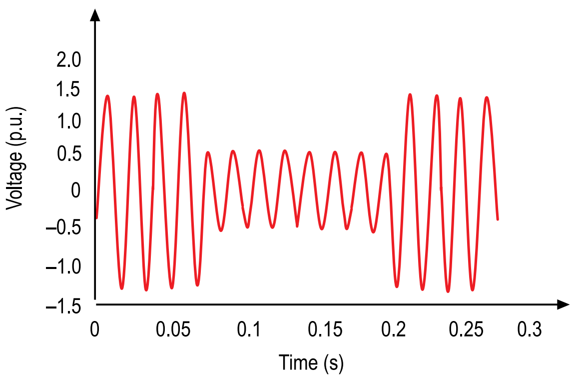


Figure 9.10 Voltage Dip: A sudden reduction in the network voltage to a value between 10% to 90% for a period from 1 ms to 1 min.

Human beings become aware of it, because the lights begin to go off and on momentarily and this may damage consumers' equipment permanently. In fact, an interruption of half a second in a process industry can cause the whole process to be blocked and it may have to be re-initiated all over again.

Dips between 10% and 15% of the terminal voltage are commonly due to switching of loads. Whereas, larger dips may be caused by lightning, trees falling on overhead line or other faults.

When a short circuit occurs in the grid, a voltage dip propagates through it and reaches the WPPs. This dip depends on the type of short circuit point (where the short circuit has occurred), the capacity and the number of the synchronous generators located near the fault.

Large capacity WPPs can cause momentary voltage sags on the local distribution system, which in turn, can cause problems for the locally served load. One way to overcome this is to reduce the current and acceleration of the WPPs by blade pitching, but then, it is not quick enough for the electrical system. In the normal operation of a WPP, the flux in the stator rotates synchronously, i.e., at the grid frequency. As the rotor turns near this speed, the voltage induced by this flux is small. The sudden dips on the grid cause the appearance of a new flux in the stator. This new flux, as opposed to the normal flux, is fixed to the stator, i.e., it doesn't rotate. Therefore, its relative speed with respect to the rotor is much larger and it induces voltages in the rotor much greater than those corresponding to the normal operation.

Voltage collapse may also occur due to excessive consumption of reactive power. When there is a voltage dip (or sag), constant speed WPPs can deliver the needed currents to activate the protection system. But when the voltage comes back, they consume great reactive power avoiding the voltage restoration after the sag. Further, the fault and reconnection provoke torque pulsations that may damage the gearbox. The slip of induction generator also increase and thus, the reactive power consumption of the WPPs also increase. This accumulating deficit of reactive power in the grid causes additional voltage depression, leading to cumulative effect. If the system voltage dips to such an extent that the corresponding pullout torque of the WPP generators fall below the mechanical infeed torque, the WPPs will start to accelerate until they are tripped.

When a voltage dip reaches constant speed WPP, the mechanical power remains constant, as the wind continuously blows, the electrical active power falls and the generator accelerates (and it is very quick if the inertia is small) increasing the current and reactive power consumption, resulting in increasing the reactive power losses. But then, the power dip is even more accentuated and consequently, it is even more difficult to bring the voltage upto its normal operating value. Therefore, beyond a specified limit, the WPP has to be disconnected. In case of a variable speed Type-C WPP, beyond the PEC limit, the crowbar circuit protects the PEC and bypasses it and the DFIG runs as a normal induction generator. In case of a Type-D WPP, the exceeding power produced by the synchronous generator can be controlled by means of a chopper circuit that maintains the DC link voltage constant but beyond the designed limit of the full rated PEC, the WPP has to be disconnected.

To prevent the occurrence of voltage collapse, fast support of reactive power is required which can be achieved by means of a properly sized and located SVCs. Use of RC surge suppressor circuits for the protection of low voltage electric circuitry is also well known.

(e) Voltage Swell (Overvoltage)

Voltage swells (see Figure 9.11) are those that increase rapidly over the nominal voltage for a short duration within the threshold limit of 1.1 p.u. to 1.8 p.u. for more than half a cycle or less than one minute. Voltage swells lasting longer than certain time duration (say 2 minutes) are categorised as *overvoltages*.

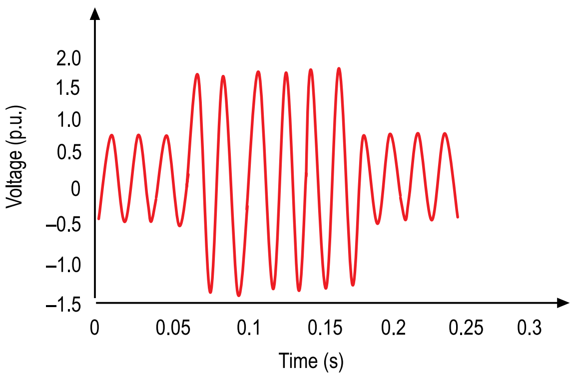


Figure 9.11 **Voltage Swell:** Voltage swells are voltages that increase rapidly over the nominal voltage for a short duration and within the threshold limit of 1.1 p.u. for the minimum duration of 10 ms.

The increase in voltage also increases the no load losses in the transformers, thereby reducing the net real power generated by a WPP.

The maximal current spike describes the maximal current peak during switching operations related to nominal current. Voltage swells affect the mechanical loading of WPPs caused by system faults, load switching and capacitor switching. The grid dependent switching is a WPP specific dimensionless parameter which depends on the angle of grid impedance and describes the influence of the current during switching operations on maximum voltage fluctuations. These are less common and are, therefore, not a major problem for WPPs. Inrush currents of WPPs lead to voltage peaks. Generally, this inrush current in constant speed WPPs is limited by a thyristor power controller (called as soft starter).

Higher voltages apart from increasing the stress on the insulation (leading to reduced life), increase the magnetising VAr requirement of the transformers. Generally, the step up power transformers are operated near saturation. In extreme cases, transformer saturation can also lead to generation of appreciable amount of current harmonics. Even a marginal increase in voltage can cause the magnetising current to increase drastically, thereby affecting the power factor.

Use of adequately rated lightning arrestors (gapless type) is effective in protecting the equipment from transient overvoltages.

(f) Voltage Imbalance (Unbalance)

Voltage unbalance (see Figure 9.12) is usually caused by the reactive power consumption during the magnetisation of the constant speed WPP's induction generators at start-ups.

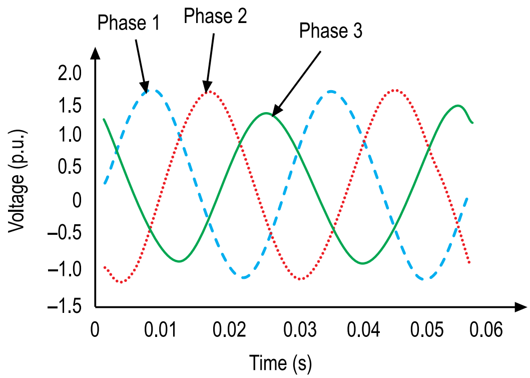


Figure 9.12 Unbalance Voltage in Three Phases: Network voltage unbalance is the difference in phase-to-neutral or phase-to-phase voltage magnitudes or phase angles of the three-phase electrical system.

Voltage unbalance is defined as:

$$\%\ \text{Unbalance} = \frac{\text{Maximum deviation from average voltage}}{\text{Average voltage of the three voltage phases}} \tag{9.16}$$

Network voltage unbalance is the difference in phase to neutral or phase-to-phase voltage magnitudes or phase angles of the three-phase electrical system. Three-phase induction generators have low negative phase sequence impedance and so they draw large currents if their terminal voltage is unbalanced. During unbalance, the power supplied by the generator to the grid is also unbalanced and may be slightly decreased as some phase may have less current than the others.

Typically, a 2% voltage unbalance may cause a 4%–6% decrease in the current in one phase and an increase in the phase current in the other two phases of about 8%–18%. Voltage unbalance (zero sequence or negative sequence) can also cause metering errors, leading to higher or lower readings of both real and reactive power as well as the life of electrical machine gets reduced.

If power is not equally balanced between all the phases, the unbalance may also go from full to zero production during emergency stop and start-up conditions of induction generators. Constant speed WPPs connected to such networks act to reduce this unbalance but in the process these are subjected to large losses due to overheating and introducing torque ripples in the drive train. Voltage unbalances in the grid can shorten the life of WPPs with induction generators. They also produce negative sequence voltage in the induction generators that affects the air gap flux and thereby, affecting the rotor current too. In symmetrical conditions, the rotor current has following frequency:

$$\text{Rotor current frequency} = \text{Slip } (s) \times \text{Frequency } (f) \tag{9.17}$$

But due to the presence of negative sequence voltage, the frequency of the rotor becomes:

$$\text{Rotor current frequency} = \text{Approximately } (2 - s) \times f \tag{9.18}$$

This distorts the sinusoidal shape of the rotor current, depending on the degree of the unbalance. More the unbalance, more will be the losses in the generator. In the worst case, unintended fluctuations occur in the mechanical parts of the WPP. Therefore, adequate compensation needs to be incorporated in the WPPs.

In case of variable speed WPPs with PECs, if in the design stage, voltage unbalance is not considered, the PECs may inject unexpected harmonic currents back into the grid under unbalanced operation, which will further aggravate the network voltage unbalance. With the use of asynchronous links (AC-DC-AC), it is possible to counter the unbalance problem.

Voltage unbalance generally occurs on weak networks in rural areas, as the majority of customer loads are single phase. The causes of unbalance can also be blown fuses, partially failed three-phase loads, asymmetrical transformer winding impedances and uneven distribution of single phase loads in distribution networks. Under such conditions, the distribution system is less stable and also suffers more losses.

(g) Voltage Step Changes

A *step change in voltage* may result in a step change in the torque of the gearbox of the WPP. Constant speed Type-A WPPs can cause voltage step changes when starting or when changing between generators (in case of two generators or dual-speed windings). Each capacitor switching event of wind turbine/wind farm (either on or off) causes a near instantaneous step change in voltage. They are not able to control their voltage and therefore, do not comply with this requirement. For very weak points on a network, this issue may be the limiting factor on the capacity and the number of WPPs that may be connected.

The other three types of generators, i.e., Type-B, Type-C and Type-D can control their step voltage changes to some extent by varying degrees. However, this requirement should be considered on the basis of the wind farm as a single electric generator rather than as an individual WPP.

Depending on the frequency and magnitude of these switching events, they can accelerate the wear and tear of the gearbox, leading to premature mechanical failure. Utilities (grid operators) specify limits on the maximum instantaneous step change in voltage that a WPP may cause.

(h) Harmonics

Harmonics (see Figure 9.13) are periodic sinusoidal distortions of the supply voltage or load current. It is a phenomenon associated with the distortion of the fundamental sinusoidal sine wave of the voltage (or current). Harmonics are always present in the grid due to non-linear loads, power electronics, rectifiers, inverters and other PECs. The effects of harmonics are overheating and equipment failure.

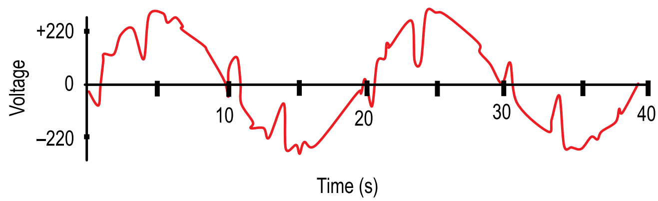


Figure 9.13 **Effect of Harmonics in a Sinusoidal Wave:** The effect of harmonics distorts the sinusoidal waveform.

Interharmonics are those components which have frequencies in between the harmonics of the supply frequency. In other words, they are distortions of the sinusoidal wave at frequencies which are not integral multiples of the fundamental. They are not linked to the grid frequency. Resonances of the grid are excited by this wide band of interharmonics and integer harmonics which may become dangerous and hence, they need to be measured properly and action must be taken appropriately.

Harmonics and interharmonics are defined in IEC 61000–4–7 and amendment (46, 47). The harmonic currents from more than one source connected to a common point are:

$$i_n = \sqrt[\alpha]{\sum_k i_{n,k}^{\alpha}} \tag{9.19}$$

where,

i_n = Harmonic current of the order n

$i_{n,k}$ = Harmonic current of the order n from source k

α = Exponent for harmonic (1 for $n < 5$, 1.4 for $5 \le n \le 10$ or 2 for $n > 10$).

Constant speed WPPs are not expected to cause any harmonics. Today's variable speed WPPs hardly emit any harmonics, as they use pulse width modulation (PWM) techniques by which low order harmonics are eliminated. The modern controlled inverters in the WPPs use insulated gate bipolar transistors (IGBT) or integrated gate commutated thyristors (IGCT).

Following two types of PWM inverters are commonly used:

- Fixed clock frequency
- Variable clock frequency.

Fixed clock frequency type produces individual interharmonics in the range of the clock frequency and multiple harmonics with such frequency. *Variable clock frequency* type, presents a wide band of interharmonics and multiple harmonics which reach their peak at the resonance frequency in the grid.

Remedies for harmonics range from simple passive shunt filters to active filters, given below:

- Provide shunt filters at the PCC of non-linear loads to reduce the harmonic currents flowing all over the network, resulting in lower voltage distortions.
- Use series filters (active and passive) for large integrated wind farms. Series tuned LC passive filters can be provided at the PCC which can be designed to provide the reactive support at fundamental frequency also.

- Use on-load tap changer (OLTC) transformers at the central substation transformer or with each individual WPP transformer.
- By proper control algorithm, the WPP side voltage can be kept constant (irrespective of the grid side variations) by using asynchronous link for interfacing the WPP to the grid.
- Amorphous metal transformers are less sensitive to overfluxing and harmonics. Hence, their use (instead of conventional CRGO steel transformers with the WPPs) reduce the no load power loss as well as the magnetising VAr requirement.

9.3.4 Overview of Local Impacts

The local impacts due to the grid connection of various types of WPPs are summarised in Table 9.2.

Table 9.2 Overview of Local Impacts of Wind Power

S.No.	Local Impacts	Type A and Type B WPP	Type C WPP	Type D WPP
1.	Changes in node voltages and branch flows	Occurs but compensation possible with capacitor banks, SVCs/ STATCOMs	Yes, compensation possible, but dependent on PEC rating	Yes, compensation possible, but dependent on PEC rating
2.	Fault currents and protection schemes	Protection possible with conventional protection schemes and mechanical torque limiters	Protection possible till PEC limit and then, immediately disconnected	Protection possible till PEC limit and then, immediately disconnected
Power Quality				
3. (a)	Slow voltage variations (*steady state*)	Present but not disturbing	Unimportant because the PEC in rotor circuit acts as an energy buffer	Unimportant, because the PEC in stator decouples the generator from grid
(b)	Rapid voltage changes (*Flicker*)	May occur particularly in weak grids	Unimportant because the PEC in rotor circuit acts as an energy buffer	Unimportant, because the PEC in stator decouples the generator from grid
(c)	Transients	Present	Present to a lesser extent	Present to a lesser extent
(d)	Harmonics	Not present	Not present in modern WPPs	Not present in modern WPPs

9.4 SYSTEMWIDE IMPACTS OF WIND POWER

Systemwide impacts are those, the cause of which cannot be localised but are a consequence of wind power that cannot be directly related to individual WPP/wind farm. Nevertheless, they are strongly related to the WPP penetration level in the

grid as a whole. As compared to conventional power plants, WPPs in a power system behave differently due to the following reasons:

- Different generator technologies used in WPPs (as against directly connected constant speed synchronous generators in conventional power plants) with indirectly connected full rated PEC with WRSGs, PMSGs, SCIGs and directly connected SCIGs, WRIGs, DFIGs employed in WPPs.
- Transient voltage support due to reactive current during faults.
- Steady state reactive power/voltage regulation abilities.

The systemwide impact affects the:

- Reactive power
- Stability
- System balancing and frequency.

9.4.1 Reactive Power and WPPs

In India and some countries, WPPs are mainly connected on distribution networks where the resistance of the lines are high, as well as the *R/X* ratio is high unlike transmission networks. The active power injection induces a significant voltage rise effect especially on weak grids, as it is distributed generation (DG). These are weak points in the grid network and hence, reactive power losses are considerable which limit substantial contribution of the WPPs to the reactive power balance at the transmission level. Therefore, reactive power and voltage control are the key issues for integrating wind power into low voltage (LV) and medium voltage (MV) networks.

When smaller generators in the WPPs (as compared to much larger conventional generators) are integrated into subtransmission or even distribution systems far from load centre, the amount of reactive power reserve needed in the transmission grid is considerably reduced. The reactive power of a WPP is specified as ten-minute average value. It is a function of the ten-minute average output power for 0.10%, ..., 90%, 100% of the rated power P_{rated}.

Although increasing the amount of wind penetration reduces the reactive power reserves in the transmission system, it can be taken care by compensating the use of switched capacitors or FACTS devices in the constant speed Type-A and Type-B WPPs. Variable speed Type-C WPPs are equipped with partial power back-to-back PECs that operate at unity power factor, as reactive power can be controlled. Variable speed Type-D WPPs equipped with full power, four-quadrant operating back-to-back PECs can either produce or absorb reactive power under normal situation.

9.4.2 Power System Stability and WPPs

In general, *stability* of a power system is defined as the ability of a system to return to a steady state after a disturbance. Power system stability can be at the local level or at the global level.

At local level, stability problems can lead to:

- Loss of synchronism of an individual generator in a WPP
- Run-away condition of induction generators in WPPs
- Tripping of WPPs due to voltage sags
- Voltage instability at the PCC in the wind farm.

At global level, stability problems can lead to:

- Loss of synchronism between network areas which may result in islanding
- Inter-area oscillations with insufficient damping
- Frequency drop which may cause excessive load shedding
- Voltage collapse which may result in power system blackout.

Power transmission in a power system is limited by the voltage stability of the power system and at the same time, by the thermal stability of the conductors. Usually, for long transmission lines (>100 kM long) voltage stability limits are reached before the thermal limits. However, with greater penetration of WPPs along with the voltage and thermal stability limits, now grid operators want wind project developers to examine the steady state stability, dynamic stability as well as the transient stability limits of the power system due to the connection of the WPP/wind farm.

To investigate the impact of wind power on the grid dynamics and stability, adequate WPP models and simulations are essential.

(a) Voltage Stability

Voltage stability is the ability of the network to maintain steady voltage at all buses within the operational ranges under normal conditions and after being subjected to disturbances. Sufficient reactive power support is essential for the voltage stability and voltage control in a grid network. A voltage stability problem occurs if the reactive power supply in the sensitive regions is not sufficient anymore, i.e., nearby reactive power sources like SVCs or generators are not providing sufficiently. A possible outcome of voltage instability is the loss of load in an area or loss of synchronism of some generators or tripping of transmission lines, leading to cascading outages. Instability can occur in the form of a progressive fall of voltage or rise of voltage in some buses especially when the WPPs are connected in network.

Voltage collapse is a phenomenon that can be caused by a reactive power shortage in a certain location of the network which is often a highly loaded region or a highly loaded interconnector between the two network areas. Voltage collapse accompanying voltage instability may lead to a blackout or abnormal low voltages in a major part of the grid which may be restored after some loads are tripped or when the transformer tap changers are activated. The major cause of a progressive (gradual) voltage collapse is often a mismatch in local reactive power consumption and production that occurs as a result of the changes in load or generation (due to changes in wind speed). Increased reactive power consumption can lead to voltage instability, if the transmission grid is weak.

Voltage stability margin is normally presented in the form of *P–V* curves (see Figure 9.14) which plot the load bus voltage as a function of power that may be sent over a transmission line at a given load power factor. In this example, *P–V* curves have been plotted for three different load power factors for a particular transmission line reactance. For each condition, the nose of the *P–V* curve represents the limit between stable and unstable operation. An attempt to transmit power beyond this limit results in voltage collapse. For a unity power factor curve, any increase in the load beyond 1 p.u. results in voltage collapse. However, when the load power factor changes to 0.9 (leading) through reactive power compensation at the load bus, then the load can be increased to nearly 1.6 p.u. before voltage collapse occurs. Hence, voltage stability margins may be improved by the application of FACTS devices such as STATCOMs, SVCs or DVRs at the PCC where the reactive power capabilities of the WPPs themselves are insufficient to maintain an adequate security. Two phenomena can have global effects on the network resulting in voltage collapse given below:

- Short term voltage stability (generally caused by the fast acting load components like induction motors, PECs and HVDC converters).
- Long term voltage stability.

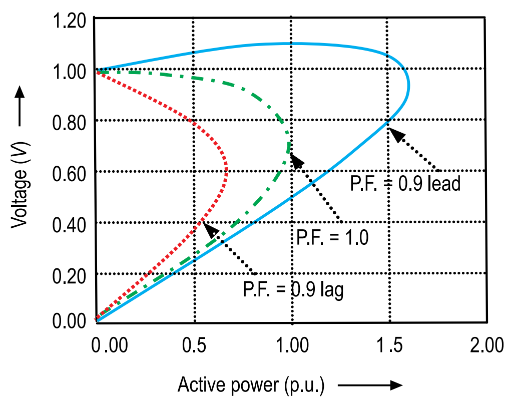


Figure 9.14 ***P–V* Curves for Voltage Stability Analysis at a Load Bus:** When the load power factor changes to 0.9 (leading) through reactive power compensation at the load bus, the load can be increased to nearly 1.6 p.u. before voltage collapse occurs.

Short term voltage stability problems can occur if the static stability limit of the network is exceeded within a time frame of a few seconds after a disturbance, such as the loss of a large generator.

WPPs can have a significant impact on the voltage stability which is a short term phenomenon following a network fault.

- Constant speed Type-A and Type-B WPPs with induction generators absorb higher reactive power when voltage is low.
- Variable speed Type-C WPPs with DFIGs Crowbar may bypass the PEC during a fault, which then behaves as an induction generator.

Reactive power reserves are not significant in the short term ranges because the excitation of synchronous generators has considerable thermal overload capabilities in the time frame of a few seconds which can provide more reactive power than in the time frame of several minutes. For SVCs and PECs, the reactive power limits in the short term and long term are the same and hence, this has to be considered during short term stability simulations. Moreover, switchable capacitor banks in Type-A and Type-B WPPs cannot support the system in the short term range because switching times of capacitor banks are usually too long. Besides the impact on dynamic reactive reserves, the impact of wind generation on short term voltage stability limits is related to the active power support of WPPs during low voltages.

Short term voltage stability is a more critical issue, even if the synchronous generators can provide much more reactive power in the short term range because of thermal overloading capabilities. The stability limits are analysed by transient simulations where the system behaviour is investigated for various critical contingencies in the system.

Long term voltage stability could let the power system run into a voltage collapse in a time range of several minutes. Immediately after a major disturbance, the voltage drops, so the loads also drop because of their voltage dependence. Subsequently, the transformers feeding subtransmission networks and distribution networks start increasing the voltage at their secondary side by tap control actions. Consequently, active and reactive power loads increase again and can possibly drive the system into a voltage collapse especially when reaching overexcitation limits of synchronous generators or when SVCs start saturating. Long term voltage stability can be analysed by using *P–V* curves (Figure 9.14), i.e., by calculating a sequence of steady state load flow calculations versus varying load levels in the network or increasing power transfer levels into weakly connected network areas.

(b) Thermal Stability

Thermal stability helps in verifying that the transmission lines, transformers and other equipments are not overloaded due to the WPP/wind farm power infeed. Overhead transmission lines reach their thermal stability limit if the electric current heats the conductor material to a certain temperature (between 50°C and 100°C) above which the conductor material starts to soften which also depends on the material, ambient temperature, wind velocity, solar radiation, surface conditions of the conductor and the altitude above the sea level. It also depends on the other associated equipment like isolators, circuit breakers, etc. and hence, the thermal limit is set at the lowest rating of the associated equipment.

When high capacity WPPs are to be connected, the current carrying capacity of the line needs to be calculated independent of the system configuration. Short transmission lines (< 100 km) have low thermal limits and hence, need to be strengthened if the wind power penetration is high (typically, above 10% or more).

(c) Steady State Stability

Steady state stability of power system refers to the ability of a system to return to the steady state after a disturbance of small and gradual changes in the load with

conventional excitation and governor controls. While planning for a grid connected WPPs/wind farms, an important factor to be considered is the effect of the WPP on the steady state voltage level of the power system. Using computer-based software, steady state analysis is undertaken through power flow simulations, usually with the WPP despatched at a power level which is expected to have the maximum system impact. Active power injected at the PCC of the grid is a function only of the WPP project size. Reactive power capability may be provided by variable speed WPPs and constant speed WPPs (with capacitor banks or STATCOMs). But from a steady state perspective, both are modelled as reactive power injected at the PCC in response to the voltage at some control bus with appropriate adjustments made for reactive power consumption on the load side of the PCC.

(d) Transient Stability

Transient stability of a power system refers to the ability of a power system to return to a stable operating condition following a major disturbance such as a transmission line short circuit or tripping of a large generating power plant. The behaviour of the system is highly dependent on the type and duration of the disturbance. To ensure transient stability in a system, often a number of critical contingencies have to be simulated at different locations. Transient stability depends on both the initial operating state and the severity of the disturbance which is usually cleared by opening up the circuit breakers to isolate the fault. The main parameters influencing transient stability are given below:

- Rotor inertia/turbine power during the fault
- Depth of the voltage sag
- Duration of the voltage sag
- Short circuit impedance of the grid to which the generators are connected.

In early years, small WPPs/wind farms did not contribute to transient stability and were tripped usually. But now, grid operators expect large wind farms to remain connected so as to maintain the stability. During transient faults, reactive power has to be fed into the grid to support the system voltage. Generators with small fault current contribution are required to support the grid voltage in case of faults by supplying reactive power proportional to the voltage drop. In order to provide this voltage control, the WPP/wind farm is expected to meet a certain range of reactive power exchange at full active power output (0.9 leading to 0.9 lagging) and rated active power. The overall impact of wind generation on the transient stability in a transmission system can be assumed to be relatively small.

To support the transient stability of a power system during disturbances, new grid codes require WPPs to ride through the fault or stay connected to the network and deliver power during low voltage transients of a given magnitude and time duration. The grid operators need some power electronics to be provided at the wind farm substation or some on-board electronics of the WPP that can help it to ride through the faults by generating extra reactive power to hold the line voltage. The new grid codes have resulted in significant design changes in the modern WPPs.

There can be no general statement possible whether the wind generation improves the transient stability margins of a power system or if the impact is rather negative. The answer depends on the location of WPPs in the power system network and the type of WPPs in the system. The problem has to be analysed on a case-to-case basis. Variable speed Type-C and Type-D WPPs have been found to have little impact on the transient stability performance of the system. The effects of wind power on transient stability are as follows:

- During faults, if the voltage control of WPPs is not fast enough, larger voltage dip will occur and dynamic power reserve will be reduced.
- A negative impact on transient stability can be there if the high capacity WPPs/wind farms are located in one particular area due to the increase of tie-line flows.
- Only a low level of kinetic energy increases during faults when the synchronous generation in the grid is less. This helps in the increase of the transient stability export limits and improves the voltage recovery.

For more accurate decisions, each wind power project has to be analysed separately (depending on the location of windy area, type of WPPs and other factors) by transient simulation with the power system analysis software DigSilent® PowerFactory, MiPower® and others. For evaluating transient stability, two indices, i.e., critical fault clearing time (CCT) and critical area exchange (CEA) are important. The former represents a useful measure for characterising the transient stability performance of a given dispatch scenario, e.g. a three-phase fault with a fault clearing time of 100 ms and hence, have to be calculated in all cases.

(e) Dynamic Stability

Dynamic stability refers to the stability of a power system subjected to a relatively small and sudden power system disturbance that can be described by linear differential equations and can be stabilised by a linear and continuous supplementary stability control. The systemwide impact on the dynamic stability of a power system is mainly due to the fact that the power produced by WPPs is not based on the conventional WRSGs but on the different types of electrical generators (i.e., SCIGs, WRIGs, DFIGs and PMSGs) used in WPPs and how they respond to changes in their terminal voltage and frequency. The voltage stability, thermal stability, steady state stability and transient stability can also affect the dynamic stability of the power system.

9.4.3 Frequency and WPPs

Frequency is the number of changes or cycles per second of the voltage and current in an AC system and is measured in hertz (Hz). The electric supply system normally operates at a more or less constant frequency of 50 Hz. It is global variable which means that wherever in the grid network it is measured, the value remains the same (unlike the voltage). In India and Europe, the nominal value of frequency is 50 Hz and when this is maintained at 50±0.1 Hz, the power system is said to be stable. Frequency deviations (see Figure 9.15) can cause malfunctioning of some equipment and frequency steered power electronic devices.

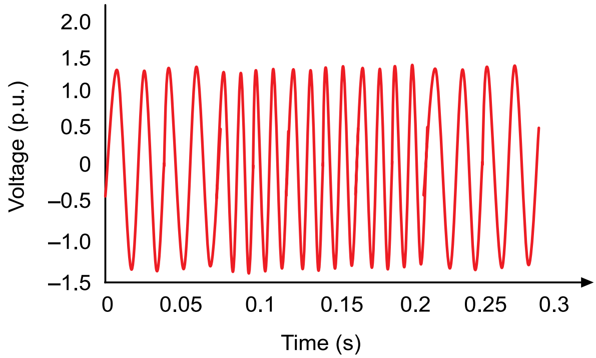


Figure 9.15 **Voltage Frequency Variation.**

The grid frequency is a result of the combined action of all the power controllers on the grid, mainly influenced by large power stations. The frequency of the grid is controlled by the flow of active power in an electric system. The power from the prime movers is adjusted to compensate and keep the frequency as constant as possible and within the designed limits. For every generator (here, the WPP) connected to the grid, the following relation is valid:

$$J\frac{d\omega}{dt} = T_m - T_e \tag{9.20}$$

where,

J = Moment of inertia of generator rotor

Ω = Angular speed of the rotor

T_m = Mechanical driving torque of the prime mover applied to the generator rotor

T_e = Electromagnetic (or load) torque due to the loads in the system.

Since each generator is connected to the grid in synchronism with the others, Eq. (9.20) may represent the operation of the whole system. The imbalance between the wind power fed to the grid and the sum of the power of the connected loads causes a variation in the network frequency. Since the power system loads change, there is an imbalance between these two torques T_m and T_e. The generator rotor tends to increase or decrease the speed which is directly proportional to the difference of the torques and inversely proportional to its own moment of inertia. Since the power can be expressed as the product of the torque by the angle speed in terms of power:

$$J\frac{d\omega}{dt} = \frac{1}{\omega}(P_m - P_e) \tag{9.21}$$

The initial rate of change of frequency that occurs is purely related to the inertia of the power system at the time when most WPPs behave differently. Therefore, the overall system inertia in smaller network or islanding areas of a power system can significantly be reduced under high wind conditions. The WPP/wind farm must also continue to operate between the minimum and the maximum frequency limits. During normal functioning, the power output of a WPP can vary upto 15% of the

installed capacity in a fifteen-minute span above all, during and immediately after extreme windy conditions.

WPPs and Frequency Variations

Electrical grids operating with WPPs connected to weak, isolated grids can have difficulty in maintaining the normal system frequency. The system frequency varies when gusty winds cause the power output of WPPs to change rapidly. But modern variable speed WPPs using PECs, interface with the grid and limit the output during gusty (or strong wind periods) winds. When frequency changes, variable speed WPPs with synchronous generators instantaneously release or absorb inertial energy and some (resistive) demand is reduced. If there is sufficient wind, the synchronous generators in Type-D WPPs contribute to maintain a constant frequency.

Within certain limits of frequency variation, grid operators require that during underfrequency excursions, WPPs are called upon to make maximum possible power injection to maintain system frequency limits. During overfrequency excursions, the WPP should remain connected and possibly respond to this situation. Generally, the supply of small amounts of wind power into strong grids is not likely to cause any operational problems. The fluctuating power production by WPPs is balanced by other production units. However, in weak grids or when WPP penetration is large (usually, the WPPs are located in rural areas) or autonomous grids (like islands) where the spinning reserve is supplied by diesel or gas systems, the fluctuating voltage and frequency from WPPs can affect the power system.

Variable speed Type-C WPP with DFIG and Type-D WPP with generators full rated PEC connected to the stator output, do not generally contribute to the system inertia. They may, however, contribute to the frequency instability, particularly in smaller power systems with high penetration of wind generation. In case of uncontrollable distributed WPPs, disconnection can be chosen. But some studies show that large wind farms are active contributors to the system stability. It should be noted that the power of constant speed WPPs in higher wind speeds, drops more than pro rata with frequency. Variable speed WPPs, on the other hand, can run at the desired speed, irrespective of the grid frequency.

Constant speed WPPs do not typically act to control the frequency. Rather, they act to synchronise with the frequency at which the grid operates. WPPs, therefore, simply follow the system frequency down during a plant outage. Therefore, high levels of wind integration require a detailed understanding of how WPPs influence the frequency after the generation is unexpectedly lost.

Extensive frequency excursions have effects on the operation of WPPs. The speed of a constant speed Type-A and Type-B WPPs depend directly on the grid frequency. The aerodynamic properties of the WPPs' blades are non-linear, depending on the TSR and hence, on the speed of the WPP. Wind farms must sustain generation between 49.5 Hz and 50.5 Hz for certain periods of time. When these limits are exceeded, the wind farms have to disconnect within 300 ms.

Frequency variations lead to operational, non-optimal TSRs and reduced aerodynamic efficiencies of WPPs. This leads to reduced energy capture and power output of WPPs. A frequency below 50 Hz increases the reactive power consumption

in constant speed WPPs with induction generators. At low frequencies, the VAr output of power factor correction capacitors reduce and affecting the power factor. Low frequency operation increase the flux in transformers pushing them near to saturation, resulting in increased VAr consumption and increased losses (and reduced generation).

A typical stall regulated Type-A WPP with an SCIG or a Type-B WPP with a WRIG cannot contribute to the restoration of system frequency of 50 Hz as in conventional power plants for stability. But, it is able to stay connected during underfrequency events. However, it is likely that these events are coupled with an undervoltage condition which results in the disconnection of generator. One possible solution is to interface the individual WPP to the grid using an asynchronous link through an appropriate control logic by which the WPP frequency is kept constant, even as the grid side frequency which varies.

9.5 WIND POWER VARIABILITY

The wind power variability is a major problem for the integration of wind power into the grid network. Even during the normal operation of the WPPs, the quality of the power produced continuously varies due to the effects of wind turbulence, wind shear, tower shadow and the operation of control systems (transformer tap changing, capacitor switching, etc.).

The variations in net wind power output that can be expected for a given time period are within the minute, hour, hour-to-hour, monthly to seasonal, annual and interannual variable. The distinction between these specific time scales can help in balancing different types of power plants including WPPs.

(a) ***Variations within a Minute:*** Due to the aggregation of WPPs and wind farms, these fast variations (seconds to minute) of aggregated wind power output (as a consequence of turbulence or transient events) do not drastically affect the power system.

(b) ***Variations within an Hour:*** The intra-hour variations are important especially when the WPPs reach their cut-out wind speeds and shut down rapidly from supplying full power to zero power during storms. When the wind penetration is high and variations in supply become equal to variations in demand, it adversely affects the power system reserves. Hence, accurate wind predictions help in avoiding such situations.

(c) ***Hour-to-Hour Variations:*** A single large WPP or a wind farm can exhibit hour-to-hour power swings of upto 60% of the capacity. But aggregating the various large WPPs and wind farm outputs installed at a variety of geographical locations can tide over this variability. Errors in the wind power hour-to-hour predictions are possible but with more research being done in this area, prediction errors are decreasing and solutions are available.

(d) ***Monthly and Seasonal Variations:*** Although these monthly and seasonal variations are not very important for day-to-day operation and management of the grid, yet they are important for power system planning and electricity trading due to forward contracts where the wind power volume has an influence on price.

(e) ***Interannual Variations:*** The interannual variability of the wind energy is also not very important for daily operation and management. However, it is seen that this variability is much less than the variability of hydro inflow.

9.6 ISLANDING

If a section of a grid is isolated (islanded) from the rest of it and if the WPP/wind farm continues to function as a power source on that section of the grid, then this phenomenon is called *islanding*. In such a condition, the system voltage rises, creating an unbalance between the reactive power production in the grid and the consumption of reactive power of the WPP(s). The worst possible case is when there is a combination of maximum wind power production and a minimum of load in the islanded network as well as fixed reactive power compensation corresponding to the full compensation of the WPP(s) at rated output power. The time taken to reach a balance depends on the electric time constants of the electric generator(s), i.e., a few cycles.

The islanding causes:

- Possible voltage problems because of reduced reactive power reserve in the islanded network
- Power reduction in the WPPs due to low voltages that can make the situation worse.

Islanding results in stability problems such as:

- Frequency drops faster, resulting in increased load shedding
- Total generation (synchronous + wind) remains constant
- Inertia J is reduced.

As long as constant speed Type-A and Type-B WPPs are connected to the distribution network, their terminal voltage is fixed and the power factor correction capacitors merely reduce the reactive power drawn from the grid. When the load is removed in the islanded condition, the induction generator also tends to accelerate, leading to increase in frequency by which a resonant condition known as *self-excitation* sets in, leading to large overvoltages and damage customers' equipment.

If WPPs keep on running in the isolated part of the grid, then it is very likely that the two separate grids will not be in phase after a short while. If the connection to the main grid is re-established in this condition, it may cause huge current surges in the grid and the WPP. It would also cause a large release of energy in the mechanical drive train (i.e., shafts, gearbox and the rotor of the WPP) much like a hard switching of the WPP generator onto the grid. The electronic controller of the WPP has to, therefore, constantly monitor the voltage and frequency of the

AC in the grid. In case, the voltage or frequency of the local grid drifts beyond the permitted limits within a fraction of a second, the WPP will automatically disconnect from the grid and stop itself immediately afterwards.

To prevent such abnormal overvoltages during islanding, it is essential that any production of reactive power in the network is very quickly absorbed or interrupted. This can only be achieved by means of dynamic compensation devices, i.e., static VAr compensators (SVCs), STATCOMs or DVRs.

With regard to systemwide impacts, the WPP responses to electric grid disturbances are summarised in Table 9.3.

Table 9.3 Typical WPP Responses to Electrical Grid Disturbances

S.No.	Typical Grid Disturbances	Typical WPP Responses
1.	Three-phase fault on a random line or transformer with definitive disconnection without any attempt at reclosing	WPP will trip if: T = 0 s for three-phase fault T = 100 ms
2.	Three-phase fault on a random line with unsuccessful reclosing	WPP will trip if: T = 0 s for two-phase fault T = 100 ms–150 ms T = 400 ms–450 ms automatic reclosing At T = 500 ms–950 ms, disconnection of the fault (may be shorter around 100 ms for distribution) Withstand 3 faults within two minutes Withstand 6 faults if the delay between the faults is of five minutes
3.	Change in terminal voltage V at point of interconnection	WPP will trip if: V < 30% for more than 100 ms V < 70% for more than 300 ms V > 110% for more than 1 s V > 113% for more than 300 ms V > 120% for more than 100 ms
4.	Change in frequency f	WPP will trip if: f > 51 Hz for more than 1 s or f < 49 Hz for more than 1 s
5.	Short circuit	For terminal voltage below 50%, constant speed type A and type B WPPs contribute to the fault, otherwise get disconnected. For variable speed Type-C and Type-D WPPs, the contribution to the fault is limited by PEC limits or they get disconnected
6.	Real power control	Follows wind speed fluctuations and produces power for light to moderate wind speeds and is held constant above the rated wind speed
7.	Reactive power/voltage control	Contributes adequately for power factor control, voltage control with additional equipment (like capacitors, SVC, STATCOM or DVR)
8.	Islanding	Not desirable. WPP is tripped at interconnect substation to prevent islanding.
9.	Zero power (idling) operation	Provides reactive power support only when generating

9.7 WPP ELECTRICAL SAFETY AND GRID

From safety point of view, every WPP is mandatorily equipped with some basic essential electrical protective provisions and some critical features are duplicated to address the systemwide impact. Some of them are highlighted below:

- Active power control of WPP/wind farm
- Overfrequency (one level delayed)
- Underfrequency (one level delayed)
- Overvoltage (one level delayed, one level instantaneously)
- Undervoltage (one level delayed)
- Loss of mains (instantaneously)
- High overcurrents short circuit (instantaneously)
- Earth fault (provided)
- Neutral voltage displacement for stability during grid faults (It puts forward new requirements to the protection of WPP.)
- Thermal overload (provided)
- Autoreclosing (if necessary) especially required for large WPPs/wind farms
- Remote control of all the above operation (optional).

9.7.1 Active Power Control of WPP

Any form of active power control of a WPP requires a reduction in the output power. Although the input, i.e., the wind is variable, but since the fuel (air in this case) is free, reduction in the wind farm output is always likely to be used as the last resort by the energy regulators of conventional power stations as the fossil fuel (come at price) and therefore, can be saved as long as the wind blows.

Active power control is possible, as the output from the pitch regulated WPPs is possible to be increased or decreased at any moment by pitching the blades. In exigencies, it is possible to even control the output from the stall regulated WPPs by shutting down individual WPPs within a wind farm, although a bit bizarre, but for the grid operator, it is an Effective and valuable strategy.

For stable operation of the grid network required for balancing, at times, the transmission operator (TSO) asks the WPP owners to operate in delta control, i.e., output is kept at a fixed level, even though more power can be extracted from the wind. Depending on the grid condition, the TSO may also instruct them to control the ramp rate, i.e., to limit the rate of output power increase if the wind speed increases rapidly or when WPPs return to service after some outage.

If the wind speed drops suddenly, it is not possible for the wind farm to control the negative ramp rate automatically. However, if the wind forecast is quite good, it is possible to predict a reduction in the wind speed in advance and the WPP output can then be gradually reduced in advance to maintain the negative ramp rate at an acceptable level.

Table 9.4 provides a summary of the WPP capabilities with respect to the grid network.

Table 9.4 Summary of WPP Capabilities

S.No.	Capabilities	Type-A WPP	Type-B WPP	Type-C WPP	Type-D WPP
1.	Reactive power compensation and voltage control	Possible with shunt capacitors, SVC/ STATCOM/ DVR	Possible with shunt capacitors, SVC/ STATCOM/ DVR	Possible with PECs	Possible with PECs
2.	Short term balancing power control and frequency	By blade pitching and WPPs being switched in and out	By blade pitching and WPPs being switched in and out but a little more better	By blade pitching and/or PEC control and WPPs being switched in and out	By blade pitching and/or PEC and WPPs being switched in and out
3.	Long term balancing output power availability	Possible only to some extent due to stochastic nature of wind	Possible only to some extent due to stochastic nature of wind	Possible only to some extent due to stochastic nature of wind	Possible only to some extent due to stochastic nature of wind
4.	Contribution to fault current	Yes. To some extent	Yes. To some extent	Difficult beyond thermal limit of PEC, as it may be damaged	Difficult beyond thermal limit of PEC, as it may be damaged
5.	Fault-ride-through (FRT) capability	Depends on wind speed, fault duration, grid strength and hence, voltage instability risk exists.	Depends on wind speed, fault duration, grid strength and hence, voltage instability risk exists.	Difficult beyond thermal limit of PEC, as it may be damaged	Difficult beyond thermal limit of PEC, as it may be damaged

9.8 WPP INERTIA

All rotating generating systems have inertia. Each element of a rotating body contributes to the stored energy in the system. This energy is released as the body reduces speed. For a WPP, the sum of the energy in all such elements like blades, hub, shaft, gearbox and generator rotor is the stored energy. The issue is how to transfer this stored energy to the electrical system which may be modelled as a rotating flux on the stator.

In constant speed WPPs, the rotor is flux-locked to the stator. The retarding electrical system brakes the generator rotor, thus extracting the stored energy. The rate of extraction of energy is, therefore, dependent upon the rate of change of frequency of the system. They exhibit inertia constants in the range of steam turbine plants which is often expressed as a per unit value in MW/MVA installed. In case of Type-A WPPs, the value lies between 4 MW/MVA–5 MW/MVA.

In variable speed Type-D WPP, the generator rotor is also flux-locked to the stator with full rated PECs and behaves almost in the same way. As seen earlier, the retarding electrical system brakes the generator rotor, thus extracting the stored energy. In this case, the inertia constant is in the range 0 MW/MVA unless it is designed otherwise.

In the case of variable speed Type-C WPP with DFIG, the partial rated PEC injects power into the rotor at varying frequencies to compensate for the difference in rotor and system speed. There is, therefore, no effective flux lock as in constant speed WPPs such as in Type-A and Type-B. This prevents the stored energy in the rotor from being extracted into the system as system speed falls. The inertia of such a device is, therefore, close to 0 MW/MVA unless it is designed to behave differently.

Type-D WPPs with full rated PECs do not generally detect the change in system frequency to serve as a trigger and as a means of extracting energy from the prime mover. So, the possible solutions for such Type-D WPPs to handle the instantaneous loading are given below:

- Ensure that the WPP is robust against rate of change of frequency (RoCoF) by adopting alternative approaches to detect power islanding.
- Equip WPPs with additional controls to modify active power output during frequency deviations as a *virtual inertia*.
- Use of large flywheel generators like large diameter direct-drive WPPs or flywheel coupled synchronous compensators is also a solution.

9.9 PLANT LOAD FACTOR (OR CAPACITY FACTOR)

A power plant with 100% load factor is one which runs every day at full 100% rated power throughout the year (8760 hours). There is no downtime for repairs or refuelling which is an impossible goal for any power plant. Typically, coal plants have 75% capacity rating, since they can run day and night during any season of the year, if coal is available in stock. Fossil fuel plants generally have a capacity factor of 75% (in 8760 hours) typically.

However, WPPs are different from the conventional power plants. The wind is not available 100% of the time. WPPs depend on the speed of the wind. Therefore, WPPs do not operate 24 hours a day. A WPP, in a typical wind farm, operates from 65% to 80% of the time, but usually at less than full rated capacity because the wind speed is not always at optimum designed WPP rating levels. Generally, over the course of a year, a typical WPP generates around 30% of the theoretical rated output. This is known as its *plant load factor (PLF)* or *capacity factor*.

$$\text{PLF} = \frac{\text{Actual annual WPP energy output}}{P_{\text{rated}} \times 8760} \tag{9.22}$$

where,

P_{rated} = Rated power of WPP.

8760 is the number of hours in one year.

The average PLF of different types of power plants is given in Table 9.5.

Table 9.5 Capacity Factors of Power Plants

S.No.	Power Plant Technology	Average capacity factor (%)
1.	Sewage gas	90
2.	Farmyard waste	90
3.	Energy crops	85
4.	Landfill gas	70–90
5.	Combined cycle gas turbine (CCGT)	70–85
6.	Waste combustion	60–90
7.	Coal	65–85
8.	Nuclear power	65–85
9.	Hydro	30–50
10.	Wind energy	25–40
11.	Wave power	25

One could over-estimate the annual energy output from a WPP by using the rated wind speed at a certain location. But, by knowing the capacity factor of WPP, the annual energy output can be more accurately calculated backwards. PLF alone is not enough to compare different WPPs at different locations but other technical data of the WPPs and wind speed distribution are also needed. This data ensures whether the WPP is efficient for the given location and compares between two sites.

Hence, depending on the location, the PLF can range between 30% to 35% in coastal areas having more and greater wind speeds and at inland locations, it could be less to around 18%.

EXAMPLE 9.1

Calculate the actual annual energy output of an 800 kW WPP if the PLF is 30%.

Solution:

Actual energy output from WPP (kWh/year) = Installed capacity of WPP × 365 × 24 × 0.30

Actual energy output from wind turbine (kWh/year) = 800 × 2628 h

Actual energy output from wind turbine (kWh/year) = 2102400 kWh

9.10 CAPACITY CREDIT

Due to its variability, wind power raises the issue of the displacement of conventional generating units (e.g. thermal units). WPPs connected to the utility grid function as fuel savers. The capacity credit is strongly dependent on the climatic and geographic conditions applicable for the considered region or country. The capacity credit of wind power is a quantification of the effective contribution of wind generation to

the power system, e.g. the amount of thermal units that can be replaced, thereby assessing the value of wind power (or any renewable energy source).

As the wind may not blow at the time of the yearly peak load the utility is forced to build generation equipment to meet the load without considering the wind, hence it can be said that the wind power cannot receive a capacity credit. But, this argument is not true because the lack of wind is not different in its effect from a power plant failure and can be treated in a standard mathematical observation to determine the effective capacity of the WPP.

Capacity credit of wind power may be defined as the power of conventional generating power plants (e.g. thermal units) that can be substituted by a variable generation (e.g. wind power or photovoltaic) without decreasing the power system's reliability.

$$D_c = P_{eR} \frac{E_w}{E_c} \tag{9.23}$$

where,

D_c = Displaced conventional power plant

P_{eR} = Rated power of the WPP

E_w = Effective capacity of the WPP

E_c = Effective capacity of the conventional power plant.

EXAMPLE 9.2

A utility system has to meet both reliability and energy production requirements. So, a state utility needs to add 200 MW of coal fired generation to its grid. The effective capacity of this generation is 0.90. With an effective PLF of 0.30, determine the rating of WPPs that is required to displace the 200 MW of coal generation.

Solution:

$$D_c = P_{eR} \frac{E_w}{E_c}$$

$$\therefore \qquad P_{eR} = D_c \frac{E_c}{E_w}$$

$$= 200 \, \frac{0.90}{0.30} = 600 \text{ MW}$$

From reliability point of view, a wind farm or several wind farms consisting of about 100 WPPs of 6 MW each is/are required to be put up to displace the proposed conventional fired plant. If, for example, the capacity factor of the coal power plant is 0.7 and for the WPP is 0.35, then the WPPs would produce more energy per year than the displaced coal plant. This means that less coal would be burned at some existing coal plant, so the WPP may have both capacity credit and fuel saving credit. Therefore, adding WPPs to maintain reliability may force the capacity factors of other power plants on the utility grid to change.

Hence, capacity credit is highly related to the reliability of the system and is typically calculated in adequacy studies. A general agreement is that the economic selection of a power plant (which is its cost when combined with the costs of other power plants making up a total electric utility generating system) should result in a minimum cost of electricity. The established method of checking this criterion is to simulate the total utility system cost over a period of time which represents a major fraction of life of the power plant under consideration.

SUMMARY

It has been seen that the impact of wind power on the grid network is different, depending on the type of WPP employed and also on the capacity and number of WPPs connected. These can impact the wind power quality at the local level and systemwide level. It can be summarised that due to wind power on the grid, there is a:

- Positive influence on transient stability in the grid, but is constrained to the export limits
- Negative impact on voltage stability in the grid, constrained to the import limits if
  - Reactive reserves are lowered leading to additional SVCs/STATCOMs/DVRs
  - Unreliable power output, low voltage ride through capability is required
- Negative impact on frequency drops in case of islanding during power import.

Therefore, proper planning and estimation is to be done for undertaking wind power projects so that the stability of the grid network is maintained in conjunction with the conventional power plants.

EXERCISES

9.1 Explain the electrical parameters that affect the power quality due to the import and export of electric power by the WPPs to the grid.

9.2 Due to the connection of WPPs to the grid, list the local and systemwide impacts on the quality of the electric power.

9.3 Explain the terms local impacts and systemwide impacts.

9.4 Justify why voltage is called a local variable and frequency is called a global variable.

9.5 Describe the significance of branch flows and node voltages.

9.6 Explain the phenomenon of self-excitation of induction generators.

9.7 Describe how Type-A, Type-B, Type-C and Type-D WPPs respond in terms of contribution of fault current during faults.

9.8 Discriminate the slow voltage variations, flicker, transients and mention their causes.

9.9 How are the voltage dip, voltage swell, voltage step changes and the voltage unbalance different from each other.

9.10 Explain harmonics related to the WPPs.

9.11 How are three-phase faults, two-phase faults and the transient faults different from each other.

9.12 Discuss the responses of Type-A, Type-B, Type-C and Type-D WPPs to faults.

9.13 Explain the impact on the voltage variation caused by the short circuit power level at a point which connects the consumer and the wind power station.

9.14 Explain the combination of high/low consumption and high/low wind gives the highest or lowest voltage.

9.15 Describe the causes of harmonics due to WPPs connected to the grid and its remedy.

9.16 Explain the term rotor speed stability with respect to induction generators.

9.17 Describe the fault-ride-through phenomenon of WPPs.

9.18 Discuss how reactive power compensation is addressed in Type-A, Type-B, Type-C and Type-D WPPs.

9.19 Distinguish between short-term balancing and long-term balancing with regard to WPPs connected to the grid.

9.20 Explain how WPPs can participate in secondary frequency control.

9.21 Discuss the phenomenon of islanding with the WPPs connected.

9.22 Explain the significance of plant load factor of WPPs.

9.23 Calculate the actual annual energy output of a 1.25 MW wind power plant if the PLF is 25%.

10

Grid Integration of Wind Power

HE makes the clouds his chariot and rides on the wings of the wind.
—Psalms 104:3

Learning Outcome

On studying this chapter, you will able to distinguish the different issues that are to be addressed while integrating wind power plants into the electrical grid network.

CHAPTER HIGHLIGHTS

10.1 INTRODUCTION

Wind power, as a generation source, has specific characteristics including variability, geographical distribution, favourable economics, abundance and environmental benefits. A moderate share of wind power in a power system does not create any problem, although it is variable. Grid integration of WPPs can be defined as the technical and economic ability of WPP/wind farms to connect and operate within the electric power supply network in a manner which is compatible with the day-to-day operation and short-term security of the electric supply system as a whole. When the wind blows, the power companies can save coal by the thermal power plants, the gas by the gas-fired plants, water in the hydropower dams and use this saved power when the wind slows down.

Conventional electric power systems are inherently variable in terms of both demand and supply but they are designed to effectively cope with the conventional variations through their configuration, control systems and interconnection. But the wind power variations and their predictability are of key importance for the integration and optimal utilisation of wind in the power system.

Although the wind power is variable, results from the analyses show that the power system can handle short-term variability. System operators only need to deal with the net output of large groups of wind farms and the wind power variability is viewed in relation to the level and variation in power demand.

When the WPPs are of smaller capacity and their contribution to the grid is smaller, the rules governing their grid connection are more relaxed because the grid is electrically stiff, as the major stable feed of electrical power is from the conventional power plants. But as the amount of wind generation increases, it raises challenges for the various stakeholders involved, ranging from generation, transmission and distribution to power trading and consumers. Therefore, regulations for grid connection of WPPs become necessary for the stability of the power system.

10.2 THE ELECTRIC GRID

An electric grid network basically consists of following three sections (see Figure 10.1):

- Interconnection network
- Transmission network
- Distribution network.

The *interconnection network* of a grid operates at high voltages of 400 kV and 220 kV AC overhead lines. Generally, these overhead lines link large centralised power stations and are primarily intended to come into action in case of power station failures. Cables are not generally used to transport high voltage AC (HVAC) due to their reactive power demand caused by capacitive nature of their isolation.

The *transmission network* located between the power production units and distribution network, generally, operates at voltages between 132 kV and 33 kV/11 kV. It connects to the distribution network at 33 kV/11 kV. Normally, when electrical

power of more than 50 MW to 132 MW is to be transmitted, the 132 kV or 220 kV line is used by the transmission system operators (TSOs) and if the power is above 132 MW, 400 kV overhead lines are used.

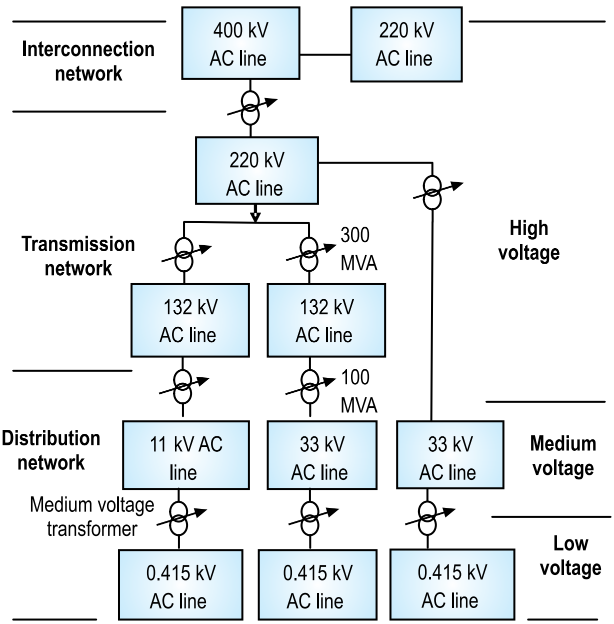


Figure 10.1 Typical Electric Grid Network: Generally, the electric distribution networks are in rural areas where the WPPs are connected. Therefore integrating WPPs into the electric network has to be taken due care.

The *distribution network* provides the power to the consumers (called *loads*) through 33 kV/400 V or 11 kV/400 V step-down transformers through low tension overhead lines or cables. Figure 10.2 depicts a simplified electric grid model. It consists of a voltage source V_s (grid), short circuit impedance Z_s, a capacitor bank, a resistance representing losses and active consumption in the installation, the necessary switches and finally, generator in the WPP. For a low order modelling:

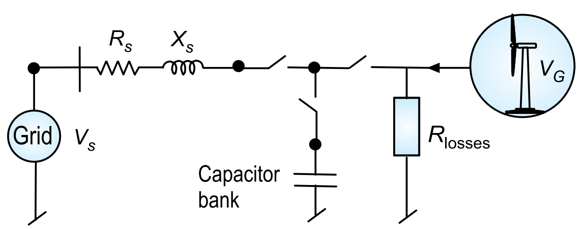


Figure 10.2 Simplified Electric Grid Model with WPP: Equivalent voltage source V_s is in series R_s and X_s of a power system, (resistance representing losses).

- All electrical variables and parameters are referred to the stator. All stator and rotor quantities are in the arbitrary two-axis reference frame (d–q frame).

- Electrical part of the machine represented by a fourth order state space model while the mechanical part is by a second order system.
- A proportional integral (PI) controller is used to control the blade pitch angle so as to limit the electrical output power to the nominal mechanical power. The pitch angle is kept constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value, the PI controller increases the pitch angle to bring back the measured power to its nominal value.

10.3 EMBEDDED GENERATION

Normally, the WPPs and wind farms are located far away from the urban areas and predominantly in weak electrical distribution networks. Wind power connected to the transmission network consists of many tens to hundreds of individual WPPs spread out over a significant geographic expanse. Each of these WPPs is quite small relative to the conventional power plants, but collectively in several places, their contribution to the grid has become significant which affect the power quality and stability of the grid network. Such a condition is called by different names such as *embedded generation* or *dispersed generation* or a *distributed generation*. This benefits the grid, as weak grids may be supported by the wind power and users may be better served, because wind power can help to control the grid voltage. Moreover, the power (if consumed within the distribution network) goes directly to the user and transmission costs can be reduced. Power electronics of wind farms can also improve power quality characteristics in the grid.

Electrical distribution systems are generally designed to distribute the electrical energy and are not designed to collect it. In other words, distribution systems are generally designed for a unidirectional flow of power from the high voltage transmission network to the low voltage customers' equipment. In the embedded generation systems, the flow of electrical energy is not unidirectional and this complicates the various grid protection schemes which require a proper design. Earlier grid codes were written for large centralised generation, but with greater wind penetration, some modifications such as in fault-ride-through (FRT) and other codes have come to render the renewable energy more grid friendly.

10.4 WPP IN THE ELECTRIC GRID

High penetration levels of wind power production affect the operation of the grid network. Voltage control in the system may be required (e.g. near large wind farms) in order to cope with unwanted voltage changes which might be enhanced by variable output wind power. Grid voltage and frequency are continuously monitored by each WPP electronic controller. No sooner is a deviation detected, the WPP has to use FRT or is immediately isolated from the grid and stopped. Once the grid fault is cleared and no other fault occurs for the next several minutes, the WPP automatically gets restarted. If a certain number of grid faults are exceeded within 24 hours of

operation, then due to its design, the WPP does not restart automatically till the cause of the frequent irregularities of the grid is diagnosed and remedied.

As a general rule, WPP/wind farm is expected to operate like any other conventional power plant. It is not permitted to disconnect as long as the voltage and frequency limits are not exceeded. The term *electrical load* is used to describe a sink for power or a specific device that absorbs power. The total electrical load on a transmission system is the sum of the several fluctuating end loads.

WPPs have to be designed to generate power at the voltages and frequencies deviated from the pre-designed rated values, depending on the grid codes. For example, (see Figure 10.3) V_L is the lower voltage limit and V_{LF} is the lower voltage limit for full load range at a network nominal voltage V_N. Similarly, V_H is the upper voltage limit and V_{HF} is the upper voltage limit for full load range. The full load range indicates the voltage range within which the wind farm can supply its nominal power in the continuous operation area.

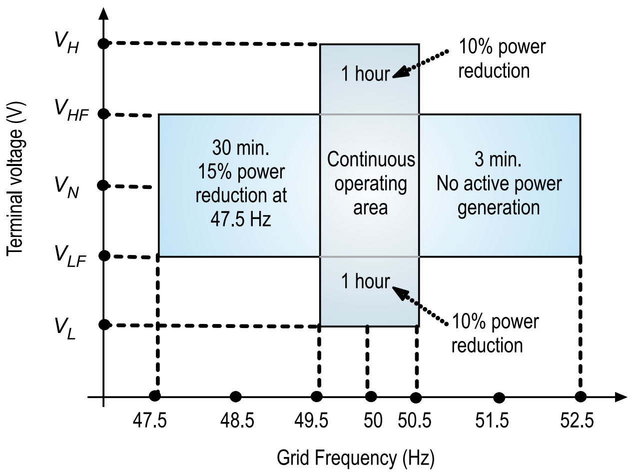


Figure 10.3 Typical Voltage and Frequency Dimensioning for WPPs.

Difficulty in controlling the voltage regulation is aggravated when the WPP is located in a remote area and connected to the distribution network through transmission lines originally designed to be only as a distribution network. However, voltage swells (or overvoltages), voltage sags (or undervoltages) and short circuit currents during and after the faults could damage the WPPs and associated equipment. Therefore, the relay protection system is to be designed to:

- Comply the network requirements of the operator to maintain system stability
- Protect WPPs against damages that may occur due to network faults.

10.4.1 Requirements of Grid Connected WPP

As with other power plants, the transmission system operators (TSO) want that WPPs/wind farms also function as below:

(a) *Feed-in quality*

- Operate within specified voltage and frequency limits
- Low inrush current
- Low flicker effect
- Low harmonic frequencies.

(b) *Grid support*

- Generate electric power at all times
- Dynamic adjustment reactive power support grid voltage: WPPs/wind farms should remain connected to the grid without power reduction even if considerable voltage deviations occur for a defined period. The voltage must be regulated so that the node voltages in the grid do not exceed their nominal values. WPPs/wind farms must be able to make a contribution to the maintenance of the voltage stability in the grid by supplying or accepting reactive power.
- Dynamic adjustment active power support of grid frequency requirements: If the grid frequency increases, the power output of a wind farm must be reduced. WPPs/wind farms must make a contribution to the reserve power in the grid.
  - Overfrequency and possible underfrequency response
  - Participate in primary and secondary frequency control

  After the remedy of a fault, WPPs must resume their power feed as quickly as possible and within the specified grid codes.
- Maintain grid stability during the short circuit situations. Remain in operation in case of sags of the terminal voltage, i.e., fault ride through (FRT) which is also called as low voltage ride through (LVRT) or under voltage ride through (UVRT).

(c) *Transmission*

- High static and transient grid stability at low short circuit ratio (SCR)
- Perform short term balancing
- Perform long term balancing
- Capability of black start
- Transient/dynamic state condition (wind farms must be able to be integrated in the grid control centre for telemonitoring and remote control of all systems in the grid)
- Respond to wind forecasting plans for efficient power despatch.

10.4.2 WPP Grid Connections

Large wind farms are connected to transmission grids which are largely inductive having network impedance angle ψ (psi) typically ranging from 55° to 85°, while for smaller wind farms the value may be between 25° to 55°. Generally, in electrical distribution networks, voltage tolerance permitted in 11 kV circuits is typically

±1% or ±2% and is passed onto the customers through fixed tap transformers. However, 33 kV and 132 kV networks operate over wider voltage tolerance (±6%), as the automatic on-load tap changing (OLTC) transformers can compensate for the variations in network voltage. Wherever the capacity of the WPPs and wind farms go up, the grid has to be strengthened by building stronger feeders from the major points of generation to the stronger points on the existing network.

Most of the large WPPs around the world are grid connected, i.e., the WPPs feed their electric power into the public electrical grid and about four types of grid connections are possible which are as follows:

- Direct grid connection of WPP
- Indirect grid connection of WPP
- Direct grid connection of wind farm
- Meshed grid connection of wind farm.

(a) Direct Grid Connection of WPP

In the *direct grid connection* of WPP the three-phase generated power from the WPP stator is connected directly to the electric grid without any treatment by power electronic circuits. Most of them are constant speed Type-A and Type-B wind power plants. The speed of the generator is determined by the grid frequency.

(b) Indirect Grid Connection of WPP

When the winding of an electric generator of a WPP is connected to the grid through a PEC, it is called an *indirect grid connection*. Type-D WPP is one such example which is indirectly connected to the grid through a full power capacity PEC. The electric generators for such applications may be either a WRSG or a PMSG. The fluctuating AC of such synchronous generators is converted into direct current (DC) in the PEC equipped with IGBTs/IGCTs and again transformed to grid friendly AC in the PEC itself. In Type-C WPP, the stator is directly connected to the grid but the rotor is indirectly connected to grid through the PEC.

(c) Direct Grid Connection of Wind Farm

When a wind farm is directly connected to the transmission grid (see Figure 10.4) without feeding into the distribution grid especially a common phenomenon for offshore wind farms, it is called a *direct connection of wind farm*. Even remotely located onshore wind farms away from the human habitation as well as from the distribution network that are large with an installed capacity greater than 100 MW, can be directly connected to the transmission lines.

(d) Meshed Grid Connection of Wind Farm

However, most of the times, the onshore wind farms feed into the distribution grid and are connected to the transmission line through a *meshed grid connection* (see Figure 10.5). Hence, a simple allocation of the wind farm to only one transmission grid node is not advisable but two or more power transmission system nodes through transformers should be preferred for reliability sake.

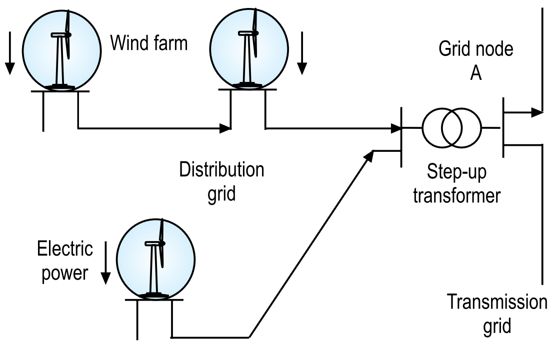


Figure 10.4 **Wind Farm Direct Grid Connection:** All the WPPs in the wind farm feed the electric power through one node via transformer into the transmission line.

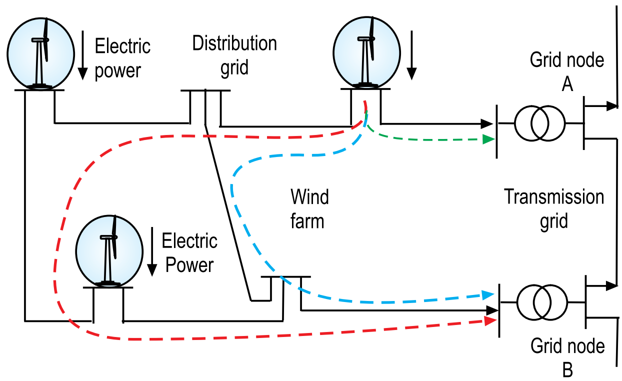


Figure 10.5 **Wind Farm Meshed Grid Connection:** A decrease in power output of a wind farm has not only an effect on the power flow via the transformer to grid node A, which should be controlled, but also on the power flow via the transformer to grid node B.

(e) Grid Connection Topologies

Figure 10.6 provides a bird's eye view of the WPP connection topologies that are possible with the grid and these also depend on various local factors and national policies:

- Nested radial network [see Figure 10.6(a)]
- Radial on ring network [see Figure 10.6(b)]
- Ring on radial network [see Figure 10.6(c)]
- Nested ring network [see Figure 10.6(d)].

(f) WPP Connection Constraints

Two of the major WPP/wind farm connection constraints are the fluctuating nature of wind and the integration of wind capacity into the existing grid which was originally designed for the conventional centralised power stations.

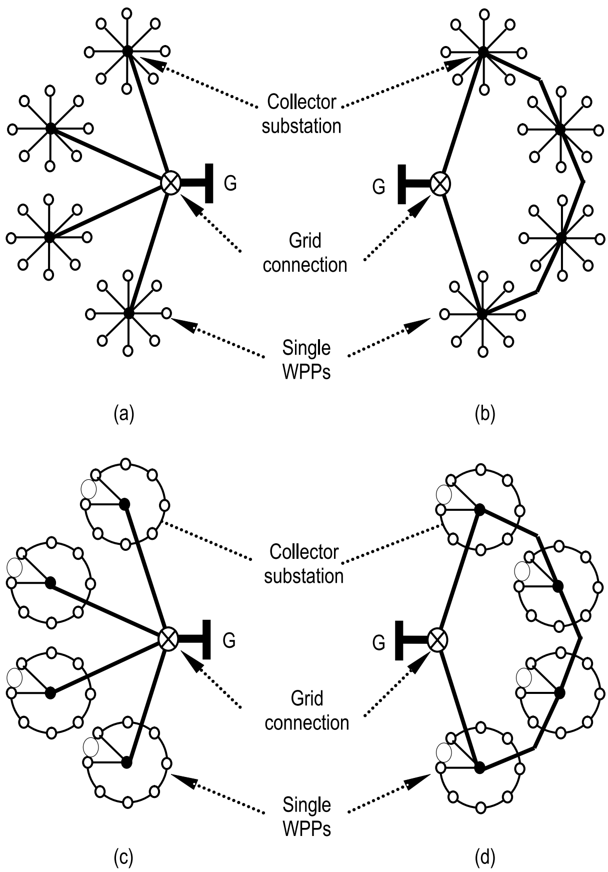


Figure 10.6 **Grid Connection Topologies:** (a) Nested radial network, (b) Radial on ring network, (c) Ring on radial network, (d) Nested ring network.

The varying wind energy coupled with the fact that the times of peak availability of wind resources in a given location may not coincide with the times of peak demand for electric power, making wind energy less attractive to the grid operators as compared to the conventional power plants that are available at all times. However, if the wind patterns tend to match the load profiles, then the wind farms can earn capacity value. The output power variations due to varying nature of wind though magnified for a single WPP gets minimised for a wind farm with many WPPs (see Figure 10.7).

The second constraint in the integration of wind power into the electric utility system applies when the wind energy exceeds 15% to 20% of the installed system capacity. At this level of penetration, utility system studies indicate that an additional spinning reserve (SR) may be needed. 'Spinning reserve' is spare synchronised generation reserve that is available to the grid in case, a generator is suddenly and unexpectedly lost. SR may be either partly loaded spinning reserve (PLSR) which is simply a generator that runs and generates power but at a lower output that allows it to increase output quickly in response to load demand.

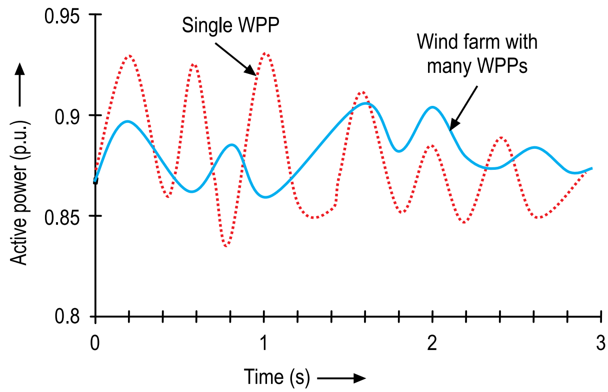


Figure 10.7 **Power Fluctuations in Wind farms:** With more number of WPPs in the wind farms, the output will tend to be more constant even if the wind speed is erratic.

The wind power integration issues could be broadly classified (see Figure 10.8) as follows:

- Interface issues
- Operational issues.

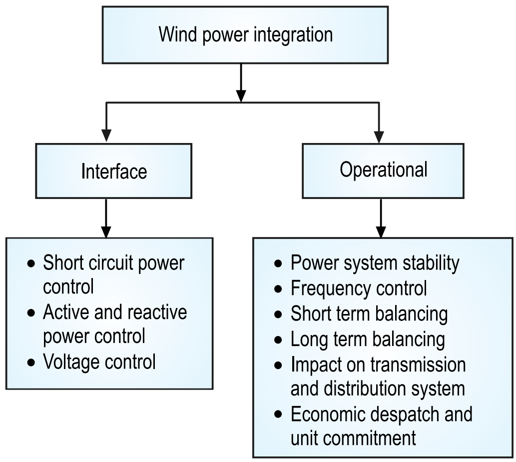


Figure 10.8 **Wind Power Integration Issues:** Since the wind speed varies and the WPPs are usually located in the electrical distribution network, these integration issues need to be addressed when connecting them to the network.

10.5 INTERFACE ISSUES

The major factors related to interface issues include the following:

- Short circuit power control
- Active and reactive power control
- Voltage control.

To enhance interface issues, the transmission capacity of the network could be enhanced in several ways:

- Add transformers to the existing substations to enable a higher load feed and in some cases, to evacuate higher generated power.
- Upgrade the transmission infrastructure, e.g. operate a line at higher voltage (within its design limits), tighten the conductors and reinforce the towers to increase the transmission capacity.
- Improve the distribution of power flows among different parallel paths by installing new facilities in grid substations such as series reactors, phase shifting transformers or devices to increase voltage support such as shunt reactive and FACTS devices.
- Improve the utilisation of existing infrastructure, e.g. by replacing line conductors with high temperature conductors or add a second circuit on an existing line (within the design limit of the towers).
- Replace the existing infrastructure with those of a higher transmission capacity, e.g. replacing an existing 220 kV line with a 400 kV double circuit line.

10.5.1 Short Circuit Power Control

An *electrical fault* (or simply called *fault*) in an electric power system can be defined as a short circuit somewhere in the system. Short circuit power is one of the indicators that indicates the capacity of the WPP/wind farm production (or consumption) which can be connected at the PCC of the grid network. The usual practice is that installed capacity of the connected object (here WPP/wind farm) should be about 10% of the short circuit power. If the short circuit power is high, then the voltage variation due to changes in power production/consumption at the connection point are low and vice versa.

During and after faults in the system, the behaviour of WPPs is different from that of the conventional power plants which use synchronous generators that are able to continue to operate even during severe voltage transients produced by transmission system faults. If a large number of WPPs are tripped because of a fault, the negative effects of that fault could be magnified. This may, in turn, affect the transmission capacity in areas with significant amount of wind power, as a sequence of contingencies would have to be considered in the security assessment instead of only one contingency.

(a) Strong Grids and Weak Grids

The definition of weak grid depends on the specific fault scenario and change, depending on the load on the grid. Weak grids are said to have low short circuit level or low fault levels. A grid is also said to be weak when the flow of active and reactive power into or out of the network causes significant changes in the voltage amplitude at the point of reference or in the neighbouring areas of that point. If a WPP is connected to a weak electrical grid, there may be some brown-out/power

surge problems. In such cases, it may be necessary to reinforce the grid in order to carry the fluctuating power from the WPP. Major problems with weak grid are as follows:

- Will the WPPs help the grid to recover after a fault?
- Will the WPPs be engaged in power system oscillations?
- Can WPPs supply both active and reactive power to the grid?

If the grid is capable of coping with the above mentioned problems, then it is said to be strong grid, else it is termed as *weak grid*. Qualitatively, a strong grid is one which is thermally limited, while a weak grid is one which is voltage limited.

The strength of a grid is measured at the PCC by the short circuit faults that it can absorb without disturbance to the grid. The variations in the WPP generated power result in the variations in the voltage at PCC. The *short circuit capacity* at a given point in the electrical network represents the system strength. It is the product of the short circuit current following a three-phase fault.

$$S_{sc} = I_F V_s \tag{10.1}$$

where,

S_{sc} = Short circuit capacity of the grid
I_F = Fault current (= V_S/Z_S)
V_S = Grid voltage
Z_S = Grid impedance.

If the impedance is small (i.e., the grid is strong) then the voltage variations are small. If the impedance is large (i.e., the grid is weak), then the voltage variations are large.

As the wind farms are usually situated in remote areas, long transmission lines are required to connect them and hence, the fault levels are generally low. Then the grid is said to be a *weak grid*. If the impedance Z_S is small then the voltage variations will be small and the grid is said to be *strong*. Conversely, if Z_S is large then the voltage variations will be large and the grid is said to be *weak*.

For any given WPP installation, the *short circuit ratio* R_{sc} at the PCC is the ratio of the short circuit power of the grid S_{sc} to the installed WPP capacity P (MW).

$$R_{sc} = \frac{S_{sc}}{P} \tag{10.2}$$

If R_{sc} is above 20 to 25 times, the grid is said to be strong with respect to the installation and is *weak* for R_{sc} below 8 to 10 times.

In case of WPP connected networks, the maximum evacuation capacity (in MVA) from the WPP or wind farm connection node (PCC) should not be higher than 5% of the minimum short circuit power before the new installation.

Depending on the type of generators installed in the WPPs, they can be sometimes programmed to operate successfully even under weak conditions. Therefore, the decision making regarding grid integration also depends much on the type of WPP that is selected and the electric generator mounted in them.

(b) WPPs and Faults

In a constant speed WPP, the reactive power demand depends on the active power generation also. Consequently, the rotor speed and reactive power reduce which enhances the rotor speed stability. When a fault occurs close to a constant speed WPP, the voltage at the induction generator terminals drops, causing decrease in the active power. If pitching is not fast enough to change the angle of attack in order to reduce the mechanical power input (in other words, spill away the excess energy), the WPP will accelerate during the fault. If a WPP has no means of controlling its power, then critical clearing time will be very short. However, constant speed WPP gearboxes are sensitive to capacitor bank switching, which can cause damage and premature failure of the gearboxes.

In earlier years, variable speed WPPs were disconnected from the grid during a fault to protect the PEC. But, of late, Type-C WPP with DFIGs is able to supply VArs during a grid fault, unless the system voltage drops to a level outside of the tolerance of the PECs. At this point, a crowbar type protection is activated on the rotor which in effect, shorts the rotor side PEC, thus transforming it into an induction generator until the system voltage is restored which means that it does not support the grid during such faults.

During transient faults, the system voltage can go down to zero for the duration of the fault clearance time. Including backup protection trip times, the clearance time can extend to a maximum of 300 ms. The acceleration of the WPPs caused by imbalance between input and output power during the fault must not compromise the WPPs' ability to supply reactive power and ride through transient faults. Of late, the grid operators want WPPs that stay connected to the grid for the duration of a fault on the system based on three-phase earth faults that are cleared in primary time and two-phase earth and one-phase earth faults that are cleared in backup time.

When a *three-phase short circuit fault* occurs in the system, the voltage at the generator terminals drops to a level depending on the location of the fault and the WPPs might not be able to export as much power as its input is wind dependent. As for conventional WPPs, the grid operator wants that for such faults, the WPPs stay on line for a normal clearing time up to nine cycles. If a wind farm is connected by only a radial feeder and a three-phase short circuit occurs on this feeder, the wind farm can only export as much power as is dissipated in the resistances of the generators, transformers, lines and the fault. The amount of power dissipated during such a fault, depending on the operation point of the wind farm is often only a fraction of the mechanical input power.

In case of a two-phase fault, the unbalance between the input and output power as well as the speed and the reactive power demand problems are less grave. But for this type of fault, constant speed WPPs draw large amounts of reactive power from the grid, rendering the system to recover more slowly after the fault which can also affect transmission capacity. The voltage becomes unbalanced and this implies that the current becomes unproportionally more unbalanced.

10.5.2 Reactive Power Control

In a power system, reactive power is produced in capacitive components (e.g. capacitors, cables) and consumed in inductive components (e.g. transformers, motors, fluorescent tubes). Reactive power is a concept associated with oscillating exchange of energy stored in the capacitive and inductive components of a power system. Reactive power causes a phase shift between them and adds geometrically to the active power. The grid operator expects individual and collective WPPs/wind farms to behave like any other conventional power plant to maintain the power system stability.

Figure 10.9 shows a lagging power factor. The notation *lagging* refers to production of reactive power and *leading* refers to absorption of reactive power. In generator sign convention, the current lags the voltage when reactive and active current are positive. Wind farms are required to have sufficient reactive power compensation to be neutral in reactive power at any operating point. If the active power is less than rated, wind farms must be able to supply the same MVArs as under full load.

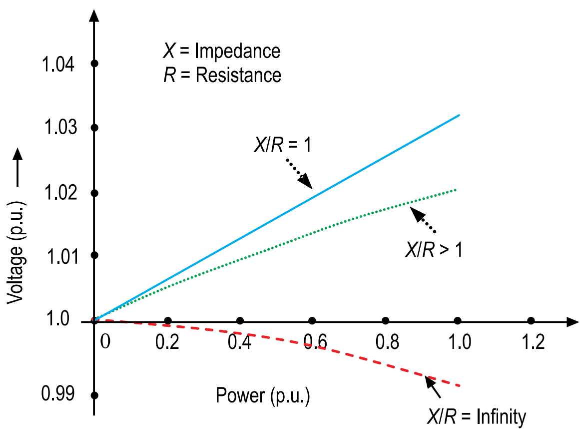


Figure 10.9 Typical Wind Power Characteristics for Lagging and Leading Power Factor.

Although reactive power causes additional loading, for steady state conditions, reactive power produced should be equal to reactive power consumed. Depending on the output and defined margins, at the PCC, the exchange of reactive power should be more or less zero. WPPs with reactive power control capability may have a characteristic (see Figure 10.10), where the reactive power within ±0.95 power factor is available over almost the entire operating range of the WPP, as indicated by the dashed line and hashed portion. It can be seen the reactive power capability reduces with generation level down to zero when the WPP does not produce active power. The dot–dash line is indicative of the reactive capability of a conventional synchronous generator where the limitation arises only due to stator current limits. Reactive active power oscillates between the energy storage elements like capacitors and inductors in the grid networks.

Reactive power in WPPs/wind farms is traditionally limited to keep the power factor at unity or quite near to it and WPPs have a considerable reactive power

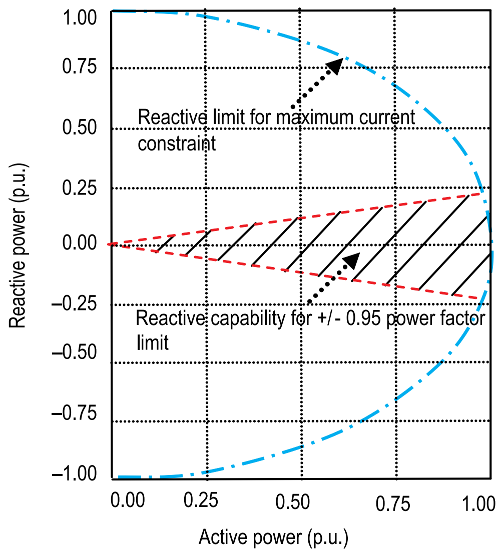


Figure 10.10 **WPP Reactive Power Capability:** It can be seen the reactive power capability reduces with generation level down to zero when the WPP does not produce active power.

range. WPPs are required to import and export reactive power over a full range of system voltages to improve the quality of power injected into the grid. Wind farms are very often connected at weak points in the network and reactive power losses are considerable which limit the possible contribution of wind generators to the reactive power balance at the transmission level. Hence, WPPs with enough voltage regulation are not able to provide any substantial contribution to the reactive power balance at the transmission level.

Voltage is closely related to the reactive power. Consequently a WPP having ability of controlling reactive power can support and regulate the PCC local system voltage. As the wind power penetration increases in the grid, the WPPs/wind farms are called upon to share the responsibility to maintain the voltage and frequency of the grid by controlling their contribution of real and reactive power as the conventional power plants.

There are strict requirements on the extent to which the network voltage can be allowed to deviate from its nominal values (±10% for low voltage networks and ±5% for medium or high voltage networks). Voltage or reactive power requirements in the grid codes are usually specified with a limiting curve (see Figure 10.11). The mean value of the reactive power over several seconds should stay within the limits of the curve.

When a WPP provides low active power the power factor may deviate from unity because it can support additional leading or lagging currents due to the reactive power demanded by the grid. When the WPP works under nominal conditions, the power factor must be kept close to unity so that it avoids excessive currents.

Another advantage of local reactive power generation is the reduction of losses in the network. As the reactive power is locally generated and locally consumed,

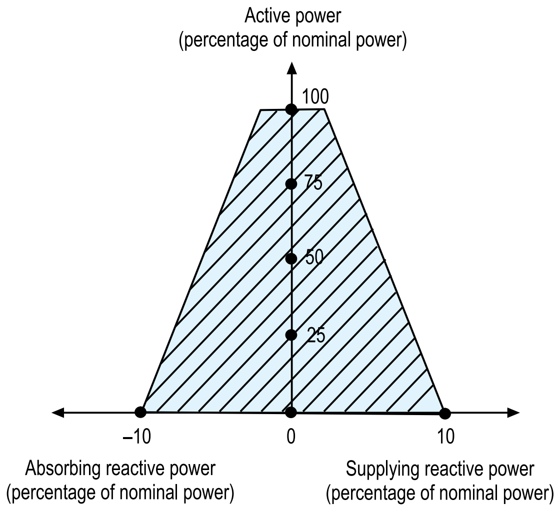


Figure 10.11 Typical Reactive Power Limiting Curve for WPPs.

the current through all upstream devices and the power losses in the network are reduced. Thus, the WPP/wind farm should have the capability to control the voltage and/or the reactive power at the PCC. This is essential to ensure secure operation of the network. The owner of the WPP has an opportunity to gain an additional income for providing reactive power.

For system stability, to behave as conventional power plants which the TSO requires, WPPs must be able to have a power factor of 0.9 for export and 0.95 for import. Therefore, they should be able to:

- Export net reactive power equal to 50% of the maximum continuous megawatt output power when operating at full load.
- Import net reactive power equal to 33% of the maximum continuous megawatt output power when operating at full load.

Wind power affects the reactive power generation and voltage control possibilities in a power system for various reasons and also because constant speed Type-A and Type-B WPPs are not capable of varying their reactive power output but consume large amounts of reactive power. Therefore, such WPPs may have full load or partial load dynamic compensation (depending on the concerned utility terms and conditions) by which a certain number of capacitors are switched in and switched out continuously, depending on the reactive power demand.

For constant speed Type-A and Type-B WPPs, the inrush current of the generators is high at the time of connection; it has to be limited to the rated value. There are two methods of reducing this. One is by increasing the firing angle of the thyristor (in the soft starter) to keep the peak current below the rated value during the starting period. The other method is by magnetising the induction generator by the capacitors instead of using grid. These are delta connected shunt capacitor banks installed at the base of the WPP tower or sometimes, in the nacelle. As they are

relatively cheaper, shunt capacitor banks are more commonly used in substations to compensate for the reactive power consumption by the wind farms. Depending on the application and type of constant speed Type-A or Type-B WPP, shunt reactive power compensation may be added at one or more of the following locations:

- WPP terminals
- Collector system
- Substation interfacing with the transmission grid.

For variable speed WPPs, inrush current is not a problem as it can be controlled from zero to rated value by the PECs. In Type-C WPPs, the Q is controllable, as they provide considerable reactive power support due to the PECs. However, it is only possible to produce or consume a reactive power upto 30% of the nominal active power.

A Type-D WPP with full rated PEC connected to the grid has even less impact on the transient stability performance of the power system than the Type-C WPP. According to the PEC's fast control, it is possible to provide reactive power to the network during steady state as well as dynamically during disturbances. Hence, no additional reactive compensation equipment is needed. If the voltage reaches 1.2 p.u. at the PCC (irrespective of the voltage level), the wind farm has to start performing voltage reduction within 100 ms of detection.

10.5.3 Voltage Control

The voltage is a local variable which means that its value is location dependent. The voltage at a given location depends on the grid parameters, viz. reactance, capacitance and current. Generally, the voltage increases at the PCC of the wind farm and on the feeder to which the wind farm is connected.

Voltage control means the task of keeping the node voltages in the grid within the required limits and preventing any deviation from the nominal value within the specified limits. Voltage control is necessary due to line impedances. High consumption and low power production renders the voltage to low levels. High production and low consumption render the voltage to the levels higher than the set limits. Hence, voltages on the transmission system are controlled through a combination of generator excitation systems, tap-changers in the transformer, static reactive devices and FACTS devices which combine power electronics and control techniques with capacitors, inductors and transformers.

If cables and overhead lines do not have susceptance and impedance, the voltage anywhere in the grid is equal to that at the generator terminals and the voltage control is not necessary due to line impedances. Since every large WPP/wind farm is also a power station, the functions of the voltage control are as follows:

- Maintain constant voltage at POI/PCC.
- Maintain stable distribution of reactive power over other WPPs.
- Prevent high voltages in case of loss of load.
- In short circuit situations, increase the grid stability by increasing the excitation of Type-C and Type-D WPPs and thereby the synchronism of the grid.

The two conventional approaches to voltage control in distribution networks are by

- Tap changing of the transformers.
- Shunt capacitors or reactors (that generate or consume reactive power).

Voltage control depends on the WPP type connected to the grid.

- Extra devices are needed in case of constant speed Type-A and Type-B WPPs.
- Reactive power is dependent on PEC current limit and rotor current of DFIGs of Type-C WPP.
- Reactive power is dependent on PEC current limit in Type-D variable speed WPPs.

Slow voltage variations are not of much concern to TSOs, as there is sufficient time for the WPPs to respond to the condition and make necessary adjustments. Rapid voltage variations (flicker) due to the WPPs have to be addressed. Voltage swells are less common and are, therefore, not a major problem for WPPs. Voltage unbalance generally occurs on weak networks in rural areas, as the majority of customer loads are single-phase and hence due care has to be taken when connecting WPPs.

(a) Flicker Control

Flicker problem is typical to constant speed Type-A and Type-B WPPs especially at the time of connection. In these types of WPPs, the variations in aerodynamic power are directly translated into output power fluctuations and passed onto the grid, as there is no energy buffer between mechanical input and electrical output. Each time, the rotor blade passes the tower (tower shadow) and gives rise to short-lived variations in power output, resulting in frequencies above 1 Hz and its multiples. Depending on the strength of the grid, the power fluctuations of the active and reactive power in these WPPs may result in grid voltage fluctuations, which can cause flicker. There are various ways of dealing with this issue in the design of the WPP, mechanically, electrically and by using power electronics.

Flicker is not much of an issue with Type-C and Type-D WPPs, as in these WPPs, the PECs take care of it. For wind farms, the maximal penetration can be added up arithmetically, whereas for the flicker and interharmonics, it gets added up geometrically.

(b) Harmonics Control

Harmonics are of concern due to potential damage to transmission and distribution network as well as to the customers' equipment. Some first generation WPPs installed in early 1980s employed older PECs which used six-pulse thyristor bridge configurations without external harmonic correction or filtering, resulting in the production of lower order harmonics. The effect of harmonics from modern WPPs is not of much concern, as sufficient care is taken in the design of the PECs. With the addition of harmonic correction devices and the current trend towards the use of advanced power electronics in variable speed WPPs, harmonics are no longer a significant grid operator concern. However, when buying a WPP, the manufacturer's literature should be checked to ensure that harmonics will not create a problem.

10.6 OPERATIONAL ISSUES

As electrical energy cannot be stored, i.e., whatever amount of energy is required at that very moment, it has to be fed into the grid to be taken out and consumed. The day-to-day operation of the WPPs and the electrical power supply into the network have raised some operational problems, as it is distributed generation (DG) source.

Since the prime mover (wind) of the WPPs is uncontrollable, it leads to the following operational issues which need to be addressed:

- Power system stability
- Frequency control
- Short term balancing
- Long term balancing
- Transmission and distribution system impacts
- Economic despatch of power and unit commitment.

10.6.1 Power System Stability

Power system stability is dependent on how it responds to the dynamic performance of the various phenomena on the grid network. WPPs can affect transmission and distribution systems by altering the designed power flow or causing large voltage fluctuations. It could also be due to a contingency (i.e., n–1 contingency or more) such as loss of a transmission line or large transformer or generating unit that causes a portion of the remaining transmission system to be operated near its steady state stability limit which can be below its thermal limit for long transmission distances.

Power transmission in a power system is limited by the thermal stability of the conductors and at the same time, by the voltage stability of the power system. Usually, for long transmission lines (> 100 km long) voltage stability limits are reached before the thermal limits. However, with greater penetration of WPPs, along with the thermal and voltage stability limits, grid operators want wind project developers to undertake simulation studies for steady state stability, dynamic stability and the transient stability limits of the power system due to the connection of their WPPs into the network.

(a) Grid Faults and WPPs

Power utility companies want that all types of power plants would support the grid and provide stability even under any fault condition by generating the needed VArs to maintain the voltage levels, obviously, within certain limits which is applicable to WPPs as well.

One way of classifying faults is as symmetrical faults and non-symmetrical faults. Out of the three main types of grid faults, i.e., one-phase, two-phase and three-phase faults to earth, the last one is the most dangerous for the generator, especially if the three-phase to earth (or line) is at a location near the WPP. However, this type of fault is considerably rare.

Experience of WPP/wind farm operators and research studies have demonstrated that grid faults negatively affect the WPPs/wind farms. Internationally, there is a growing need for WPPs to provide an acceptable calculable risk for grid stability. If a large amount of wind power generation is tripped, the negative effects of that fault could be magnified. Therefore, if the percentage of the wind power fed into the grid is substantial, the transmission capacity would be affected.

A transient fault in an interconnected power system can lead to swings in the system frequency. It is desirable that the frequency tolerance of WPP generators is as wide as possible so that under such post-fault conditions, the situation does not get worse because of which power generation may be lost again.

(b) Fault-ride-through (FRT) and WPPs

During a fault, when the grid penetration is less, disconnection of a WPP helps to prevent islanding and also to protect the PEC in WPPs from damage due to thermal overload. However, when the wind penetration increases (typically, beyond 5%), a quick disconnection is not desirable, as it could lead to loss of large amounts of generation when a fault occurs. Therefore, the FRT or the so-called low-voltage-ride-through (or under voltage ride through) capability gains prominence. Like conventional power plants, all types of WPPs are expected to supply fault current in order to help the protection scheme to differentiate between faulty and normal situations (see Figure 10.12).

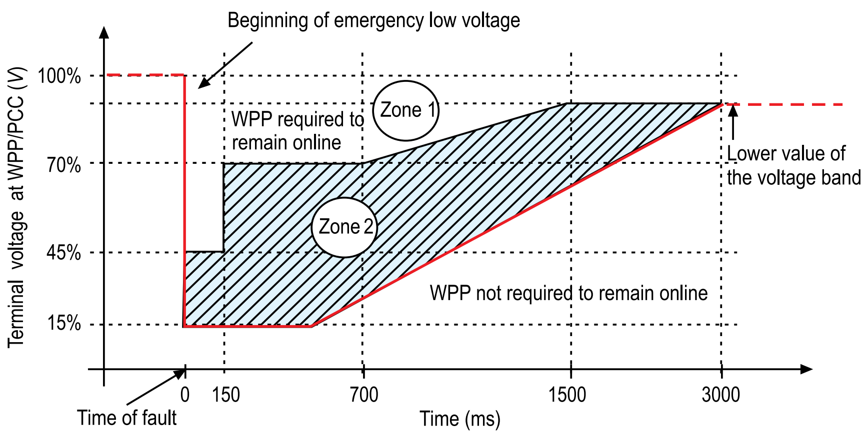


Figure 10.12 Minimum Required WPP Response Time to Emergency Low Voltage: FRT curve is different in different countries for this typical FRT curve.

WPPs must support the voltage in case of three-phase short circuit in the grid. If this three-phase fault is close to WPP, there should neither be instability of the WPP nor disconnection from the grid for voltage–time values exceeding the bold line (see Figure 10.12):

- In zone 1, active power generation capacity must be recovered after the identification of the fault and increased at a gradient of 20% of the rated power per second.

- In zone 2, instead, a short disconnection of the WPP from the grid is allowed; however, a quick resynchronisation should follow after the fault clearing and it must return to the prefault standard generation conditions so that the outage lasts for maximum 10 s. Therefore, a WPP must return to supplying active power within 2 s after the fault is cleared at a gradient of 10% of the rated active power per second.
- If the short circuit is far from the WPPs, they should not disconnect from the electrical system, as such fault is generally eliminated by the network protection in 5 s.

Voltage dips of 10% to 90% variation are between a period of 1 ms to 1 min. Conventionally, when the wind power penetration was less, the WPPs were disconnected when the voltage dips were higher than 10% to 20%, as their disconnection did not cause much voltage instability. Most WPPs were designed to disconnect themselves from the grid when the voltage drops 30% for 50 ms. The challenge is, as the voltage dips, the current output must increase or else, the WPPs must overspeed and cause mechanical failures.

FRTs also called as low voltage ride through (LVRT) or under voltage ride through (UVRT) is now almost a mandatory requirement for modern WPPs. Low voltage situations occur on the grid through natural phenomena like falling trees, storms, equipment failure or human error. For acute disturbances on the grid (such as three phase faults) and voltage dips, the disconnection of the WPPs can worsen the situation especially on the transmission network with a high WPP penetration or on island grids leading to loss of generation, that may result in load shedding or even a black out in the worst case. Depending on the voltage level at the PCC, FRT has become a challenging requirement for grid connection of large WPPs/wind farms.

Anyway, WPP manufacturers obviously do not want to describe their systems and publicise the details of their WPP FRT systems.

(c) FRT and Constant Speed WPPs

When a grid fault occurs after a pre-determined time, the circuit breakers open to isolate and clear the fault and in the process, the WPP/wind farm also gets isolated and cannot export any power. During a fault (and even more, during the clearance of the fault), the WPP/wind farm can only store the mechanical input power by accelerating.

As long as the WPPs freely accelerate, the slip in constant speed WPPs becomes zero. Acceleration implies that the slip after the clearance of the fault is bigger than that prior to the fault. The bigger the slip, the bigger will be the reactive power demand of the generator which means that it is much more difficult for the voltage at the WPP/wind farm terminals to recover after the fault is cleared. The longer it takes for the voltage to recover, the longer will be the period during which the WPP is in unbalance between mechanical input power and electrical output power, i.e., the WPP accelerates or at least draws more reactive power creating voltage stability problems.

When a fault occurs, the source of excitation of the constant speed WPP gets removed. The main flux of the induction generator collapses and the torque production or power flow is lost. But the collapse of the main flux is not instantaneous. It takes some finite amount of time for it to completely collapse during which, it decays to some new value and continues to contribute current to the fault.

When the stator of an induction generator (directly grid connected) is subjected to a nearby fault, its rotor may accelerate to very high speeds due to severe voltage sag. This kind of stability phenomenon of the constant speed WPP is referred as *rotor speed stability*. To improve the rotor speed stability, the WPP output power is to be reduced by pitching the blades, through which the reactive power drawn by the WPP is reduced (due to the reduction in the slip).

Voltage stability is the ability of a power system to maintain voltages at all buses in the grid after any disturbance. Voltage stability problems during faults are much lower in WRSGs of the conventional generating stations because their separate excitation winding contribute to the recovery voltage. Voltage stability phenomenon may occur because after fault clearance, the system voltage may recover to a new allowable value, as the induction generator speed may rise to unaccepted dangerous values. The risk of the voltage stability increases when the fault duration increases and when the grid is weak. The voltage stability can be aggravated if the shunt capacitors are connected to the intermediate bus.

Directly grid coupled constant speed WPPs, typically, come equipped with power factor correction capacitors to maintain the power factor at unity. These WPPs supply a fault current. Although these WPPs are capable of delivering a fault current, but its FRT capability depends on the actual wind speed, fault duration and the grid strength. Their behaviour resembles that of a synchronous generator delivering a large current.

To either ensure LVRT through of the WPPs, to prevent voltage collapse near the PCC of the wind farm or to help in complying with the grid connection code, providing reactive power during faults, additional components like SVCs, STATCOMs are often used at or near the wind farm PCC having more number of constant speed WPPs.

Therefore, under grid fault conditions, stability of a constant speed WPP can be classified as follows:

- Voltage stability (may rise during faults)
- Rotor speed stability (may also rise)
- Frequency stability (even if the frequency is acceptable after fault clearance, the rotor speed maybe excessively high).

Although the constant speed WPPs are electrically the most simple, during grid faults the mechanical stresses on the drive train are the highest as compared to the variable speed WPPs.

(d) FRT and Variable Speed WPPs

The response to faults by variable speed WPPs is quite different from constant speed WPPs due to the inclusion of PECs in their circuits. During the fault, the

rotor speed hardly affects the behaviour of the WRSG after the disturbance, as the PEC decouples the rotor speed and the terminal voltage and current. Hence, there is no need for a variable speed WPP with WRSG or PMSG to get resynchronised by the grid. Instead, the PEC can run the WPP at higher speed and then, drive it back to the wind speed that leads to maximum energy yield. These WPPs can fault ride through only within the thermal limits of the PEC after which they trip and become isolated from the grid. But the PECs keep the WPP under control. When the terminal voltage is recovered, the WPP can quickly resume normal operation.

Large disturbances lead to large initial fault currents both at the stator and the rotor of a DFIG in Type-C WPP. The FRT systems in Type-C WPPs are a mixture of protective crowbar (active or non-active) activation circuits, power limitation devices, pitch control and variations in control strategies that provide better voltage tolerance. The RSC is less tolerant to high currents likely to activate the protective crowbar circuit which may lead to tripping of the WPP. Further, additional energy goes into charging the DC link capacitor leading to the rapid rise of DC bus voltage. Due to the voltage dips the stator current also rises quite fast. Therefore, no sooner a voltage dip is detected by the grid protection scheme and if the feeding of the fault current approaches the thermal limit of the PEC and the DFIG voltage tolerance equals or exceeds the grid operator minimum requirements, the WPP is disconnected to avoid its damage.

The DFIG is also not able to tolerate the actual worst case (maximum) requirements especially during the time period of 0.2 s to 1.0 s after fault initiation. But if not, it may become necessary to improve the fault clearance time on large sections of the transmission network. The ideal solution may be the utilisation of low cost additional hardware (active crowbar) and adaptation of control strategies.

When there is a temporary reduction of active power, it is ramped down by the Type-C WPP for a pre-defined time and then ramped up again to prefault value. This stabilises WPP during the fault and reduces the current in the RSC. The rotor can speed up causing overspeed protection to trip the WPP, but it can be handled by the pitch controller. During the fault, temporary reduction of active power with reactive power boosting, increases the terminal voltage, thereby improving the system stability.

The FRT capabilities of constant speed WPPs, Type-C and Type-D WPPs are compared in Table 10.1.

Table 10.1 Comparison of FRT Capabilities in WPPs

S.No.	Constant speed WPPs	Type-C with DFIG	Type-D with WRSG/PMSG
1.	Contributes to fault to some extent, as stator of generator is directly connected to the grid	Partial scale PEC; hence reactive power supply limited	Full scale PEC; hence relatively greater amount of reactive power supply possible
2.	Considerable mechanical stresses on the drive train	Additional PEC protection (like crowbar circuits) provided	FRT possible without any extra protection
3.	Disconnects after the designed limit	Generator and turbine directly subjected to the grid fault	Generator and turbine are not directly subjected to the grid fault as they are decoupled by the PEC

Type-D WPP with hydrodynamic gearbox and fixed speed WRSG is not compared to the other topologies, as its behaviour is similar to the conventional power plants and can contribute to the fault in a better way due to the absence of PECs in their circuit. Their main advantage is their direct grid connection (without PEC) by which they remain in synchronism during and after major voltage sags. The WRSGs in these types of WPPs do not face instability when the wind farm is connected to a sufficiently strong network in relation to the total rated wind farm power. In case of an extremely low short circuit level and full load operation, transient stability could have been a problem, but the extreme mechanical torque during grid faults is reduced due to the ability of hydrodynamic gearbox. During the fault, the WRSG can support the voltage by large reactive currents which are much higher than reactive current support that can be achieved by other types of WPPs.

10.6.2 Frequency Control

As the integration of wind power progresses, growing concerns on the frequency control have been raised and discussed around the world. The frequency of an electrical power system is determined by the equilibrium between the power demand and the power produced minus the losses. If generation exceeds consumption, the frequency rises and if consumption exceeds generation, the frequency falls.

$$P_{\text{produced}} = P_{\text{demanded}} + P_{\text{losses}} \tag{10.3}$$

Any imbalance between the left hand side and right hand side of Eq. (10.3) causes a frequency drift. Therefore, electrical frequency is an indicator of balance between the supply and the demand of power requirement in an interconnected electric power system. In electric power systems, the balance between the generation and the consumption must be maintained continuously (see Figure 10.13). Surplus generated power leads to frequency increase (i.e. > 50 Hz) and if the generated power is short of demand, it leads to frequency decrease (i.e., < 50 Hz). The frequency drift continues till the Eq. (10.3) is not fulfilled and a steady state condition is reached. Therefore, power plants constantly monitor the frequency.

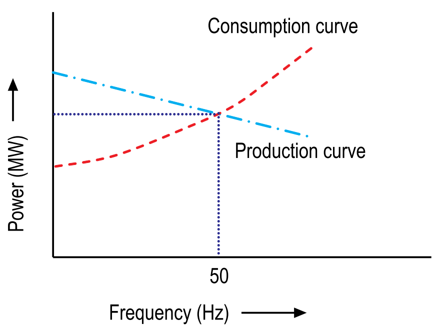


Figure 10.13 Demand Production Curve: If power demand is constant and the power generation increases, then frequency will increase and vice versa.

Maintaining a constant system frequency is vital for grid security. Hence, any event that causes frequency changes must be quickly corrected. The frequency has to be kept within strict limits to avoid system degradation, usually ±1% for normal operation. If the frequency deviates beyond 2%, automatic disconnection is necessary to arrest the slide and avoid collapse.

Though power system frequency deviations are not uncommon, but due to the adherence to reliability standards and practices, often, the disturbed system does settle down to a stable operating point after specified period. However, situations do occur when the mismatch between the load and the generation become significant, leading to the tripping of very large generating plants or an entire power station or the loss of a major transmission line.

When system frequency is suppressed (i.e., demand is greater than generation), every available generator has to be sustained, i.e., it is not desirable to lose generation due to all too tight operating limits. When system frequency rises beyond nominal, power output from the generators should be reduced rather than their disconnection.

No sooner does the grid frequency starts to drift, the power plants slightly change the generated power to stop the frequency drift. This strategy is called the *frequency control*. However, this control is only feasible when the unbalance between the generation and the load is relatively small. For large unbalances, the control range of the power plants are not large enough to restore the balance. This situation is then taken care by switching on new power plants (or switching off some loads) or by stopping some power plants according to the need.

When comparing the frequency operating ranges, the stiffness of the grid has also to be borne in mind. As compared to large systems, smaller power systems are more prone to deviate from the nominal frequency in case of unbalance between the load and the generated power.

If frequency moves outside the normal safe limits then the following results might be obtained:

- Thermal power plants will reduce the output when frequency falls and some thermal turbines can be damaged by vibration at low frequencies.
- Industrial processes and equipment can be damaged by excessive frequency excursions.

Power system controllers report on growing difficulty to control the frequency when the wind power output is high. One report says that frequency control becomes very difficult when frequency changes due to wind, reach 1.5 Hz/min.

How far the frequency falls when generation is lost is highly dependent on the physical characteristics of all the generators that are connected and run at that point of time including the WPPs. While some modern wind farms are capable of providing so called instantaneous reserves when the wind blows, a more important consideration is how individual WPPs assist in slowing the rate at which the frequency falls. Under-frequency events in which frequency drops below 47 Hz are very rare.

Types of Frequency Control

Increasing the electrical load in the power system tends to brake the generators, tending the frequency to fall. The frequency control of the system then increases the torque on some of the generators until equilibrium is restored and the frequency becomes 50 Hz again. The aim of frequency control is to maintain the balance between the load and the generation within a control area. Frequency control is generally based on three control actions:

- Primary frequency control
- Secondary frequency control
- Tertiary frequency control.

There is always a chance for imbalance due to the changes in load and generation. Therefore, primary and secondary frequency controls operate continuously to maintain the power system stability.

(a) Primary Frequency Control: Imbalances in power systems may occur due to the tripping of a thermal unit or due to the sudden disconnection of a large load. To maintain power system stability, an immediate response for this called the *primary frequency control* is required. This frequency control stabilises the frequency after a large disturbance. These are fast frequency deviations and the primary frequency control is activated for maintaining the equilibrium between instantaneous power consumption and production for the whole area. For this to happen, near immediate response to power imbalance and adequate generation reserves must be available in generation units under operation. Such generators respond automatically and rapidly (typically within 30s–60s to the frequency fluctuations to reinstate the power balance. However, the frequency stabilises (not necessarily) at the pre-disturbance value.

Wind power may seem to have little or no influence on the amount of primary reserves required. On second per minute time-scales, rapid variations in the total wind power capacity output occur randomly such as existing load variations. When aggregated with load and generation variations, the increase in variability due to wind is very small. However, WPPs have the capability, even if limited, to take part in the primary control through a control equal to 3%–5% of the output power of the WPPs.

(b) Secondary Frequency Control: Secondary frequency control is a centralised automatic generation control which brings frequency back to its reference value. These are relatively slow frequency variations and are aimed at keeping the balance between power production and power demand within the individual zone and keeping up the agreed exchange of power with other zones. Following an imbalance, it restores the interchanges with surrounding power systems in each control area. To restore the frequency to its nominal value, i.e., 50 Hz, the secondary reserve is activated either manually or automatically, within ten minutes to fifteen minutes following frequency deviation. Thereby, the secondary control results in slower increase or decrease of the generation.

The impact of wind power on the need for secondary reserves is increasingly significant only from the wind energy penetrations levels of 10% upwards. The main

impact of wind power is on how conventional units are scheduled to follow load hour-to-day time-scales. This secondary reserve may be a spinning reserve (hydro or thermal plants in part load operation) and/or a standing reserve (rapidly starting gas turbine power plants and load shedding). It backs up the primary reserve and stays operational until long term reserves take over (see Figure 10.14).

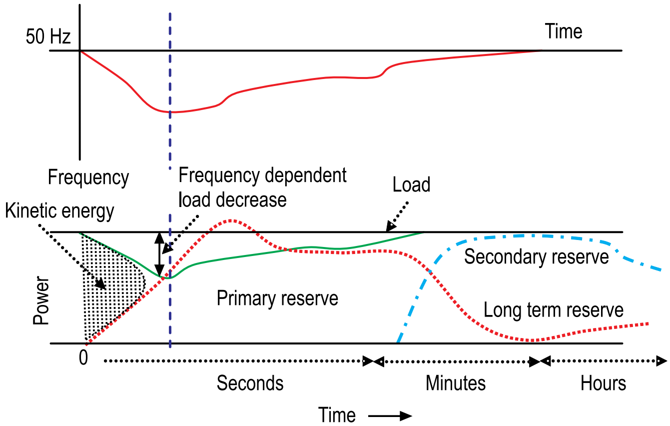


Figure 10.14 Frequency Change due to Disconnection of Large Power Plant Prompting Power Reserve Activation.

Now, the issue is the capacity of the WPPs/wind farms to participate with the grid for stable operation, if not in the primary, it must be at least in the secondary frequency control. Actually it is possible. When necessary, the wind farm power production has to be regulated down for secondary frequency control called *balance control* [see Figure 10.15(a)]. Lesser power is produced than that is possible for a little while after which the WPP/wind farm can return back to the normal operation.

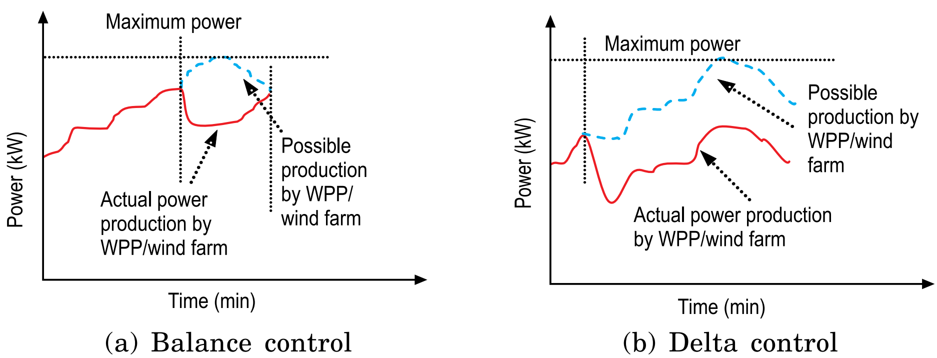


Figure 10.15 Secondary Frequency Control: (a) *Balance Control:* Regulating down the WPP/wind farm power production when necessary, for secondary frequency control. After the fault situation, the WPP/wind farm can return to the normal operation; (b) *Delta Control:* Intentionally producing less wind power than that is possible all the time, so that the WPP/wind farm is able to participate in the secondary frequency control and regulate its production up, when necessary.

As the wind speed is unpredictable, one strategy is to intentionally keep the power production at slightly lower level so that the secondary control is possible during under frequencies. *Delta control* [see Figure 10.15(b)] corresponds to the WPP/wind farm intentionally producing less wind power than that is possible all the time, so that, when necessary, the WPP wind farm is able to participate in the secondary frequency control and regulate its production up.

By *gradient power control* (see Figure 10.16) the actual and possible ramp up of the power production subjected to the availability of sufficient wind speeds could be achieved.

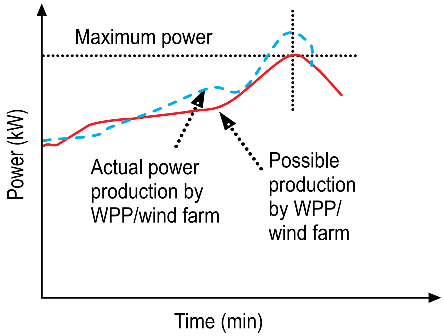


Figure 10.16 Secondary Frequency Gradient Power Control: Regulating the ramp up of the WPP/wind farm power production when necessary, for secondary frequency control. After the fault situation the WPP/wind farm can return to the normal operation.

Some system operators require WPP operators to include primary frequency control (quick frequency variations) possibility of 3%–5% (as required by thermal power plants) into the control of wind farm power output and also be a party to the secondary frequency control (slow frequency deviations). However, WPPs have the capability, even if limited, to take part in the secondary control as well. In particular, when the frequency exceeds the rated value over the tolerance, the contribution to the secondary control can be obtained by shutting down some WPPs by using the pitch angle control.

(c) Tertiary Frequency Control: Tertiary frequency control is achieved by the manual changes in the connection/disconnection of the generating units (which is possible with WPPs/wind farms), changes in the dispatching of units and changes in the interchange program or load control. The aim of tertiary frequency control is to restore primary and secondary reserves and make large generation adjustments, if required. Primary and secondary controls are fast and automatic unlike tertiary frequency control.

10.6.3 Short Term Balancing

Balancing is dependent on power system frequency. For power balance to be maintained in a power system, the frequency requires to be continuously stabilised.

Typically, an AC grid network is said to be stable when the voltage variation is 90% to 105% and the frequency variation is between 49 Hz to 50 Hz. Short term balancing of WPPs capabilities are determined by the output power controllability (when the output power needs to be changed quickly but in small amounts). Usually, low frequency occurs more often than the high frequency.

Although short term balancing may be possible, in some cases, in the strictest sense, prima facie the WPPs are not suitable for both types of balancing (as the wind speed is not exactly predictable). Therefore, as long as there are cheaper means available to keep the power system balanced, WPPs will probably not contribute to the system balancing. Variable speeds WPPs have much more short term balancing capabilities than constant speed WPPs. When frequency goes high, depending on the degree of controllability and ratings of WPPs in a wind farm short term balancing can be achieved by:

- Switching off the WPPs one by one
- Increasing the pitch angle of the WPPs so that lesser energy is extracted from the wind to cancel out the power fluctuations on the grid.

When frequency goes low, for short term balancing to be achieved, increasing the power output is more difficult in the WPPs because at that point of time, winds may not be strong enough to decrease the pitch angle and extract more energy from the wind. However, it can be done in the following ways that are complimentary to reduce the output:

- Some of the WPPs should purposefully stay disconnected (Figure 10.15b) so that when frequency goes low and more power is required, these WPPs can be connected. However, there is a catch. This process does not happen instantaneously. For both constant speed and variable speed WPPs, it takes some time as the wind turbine rotors have to get started and accelerate upto the nominal value and supply power to the grid.
- Alternatively, variable speed WPPs which are already rotating, can be operated with a pitch angle different from the value (Figure 10.16) that would otherwise result in maximum power generation. So, whenever there is a demand for more power, there is enough time to decrease the pitch angle in order to increase the power harnessed from the wind.

However, impact on short term balancing is normally limited with:

- Few WPPs (short term fluctuations are too small to affect system balance)
- Many WPPs (short term fluctuations are evened out).

A cause that affects the day-to-day short term balancing in the WPP is power fluctuations affected by the turbulence is a stochastic quantity. When many WPPs are considered, as in a wind farm, this turbulence is evened out and therefore, is not a problem. Stochastic turbulence is induced by the storm fronts and exceeds the cut-out wind speed value of the WPP. Such disturbance is grave, as it affects a large number of WPPs and hence the power output too. But when the wind power penetration becomes higher than 10%, short-term balancing becomes difficult.

(a) Ramp Rate

The *ramp rate* is defined over fixed periods say one minute or ten minutes. For thermal power plants, normally, maximum ramp rates are around 10 MW/minute. In addition, each of these thermal power plants requires a minimum notice period to synchronise and consume start-up heat to bring it on the load. Both these actions increase with the time if the generator is shut down. Therefore, at all times, some power plants are purposefully part-loaded for quicker response, reserve and spare duty to cover unexpected demand or generation changes. Such actions are also expected from the WPPs by the grid operators.

The WPP output varies with the wind resource which means:

- Power cannot be despatched like conventional power plants.
- System operators cannot control the rate of power decrease, i.e., ramp down due to falling wind speeds.
- Ramping up is not simple. Some manufacturers provide the option of controlling rate of power increase.

Therefore, the ramp rate is also a matter of concern for the grid operator, as the power has to be quickly ramped up after a fault is cleared. This requirement is made to avoid power surges on one hand and on the other hand, to avoid the generation that is missed if the electric generators ramp up too slowly. Both cases result in power imbalance, which could lead to instability although the initial fault is cleared.

WPPs with a small fault current contribution may disconnect for a short duration if the voltage behaves in such a way that the power ramp is 5% of the nominal power per second. In such a case, the generator has to re-synchronize, not later than 2 seconds after the fault clearance and power output has to ramp up with at least 10% of the nominal power per second.

The ramp rate of the power control, also given by a set point, can be in the range of 10% to 100% of the nominal power per minute. In case of passive stall WPPs like Type-A WPPs, the power output can be controlled by cut-in and cut-out of a single WPP. In a transient fault situation, the full power decrease and a subsequent power increase must be possible within approximately 30 s.

(b) Power Reserves

The electrical system needs power reserves to face the disturbances in the grid as well as to follow the load curve. The variable production pattern of wind power production leads to the changes in scheduling of the other large conventional production plants and the power flows in the transmission network. Therefore, an adequate reserve has to be provided.

(i) Maintaining Operating Reserve: To guard against sudden loss of generation (from WPPs due to periods of calm or storm related shut downs), off-system purchases, unexpected load fluctuations and/or unexpected transmission line outages, operating reserves or so called *shadow power stations* are maintained by grid operators to assure a stable power system performance. Fluctuating and the non-despatchable

electric power generated from the wind can increase the costs for regulation and incremental operating reserve. Operating reserves can be spinning or non-spinning ones.

Any variation in the probable load or generation that cannot be forecast has to be considered when determining the amount of operating reserve to be maintained. The exact point at which the integration of the intermittent WPP generation begins to degrade the system economics is unclear. But experience suggests that if the wind penetration levels are in excess of 5%, fluctuation will be of increasing concern to the grid operators, particularly during low demand periods. Experience of the past shows that whenever electric power consumption was comparatively high because of the weather during cold winters or hot summers, the contribution from the WPPs was only minor which means that they cannot replace the conventional power plants to a significant degree but can substantially save the fossil fuel consumption.

(ii) Instantaneous Reserves: At times when the wind speed exceeds WPP cut-out speed, the sudden shutting down of a large wind farm/WPP is what grid operators do not like. This would be equivalent to the disconnection of a large conventional power plant. If a number of wind farms are clustered in a relatively small geographical region, there may arise occasions when a large storm with high winds may shut down a large amount of wind power generation. In such cases, a grid operator has to make arrangements for the instantaneous reserves also. But such conditions are quite rare.

(iii) Disturbance Reserves: Disturbance reserves are usually dimensioned according to the largest unit outage. As WPPs are relatively small units, there is no need to increase the amount of disturbance reserve. Variations of wind power in smaller duration of seconds and minutes (primary control of frequency) have little effect on the power reserve, since small variations in the various WPPs placed on large areas are not correlated and therefore, they cancel out each other. Instead, the variation of wind power for duration of one hour or for a lower time affects the reserve power used for the frequency control. On an average, for a 10% penetration level of wind power, the extra reserve requirement of wind power is in the order of 2–8% of the installed wind power capacity.

10.6.4 Long Term Balancing

The variability of the wind in the longer term (from fifteen minutes and may be for several hours) tends to complicate the despatch of the power from the remaining conventional power plants that supply to the load because it causes the demand curve to be matched by these units (which is equal to the system load minus the wind power generation) to be far less smooth than would be the case without wind power.

Long term balancing for WPPs is difficult because it is determined by the actual availability of output power which depends on the wind. In fact, if the wind power penetration becomes higher (typically more than 5%), long term balancing is

more complicated because if there is no wind at the predicted time, all the WPPs will stop producing power that can affect large regions. Therefore, for long term balancing, load flow studies and transient stability analysis are to be done thoroughly using relevant computer software which should include load forecast, coverage of demand, probable network availability, programmed maintenance of generators and transmission assets.

10.6.5 Transmission and Distribution System Impacts

The day-to-day operation of the power system in high level of wind power penetration is a challenging experience. The grid operators must balance the generation without breaching system constraints and maintain the quality of supply to the consumers while operating the system economically. The variability of the wind, on timescales of seconds to hours makes these tasks more difficult. If these variations are big and quick, there will be corresponding changes in the magnitudes and directions of the power flows from the WPPs and from the conventional generators providing regulating and operating reserve services in the other parts of the system. Unless these variations are addressed quickly, the voltages on the grid will vary and if the variations are large enough, the limits may get infringed, which is not desired by the grid operators.

A large proportion of WPPs are generally embedded in the local distribution network. Therefore, connection of large WPPs or wind farms to the distribution system introduces some additional complexity to the connection arrangement owing to the radial nature of most distribution feeders. The individual wind farms can be transferred across the grid network, as they outgrow the capacity of the local distribution network. However, for a fault on a distribution system where a circuit breaker connecting the distribution feeder to the transmission grid opens, it is important to note that the wind farm trips offline to prevent creating an islanded network. To cover both instances the wind farm needs to provide both voltage ride through capability and also anti-islanding protection. Sometimes, it may be difficult to meet both of these objectives satisfactorily.

10.6.6 Economic Despatch and Unit Commitment

The power demand continually changes, requiring generation to be monitored, scheduled and despatched. Unit (power plant) commitment is the scheduling of specific power plants to meet expected electrical energy demand on a day-to-day basis. Some generators require several hours to get started and synchronised to the grid while in many cases, the shutdown process of the conventional power generators is also lengthy and units may require several hours of cooling prior to restarting. This timescale is called *unit commitment*, and it can range from several hours to several days, depending on the specific generator characteristics and operational practice.

System operators have the information on schedules for production, consumption and interconnector usage. If the output from a WPP is accurately predicted one to two days in advance, then the grid operators can more easily determine the units that

would need to be committed. The lack of an accurate forecast adds further uncertainty to the commitment decision. The result is that the optimised unit commitment is complicated due to the variable output of the WPPs. Units are committed to the schedule based on the generation maintenance schedules, generator start-up and shutdown costs, minimum fuel burn requirements and seasonal availability of intermittent resources such as hydro and wind. This schedule is usually made at least 24 hours in advance.

Another problem is that as the output powers from the WPPs follow long term wind speed fluctuations, the remaining conventional generators face complicated demand patterns. As the conventional generators are already connected to the grid, they have not only to cope with the normal load variations but also with the differences resulting from the variability of the WPP output power and this is aggravated especially when there is a simultaneous wind speed decrease and load increase. This heavily affects the despatch of the conventional power producing units and the required reserve margins.

As wind power capacity within a control area increases, the variability of wind power can have a significant impact on the:

- Efficiency of unit commitment process
- Reserve requirements to meet reliability performance standards.

Based on the prediction reports, grid operators can coordinate the electrical generation scheduling process efficiently as well as buy clean wind power as soon as it is produced on the following day. Large swings in WPP/wind farm output over periods ranging from minutes to hours require commensurate changes in the output of conventional power plants to ensure that demand is always met. Such wide range swings may also increase the frequency of occasions when lines on the grid reach or exceed their safe operating limits and disturb the security of the grid.

Clustering of WPPs into wind farms improves the economic despatch and unit commitment to some extent. When the wind blows, it does not blow equally at all locations across the country. However, clusters of wind farms within small geographical regions on the grid tend to increase or decrease their output together, potentially creating large swings in their collective generation. But, if the wind farms are geographically dispersed, then swings in the combined output of all wind farms will be minimised and the limits on wind energy integration will be potentially higher than they would be if the wind generation develops in one or two clusters. As the WPP technology has developed, control functions that can also limit the magnitude of swings in wind farm output have increasingly become a standard issue.

Economic despatch and unit commitment is also committed to the schedule based on the generation maintenance schedules, generator start up and shutdown costs, minimum fuel burn requirements (for thermal power plants) and seasonal availability of intermittent resources such as hydro and wind. In many places, the WPP output may be fairly predictable as in Muppandal (South India) or California (USA) and such other places, due to seasonal and diurnal wind resource characteristics observed over many years of wind farm operation or as a result of wind resource monitoring programs.

Although the wind resource is not fully programmable, it is becoming more and more predictable, with a margin of uncertainty of almost 5% in a time period of 72 hours. This uncertainty further decreases when reducing the time interval which leads to an improvement of the capacity of managing the energy contribution of the WPP to the control area.

Changing from day-ahead to intra-day unit commitments have drastic impacts on the accuracy and the cost of balancing the power system. However, it should be noted that it is not just wind forecasting accuracy that is relevant for balancing but also the sum of all demand and supply forecast errors in the operation of the power system. Following are some of the planning schedules:

- 0–3 hours ahead of wind forecasting is commonly used for planning horizons.
- 0–8 hours ahead can be used for trading in a regulating market.
- 8–48 hours ahead can be used for contingency analysis and also for system unbalance.
- 42–120 hours ahead can be used for secondary input for outage planning and estimating system balance.

10.7 PER UNIT CALCULATIONS

The per unit system is a method used by electrical engineers to simplify the calculations by expressing all values as a ratio, i.e.,

$$\frac{\text{Actual value (in any unit)}}{\text{Base or reference value (in the same unit)}}$$

The advantage of the per unit (p.u.) system is that the product of two quantities expressed in per unit is also in per unit. Secondly, a reduction in the appearance of $\sqrt{3}$ in the calculations. Thirdly, the per unit impedance of an AC generator is essentially a constant for a wide range of actual sizes. The following steps can be followed:

(a) Assume an arbitrary voltage VA (e.g. 20 MVA).

(b) Select the voltage bases of each voltage level of the grid network (e.g. 33 kV, 66 kV). These voltage bases should be related to the nominal turn ratios of the transformers.

(c) Calculate the appropriate active and reactive power flows at the generator terminals as a per unit value (i.e., for a power of 10 MW with a base VA chosen for 20 MVA, the per unit value is P = 10/20 or 0.5 p.u. Similarly, for the reactive power flow of 2 MVAr, the per unit value is Q = 2/20 or 0.1 p.u.).

(d) If necessary, transform the impedances of the circuit from the ohmic to per unit values using a base impedance $Z_{\text{base}} = V^2_{\text{base}}/\text{VA}_{\text{base}}$.

(e) The base current at any particular voltage may be calculated from $I_{\text{base}} = \text{VA}_{\text{base}}\sqrt{3} \times V_{\text{base}}$.

10.8 SIMULATION OF GRID CONNECTED WPP

IEC 61400–27 provides some standards for the electrical simulation models for wind power generation which can also be referred. There are several softwares wherein wind power simulations can be done in the process of grid integration. For instance, load flow, short circuit and transient stability studies are conducted in Example 10.1 using MiPower simulation software package. The performance and evaluation of the power system (refer Figure 10.17) for parameters like voltage profiles, phase angles and short circuit currents, short circuit MVA and variations in frequency, variations in voltages during a fault or outage of a line etc. can be undertaken by the *load flow* study, *short circuit* study and *transient stability module* of MiPower® respectively. This network is modelled in the *power system network editor* module of MiPower®. All the exercises are conducted on the system which help in analysing the power system and determining its limits for its safe operation.

EXAMPLE 10.1

Figure 10.17 depicts a single line diagram of a constant speed Type-A WPP with SCIG connected to the 220 kV electrical grid network. The network consists of a 1.25 MW constant speed Type-A WPP with SCIG, WPP transformer, transmission line and pooling substation with transformer. The stator of the SCIG is connected to a step-up transformer of 0.69 kV/33 kV. A 33 kV feeder line connects the step-up transformer and the pooling substation located 2 km away from the wind farm. The pooling substation is equipped with 33 kV/220 kV transformer which is connected to the transmission grid. The specifications are as follows and all the values are in per unit on machine MVA rating.

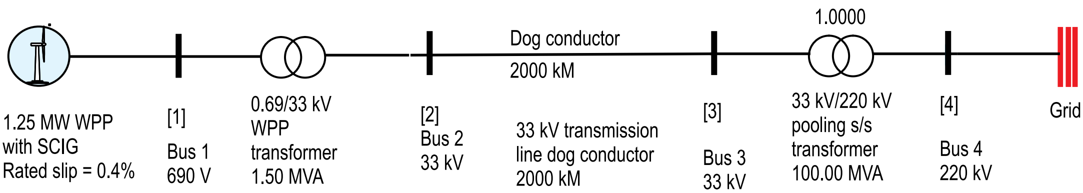


Figure 10.17 Grid Connected WPP with SCIG—Single Line Diagram.

(a) SCIG specifications

1.404 MVA; 1.25 MW; 690 V; 50 Hz; 4 poles; rated slip = 0.4%; H = 0.384 s; 1500 RPM.

Parameters: $R_s = 0.006294$; $X_s = 0.9714666$; $X_m = 3.12254$
At slip $= 1$, $R_s = 0.01527333$; $X_s = 0.04449$
At slip $= 0$, $R_s = 0.004214666$; $X_s = 0.09093$
Values are in p.u. on its own rating.

(b) WPP transformer specifications

0.69 kV/33 kV; 1.5 MVA; Z = 6.25%; Number of taps = 5, ±6%; X/R = 20
Impedance is in p.u. on its own rating.

(c) Pooling substation transformer specifications
33 kV/220 kV; 100 MVA; Z = 13.93%; Number of taps = 17; ±10%; X/R = 20
Impedance is in p.u. on its own rating.

(d) Transmission line specifications
Thermal rating = 17 MVA; 2 km dog conductor; 33 kV
R_p = 0.379 Ω/km/ckt; X_p = 0.345 Ω/km/ckt
$B/2 = 1.67 \times 10^{-6}$ ℧/km/ckt.

(e) Grid fault level
Three-phase to ground fault level = 2000 MVA
One-phase to ground fault level = 2000 MVA.

Solution:
The equivalent circuit considered for the induction generator is shown in Figure 10.18. The values shown in the equivalent circuit are in per unit on its own rating. Equivalent impedance of the induction generator is calculated by calculating the Thevenin's equivalent impedance across terminals AB, as shown in Figure 10.18.

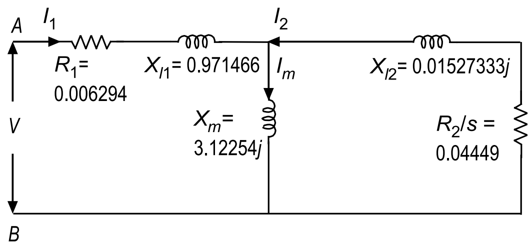


Figure 10.18 Equivalent circuit of SCIG.

The SCIG parameters are:

R_1 = Stator winding resistance
X_{l1} = Stator leakage reactance
X_{l2} = Rotor leakage reactance
X_m = Magnetising reactance
R_2 = Rotor winding resistance
$s = (\omega_s - \omega_r)/\omega_s$

Power system calculations are always done on a common MVA base.
Therefore, base MVA considered = 100 MVA
Converting the resistance and reactance values on 100 MVA base

$$R_1 = R_{1\text{old}} \times \frac{MVA_{\text{new}}}{\text{MVA}_{\text{old}}} \tag{10.4}$$

$$R_1 = 0.006294 \times \frac{100}{1.404} = 0.448291 \text{ p.u.}$$

$$X_1 = 0.9714666j \times \frac{100}{1.404} = 6.919278j \text{ p.u.}$$

$$X_m = 3.12254j \times \frac{100}{1.404} = 222.4j \text{ p.u.}$$

$$R_2 = 0.01527333 \times \frac{100}{1.404} = 1.087844 \text{ p.u.}$$

$$X_2 = 0.04449j \times \frac{100}{1.404} = 3.168803j \text{ p.u.}$$

Equivalent impedance value of SCIG in p.u.

$$Z_{\text{eq\_m}} = ((R_2 + jX_2)\,||\,jX_m) + (R_1 + jX_m) \tag{10.5}$$

$$= \frac{(1.087844 + 3.168803\,j) \times 222.4}{(1.087844 + 3.168803\,j) + 222.4} + (0.448291 + 6.919278\text{j})$$

$$Z_{\text{eq\_m}} = 1.505761 + 10.048665j \text{ p.u.}$$

Impedance value of WPP transformer on 100 MVA base in p.u.

$$Z_{\text{tr1}} = Z_{\text{tr1\_old}} \times \frac{\text{MVA}_{\text{new}}}{\text{MVA}_{\text{old}}} \tag{10.6}$$

$$Z_{\text{tr1}} = 0.0625 \times \frac{100}{1.5} = 4.16667j \text{ p.u.}$$

Actual values of transmission line

$R_l = 0.379\ \Omega/(\text{km/ckt})$
$X_l = 0.345\ \Omega/(\text{km/ckt})$
$B/2 = 1.67e - 6\ \mho/(\text{km/ckt})$
Line length = 2 km
$R_l = 0.379 \times 2 = 0.758\ \Omega$
$X_l = 0.345j \times 2 = 0.69j\ \Omega$
$(B/2) = 1.67 \times 10^{-6} \times 2 = 3.34j \times 10^{-6}\ \mho$
$[1/(B/2)] = 299401.2j\ \Omega$

Actual values of transmission line in p.u. on 100 MVA base

$$Z_{\text{base}} = \frac{\text{kV}^2}{\text{MVA}} \tag{10.7}$$

$$Z_{\text{base}} = \frac{33^2}{100} = 10.89\ \Omega$$

$$R_l = \frac{0.758}{10.89} = 0.069605 \text{ p.u.}$$

$$X_l = \frac{0.69}{10.89} = 0.063361\,j\Omega$$

$$[1/(B/2)] = \frac{-299401.2\,j}{10.89} = -27493.22\,j \text{ p.u.}$$

Impedance value of grid transformer in pu on 100 MVA base

$$Z_{tr2} = 0.1393j \times \frac{100}{100} = 0.1393j \text{ p.u.}$$

Grid fault level and X'_d value

Three-phase to ground fault level = 2000 MVA

One-phase to ground fault level = 2000 MVA

$$X'_d = \frac{\text{MVA}_{\text{base}}}{\text{Three-phase MVA}_{\text{fault}}} \tag{10.8}$$

$$X'_d = \frac{100}{2000} = 0.05\,j \text{ p.u.}$$

The positive sequence diagram for the example is shown in Figure 10.19.

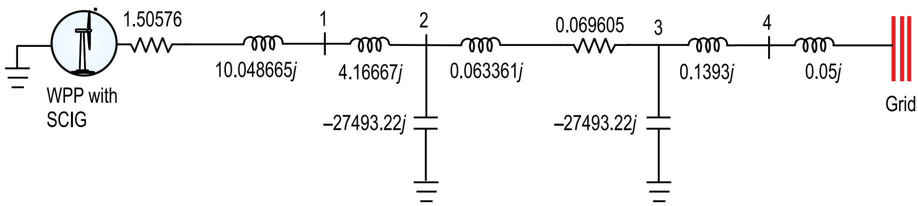


Figure 10.19 Sequence Diagram of the Typical Power System with Type-A WPP.

To calculate the fault current at bus 3, equivalent impedance at bus 3 is calculated. There are two paths for short circuit current contribution at bus 3. One of the paths will be the contribution from induction generator and another path will be from the grid.

The equivalent impedance of the SCIG path is calculated as follow:

$$Z_a = [(1.50576 + 10.048665j + 4.16667j) \,||\, (-27493.22j) + 0.069605 + 0.063361j) \,||\, (-27493.22j)]$$

$$Z_a = \frac{(1.50576 + 14.215335\,j) \times (-27493.22\,j)}{(1.50576 + 14.215335\,j - 27493.22\,j)} + 0.069605 + 0.063361j \,||\, (-27493.22j)$$

$$Z_a = \frac{(1.576923 + 14.28596\,j) \times (-27493.22\,j)}{(1.576923 + 14.28596\,j - 27493.22\,j)}$$

$$Z_a = 1.578563 + 14.2933j \text{ p.u.}$$

The equivalent impedance of the grid path is calculated as follows:

$$Z_b = 0.05j + 0.1393j$$

$$Z_b = 0.1893j \text{ p.u.}$$

The total equivalent impedance at bus 3 is

$$Z_{eq} = Z_a \;||\; Z_b$$

$$\therefore\ Z_{eq} = \frac{1.578563 + 14.2933j \times 0.1893j}{1.578563 + 14.2933j + 0.1893j} = 2.66526 \times 10^{-4} + 0.186854j \text{ p.u.}$$

$$I_{\text{fault}} = \frac{V\delta}{Z_{eq}} \tag{10.9}$$

$$\therefore\ I_{\text{fault}} = \frac{1 < 0°}{2.66526 \times 10^{-4} + 0.186854\,j} = 5.351745,\ < -89.91° \text{ p.u.}$$

Base current at the 33 kV bus voltage is

$$I_{\text{base}} = \frac{\text{MVA}_{\text{base}}}{\sqrt{3} \times \text{kV}} \tag{10.10}$$

$$I_{\text{base}} = \frac{100 \times 10^6}{\sqrt{3} \times 33000} = 1.7495 \text{ kA}$$

$$I_{\text{actual}} = 1.7495 \times 10^3 \times 5.351745 < -89.91° = 9362.87 < -89.91°\text{A.}$$

The simulation of the sample in MiPower shows the fault current at bus 3 as 9364.62 A, –87.73° in Figure 10.19. The calculated current and simulated current are almost equal.

Now, we will illustrate and calculate the current contribution from the SCIG and the grid separately and compare it with the simulation results.

Current contribution from the SCIG

$$I_{\text{scig}} = \frac{V\delta}{Z_a} \tag{10.11}$$

$$I_{\text{scig}} = \frac{1 < 0°}{1.578563 + 14.2933\,j} = 0.007633645 - 0.0691198j \text{ p.u.}$$

$$I_{\text{base}} = \frac{100 \times 10^6}{\sqrt{3} \times 690} = 83.6739 \text{ kA}$$

Therefore, actual fault current contribution from SCIG is

$$I_{\text{actual1}} = I_{\text{base}} \times I_{\text{scig}} \tag{10.12}$$

$$I_{\text{actual1}} = 83.6739 \times 10^3 \times (0.007633645 - 0.0691198j) = 5818.6 \text{ A},\ < 83.7°$$

The simulation of the sample in MiPower shows the current contribution from induction generator is 5805.26 A 97.12°. Figure 10.19 shows the simulated current. Hence, the calculated current and simulated current are almost equal.

Current contribution from the grid

$$I_{grid} = \frac{V\delta}{Z_b} \tag{10.13}$$

$$I_{grid} = \frac{1}{0.1893\,j} = -5.2826\,j \text{ p.u.}$$

$$I_{base} = \frac{100 \times 10^6}{\sqrt{3} \times 220 \times 10^3} = 262.432 \text{ A}$$

$$I_{actual2} = 262.432 \times (-5.2826j) = 1386.32 \text{ A, } 90°$$

The simulation of the sample in MiPower shows the current contribution from grid is 1386.57 A 92.21°. Figure 10.19 shows the simulated current. The calculated and simulated currents are almost equal.

EXAMPLE 10.2

For the above mentioned SCIG connected to the grid with the same specifications, what simulations are to be undertaken in MiPower (similar) simulation software to compare the output?

Solution:

For a power system study to be undertaken, the initial conditions need to be established. These act as inputs for the further studies. To determine initial conditions, load flow study is carried out in the software and the results are shown in Figure 10.20. The results show that the SCIG generates 1.23 MW and consumes 0.66 MVAr. The voltage profiles of all the buses are within the limits. The power generated is fed into the grid at 220 kV bus (bus 4).

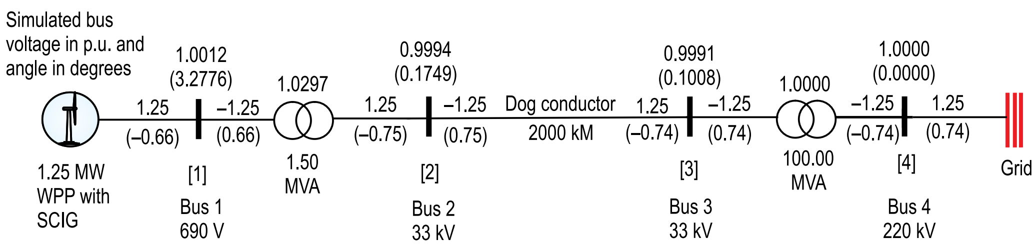


Figure 10.20 Load Flow Results of SCIG and Grid.

When the initial conditions are established, the system is simulated for a three-phase to ground fault at bus 3. Short circuit study can be conducted by selecting the short circuit study option in *Solve Menu* of the software three-phase to ground fault at bus 3 is selected. The induction motor is modelled as SCIG with negative slip. Fault contribution from SCIG and the grid can be known from the simulation. Hence, the stator impedances, the rotor impedances and slip are necessary as these

parameters are input for the equivalent circuit of SCIG. Figure 10.21 shows the contribution from SCIG during the fault is 5805.26A, 97.13° and contribution from grid is 1386.57 A, 92.21°. The total bus fault current is 9364.62 A, –87.73°.

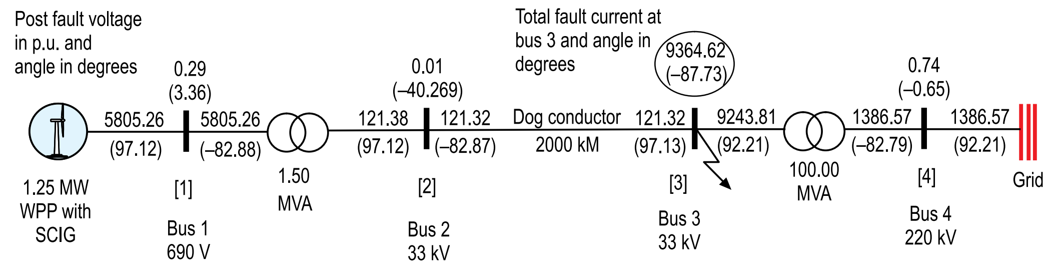


Figure 10.21 Short Circuit Results SCIG and Grid.

EXAMPLE 10.3

Example 10.2 is repeated for the transient stability case fault condition is same. Assume that three-phase to ground fault occurs at bus 3 (similar to the short circuit study). The fault occurs on t = 1 s and it is cleared at t = 1.1 s. The simulation is carried out for 10 s. The variations in voltage, frequency, current, slip and torque–slip characteristics of the machine are seen in the following figures.

Solution:

Figure 10.22 shows the drop in the voltage during the fault duration. The grid terminal voltage drops down to 0.73 p.u. Whereas, the SCIG terminal voltage drops down to around 0.2 p.u. Once the fault is cleared at t = 1.2 s, the voltage recovers and maintains its value within the limits.

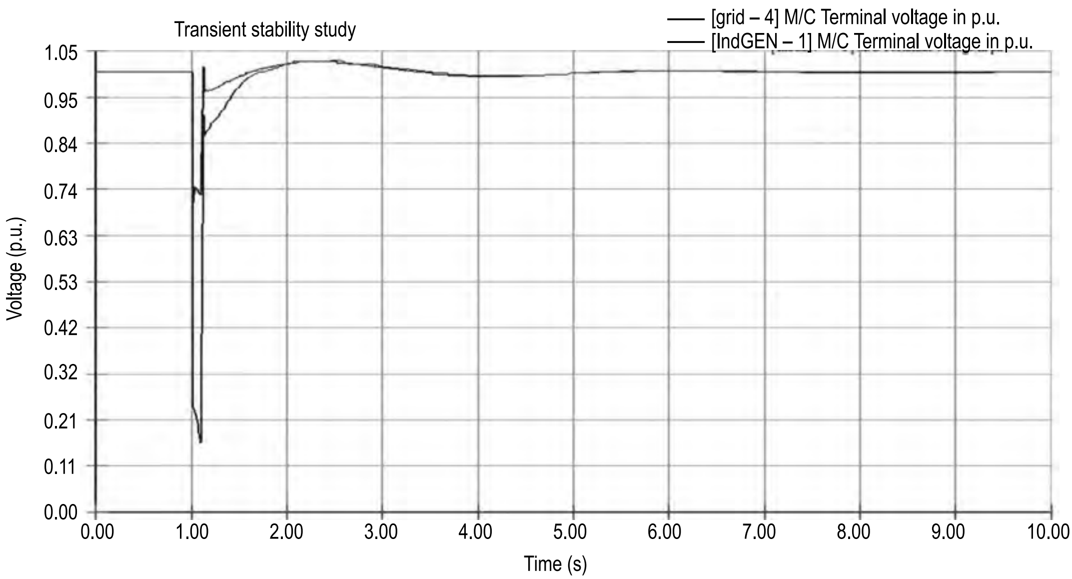


Figure 10.22 Voltage Profile for Fault Clearance of 1.1 s with SCIG in Grid (Case-1).

Frequency variation can be seen in Figure 10.23. The SCIG stays connected during the fault and the SCIG frequency increases to 50.7 Hz briefly during the fault. The transients in the grid frequency are very negligible, as it has large inertia behind it.

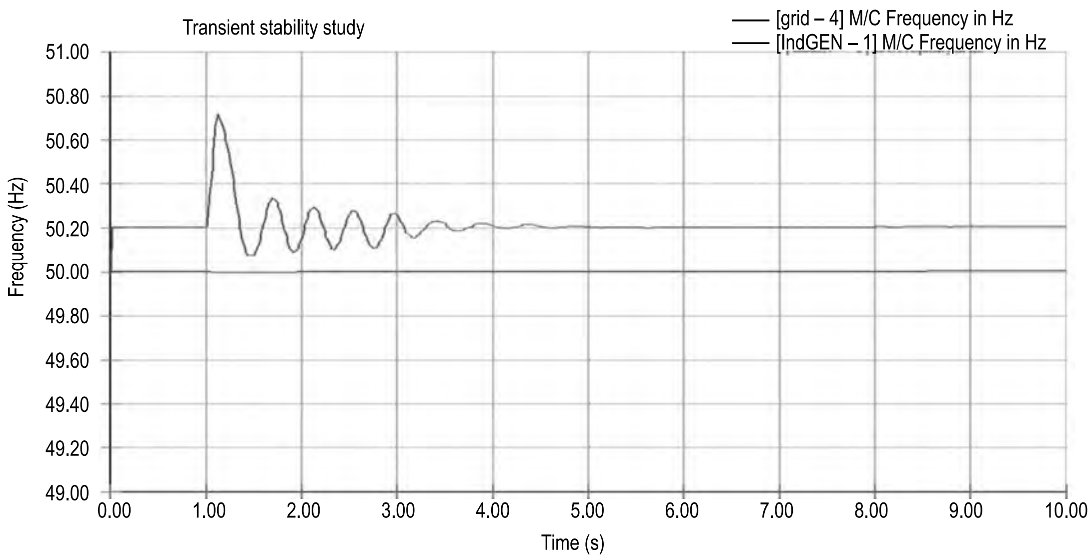


Figure 10.23 Frequency Variations for Fault Clearance of 1.1 s with SCIG in Grid (Case-1).

Slip increases during the fault (negative slip) and the SCIG starts rotating with higher speed until the fault is cleared. Figure 10.24 shows the variation in the slip and machine stabilizes after the disturbance.

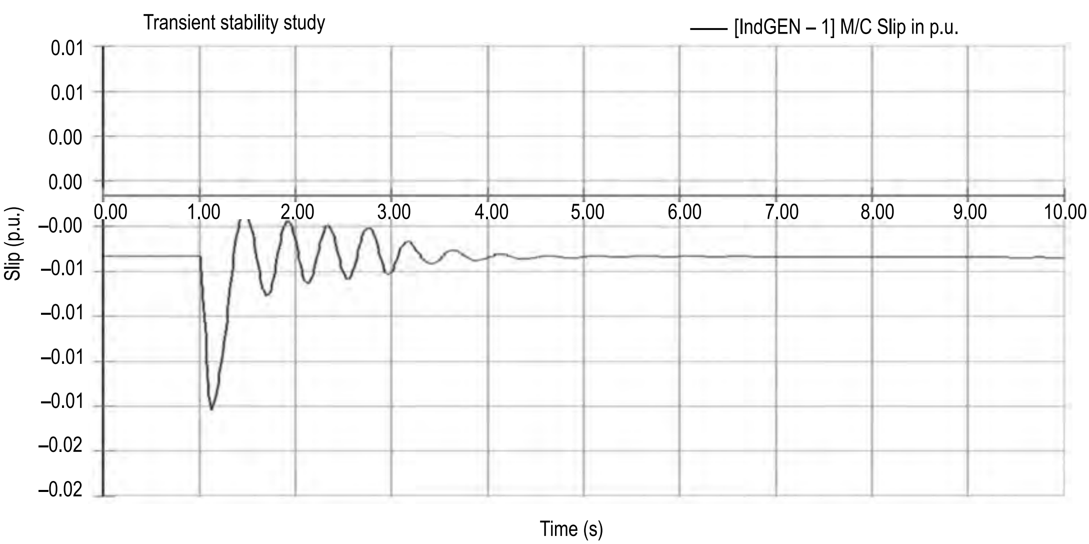


Figure 10.24 Slip Variations for Fault Clearance of 1.1 s with SCIG in Grid (Case-1).

Figure 10.25 shows the operating point of the SCIG. The operating point is the intersection of the electrical torque and the operating slip of the induction machine. During the disturbance, the operating point moves away from initial position. Once the disturbance is cleared, it oscillates and settles at the initial operating point. If there are any changes in network topology as a consequence of the disturbance, then the new operating point will differ from the initial point.

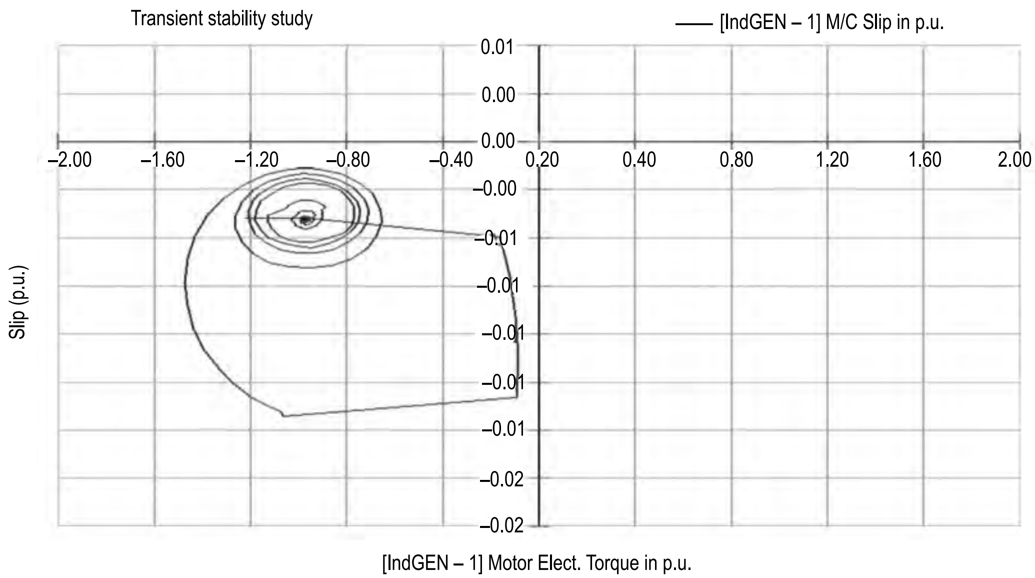


Figure 10.25 Torque v/s Slip Characteristics for Fault Clearance of 1.1 s with SCIG in Grid (Case-1).

EXAMPLE 10.4

In contrast to the above example, this example discusses about the situation when fault clearing is delayed with respect to Example 10.3. Assume three-phase to ground fault occurs on bus 3 (similar to the short circuit study). The fault occurs on t = 1 s and unlike Example 10.3 it is cleared at t = 1.3 s. The simulation is carried out for 10 s. The variation in voltage, frequency, current and slip of the machine are studied and shown in the following figures.

Solution:

Figure 10.26 shows that the fault is cleared at 1.3 s. The delay in the fault clearance leads to further decrease in the voltages of the machine and the gird. Figure 10.20 and Figure 10.24 show the difference in voltage dip in Example 10.4 as compared to Example 10.3.

In Figure 10.27 (as compared to Figure 10.23), the graph shows that SCIG frequency increases more than 52 Hz for a period of around 0.2 s. The transients in the frequency settle in around 4 s. The settling time also depends upon the nearby utility generators and their control systems.

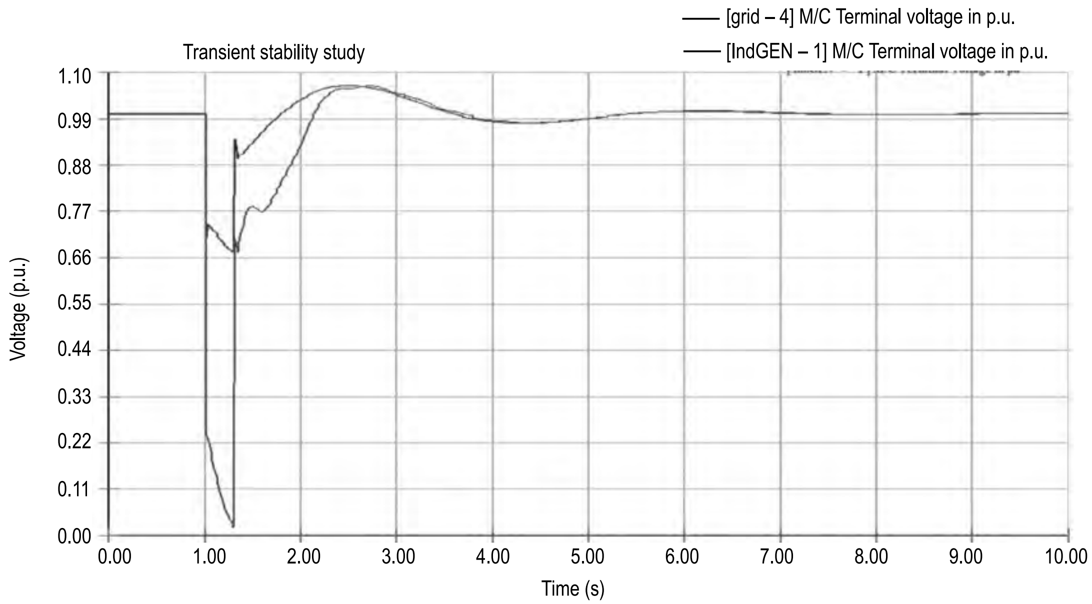


Figure 10.26 Voltage Profile of the SCIG and the Grid for Fault Clearance of 1.3 s (Case-2).

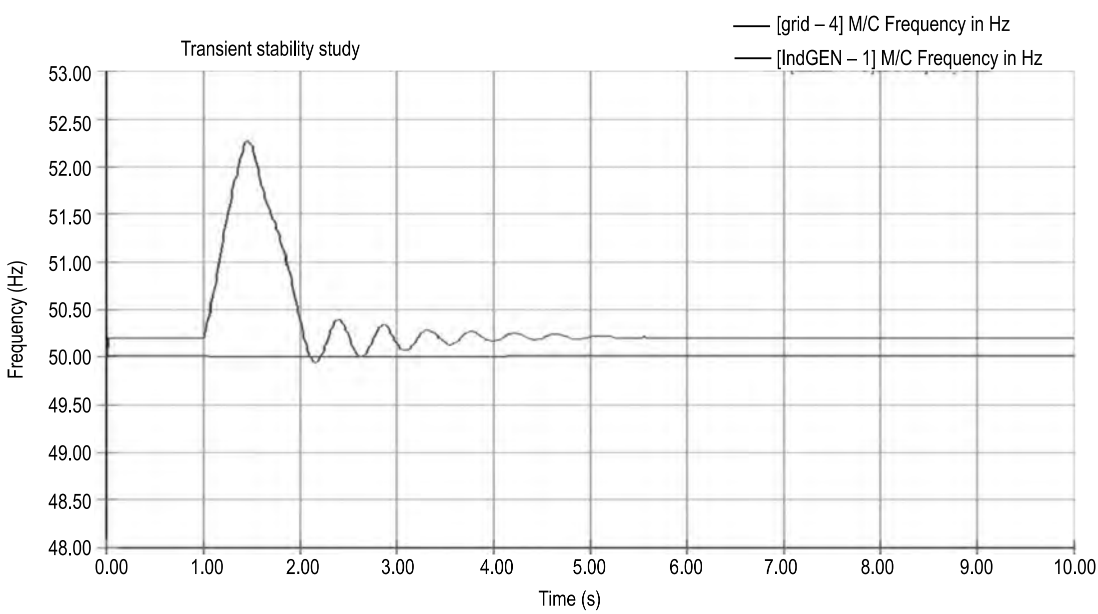


Figure 10.27 Frequency Variations for Fault Clearance of 1.3 s (Case-2).

Figure 10.28 (as compared to Figure 10.24) shows the variation in the slip due to the fault. The increase is around –5% during the fault. In Example 10.3, the variation in slip is less as compared to Example 10.4. The slip of the machine becomes stable after the disturbance is cleared.

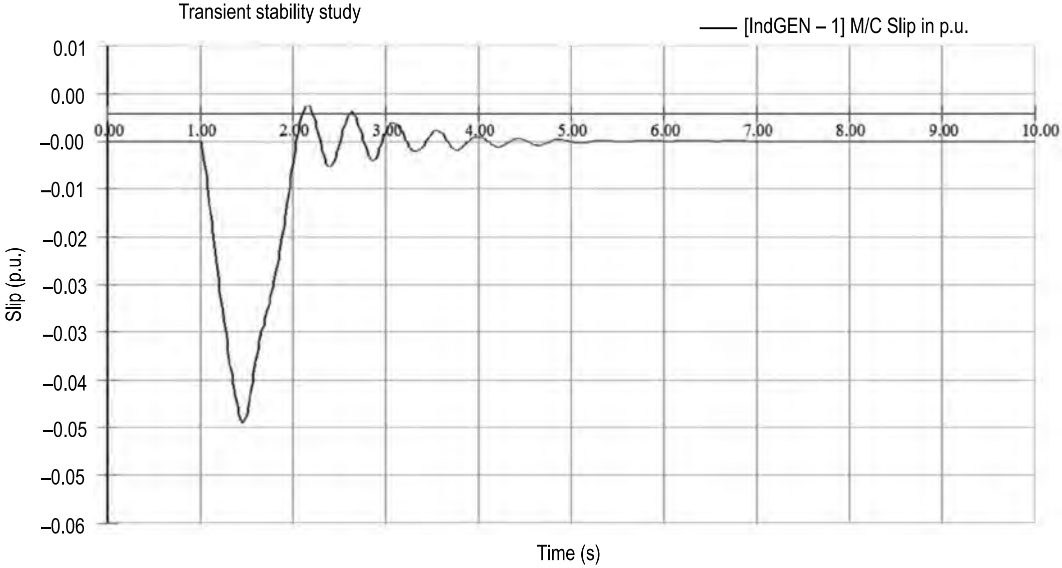


Figure 10.28 Slip Variations for Fault Clearance of 1.3 s (Case-2).

Figure 10.29 (as compared to Figure 10.25) shows the torque–slip characteristics of Example 10.4. The operating point jerks off from its initial position, traverses certain path, oscillates and settles around its initial operating point. The traversed path of the operating point is different as compared to Example 10.3.

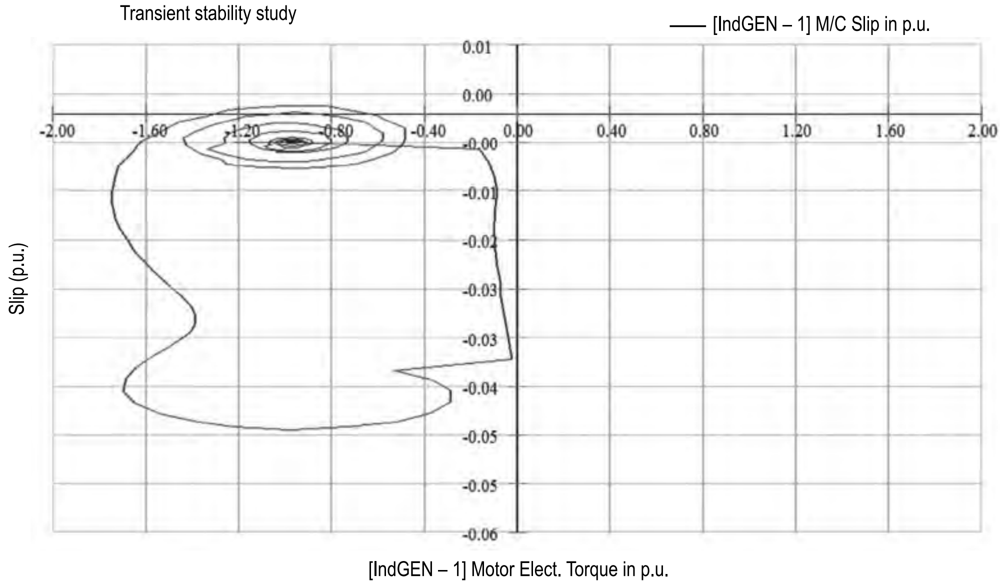


Figure 10.29 Torque v/s Slip Characteristics for Fault Clearance of 1.3 s (Case-2).

EXAMPLE 10.5

In contrast to the above example, this example discusses about the situation when fault clearing is delayed still further as compared to Example 10.4. Assume that the fault clearing time is further delayed, i.e., fault occurs at t = 1 s and clears at 1.5 s.

Solution:

The SCIG hunts before it obtains a steady operating point. Figure 10.30 (as compared to Figure 10.25 and Figure 10.29) shows that the SCIG starts hunting between different operating points and tries to obtain a steady state operating point.

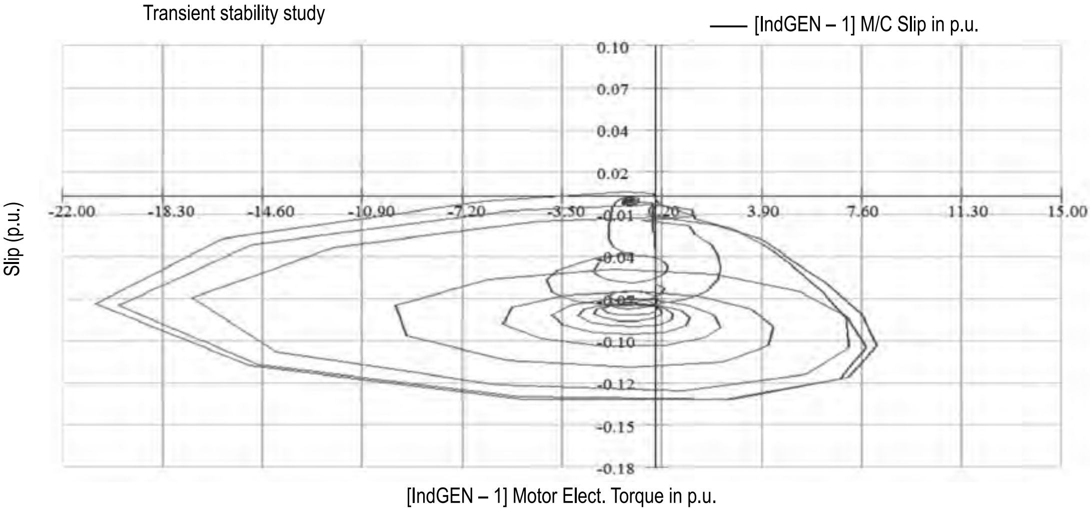


Figure 10.30 Torque Slip Characteristics for Further Delayed Fault Clearance of 1.5 s (Case 3).

On observing Figure 10.30, it can be said that if the fault is cleared after the *critical clearing time*, then the SCIG overspeeds and falls out of step, i.e., it loses synchronism with respect to other conventional generators in the grid network. Due to this, the fault is so severe and the out-of-step generator pulls out other generators thus creating a cascading effect. This brings down the wind generation temporarily and the consequences on the utility grid are very high. If such kind of situation occurs during peak load hours, then it would pose a serious threat to the stability of the entire neighbouring wind farms as well.

SUMMARY

WPP behaviour is different from the conventional power plants but is compatible and improving. With greater WPP penetration, more demands will be placed on WPPs for more output, better voltage control, fault ride through, more of short circuit contribution, better reactive control, dynamic voltage support for safety and reliability, faster ramp rate, lesser flicker problems, better inertia and governor response.

With increased penetration of wind power, integration is to be taken seriously for which indepth load flow studies need to be undertaken. The need for grid reinforcements and other adaptations depend, to a large degree, on the load variations and capacity to import and export power from the grid. The wind is never the same everywhere. Therefore, stronger the power system, more will be the WPPs that can be accommodated, as the wind speeds are different in other geographical areas evening out and neutralising the wind speed variations at different locations.

EXERCISES

10.1 Describe the five functions of the electric grid.

10.2 Describe the five functions of WPPs and wind farm to function effectively and efficiently when integrated into the grid.

10.3 Explain the features of embedded generation system along with its benefits.

10.4 Compare the four main requirements of a TSO with regard to electric power feed-in quality from a generator.

10.5 'Even the electrical generator of WPPs is required to support the grid'. Justify this statement with at least seven salient points.

10.6 Choose the grid network voltage to which a 24 MW wind farm can be connected with justification.

10.7 Discriminate between direct connection and meshed grid connection of WPPs.

10.8 Compare the three major interface issues that arise while connecting WPPs to the grid.

10.9 Compare four major operational issues associated with the WPPs in the grid.

10.10 Distinguish between strong grids and weak grids.

10.11 Distinguish the responses of different types of WPPs to big and small fault current contribution to the grid.

10.12 Explain the concept of fault ride through in WPPs with respect to their application in different types of WPPs.

10.13 Describe the measures that can be taken to compensate for the reactive power control when connecting different types of WPPs to the grid.

10.14 Analyse the effect of harmonics on the grid when connecting different types of WPPs to the grid.

10.15 Explain the impact of short circuit power level at the PCC wind power station.

10.16 Differentiate the combination of high/low consumption and high/low wind power production that gives the highest or lowest voltage?

10.17 Describe the problems of short term balancing in the grid when WPPs are connected.

10.18 Explain the frequency stability problems in a power system due to daily load variations and seasonal variations.

10.19 Describe the responses of WPPs/wind farms to maintain frequency stability.

10.20 Analyse the problems of long term balancing.

10.21 Describe the capacity factor and its influence on long term balancing.

10.22 Differentiate between capacity factor and capacity credit.

10.23 Justify the need for unit commitment and economic despatch with respect to grid integration of wind power.

10.24 Undertake a software simulation of a three-phase short circuit study with a fault clearance of 1.4 s on some relevant software or on the transient stability module of MiPower simulation software and discuss the results obtained.

11

Wind Resource Assessment Technologies

HE brings forth the wind from HIS storehouses.
—Psalms 135:7

Learning Outcome

On studying this chapter, you will able to select an appropriate wind resource assessment instrument to assess the wind power potential.

CHAPTER HIGHLIGHTS

11.1 INTRODUCTION

Wind resource assessment is most crucial for the success of any wind power project. It is a process by which the future energy production of a wind power plant is assessed and the annual energy production (AEP) is predicted. About a year or two in advance, this process is undertaken by using a number of hardware and software tools. Understanding the wind resource assessment technologies is quite important because even small deviations in the results can lead to big miscalculations, building up the risk of an uneconomical operation of the planned wind power investment. The variation of wind speed with height is crucial, since the wind maps always refer to a specific height above the ground level which often differs from the hub heights of the WPPs. Therefore, for better estimation of wind power potential at a particular site, the right application of the best wind resource assessment tools is essential.

Unless used for siting of WPPs, hardly any of the wind resource assessment tool/equipment demands high accuracy and reliability. Most important for the precise measurement, is the choice of sensors along with their accurate calibration and installation.

11.2 WIND RESOURCE ASSESSMENT

Although the accuracy has improved, it is unlikely that wind resource maps, whether public or commercial, will eliminate the need for the on-site measurements for grid connected wind projects. Wind resource maps give a broad area and micrositing is crucial for the installation of WPPs at the best location, as even within a kilometres distance, the wind speeds can be much different. All these aspects necessitate an accurate wind resource assessment for at least about an year and a half to check the repeatability of the wind patterns in the next year.

Although there is wind in every place, the main objective of the wind resource assessment is to find a practical ideal windy site with steady winds and select a WPP that is able to make the maximum utilisation of these steady winds whilst surviving the strongest gusts. The three fundamental steps for wind project development are given below:

- Prospecting
- Validation
- Micrositing.

Prospecting, also called *preliminary area identification* is the process of identifying the potential windy sites within a large area of several square kilometres maybe using airport wind data, topographical maps, flagged trees, climatological data from meteorological stations, satellite imageries, etc. Prospecting is done by undertaking large area screening to locate the concerned site on the state/county wind maps. Large area screening is done by geographical information systems (GIS), a computer mapping and analysis tool to screen potential sites. Meso and microscale modelling helps in making national wind resource maps of sufficiently high quality. Wind maps generated through mesoscale modelling can also be used for large area screening.

Typical airport data are measured in the range of 6 m to 15 m wind mast height. Wind speeds can be adjusted to another height using the power law equation $v_2/v_1 = (h_2/h_1)^{\alpha}$. The value of wind shear α is usually 0.143 for a well mixed atmosphere over flat open terrain.

EXAMPLE 11.1

From an airport wind data, the average wind speed for a particular month reported is 4 m/s at height of 10 m. If a WPP with a hub height of 80 m is to be installed at that place, determine the wind speed at that height.

Solution:

It is known that $\dfrac{v_2}{v_1} = \left(\dfrac{h_2}{h_1}\right)^{\alpha}$

where

α = Wind shear exponent or power law index

v_2 = Wind speed at height h_2

v_1 = Wind speed at height h_1

$$\therefore \quad v_2 = v_1\left(\frac{h_2}{h_1}\right)^{\alpha}$$

$$\therefore \quad v_2 = 10\left(\frac{80}{10}\right)^{0.143}$$

$$\therefore \quad v_2 = 10 \times 1.35$$

$$\text{i.e.,} \quad v_2 = 13.5 \text{ m/s}$$

Therefore, the wind speed at the hub height is 13.5 m/s which approximately corresponds to the rated speed of a typical WPP and hence, quite a good value.

The analysis of topographical maps is one of the effective strategies of preliminary area identification of vast tracts of land. In addition to the terrain, topographical maps also provide the position of transmission lines, existing roads and buildings as well as political boundaries. It also help in locating likely windier places such as:

- Ridges oriented perpendicular to the prevailing wind direction [see Figure 11.1(a)].
- Highest elevations within a given area [see Figure 11.1(b)].
- Locations where local winds can funnel through because of the tunnel effect [see Figure 11.1(c)].

Validation, also called *area wind resource evaluation* involves a more detailed level of investigation in a defined area or set of areas where a wind power development project is considered to be taken and also involves detailed wind resource assessment by installing wind masts that has to be undertaken for assessing economic viability of selected WPPs.

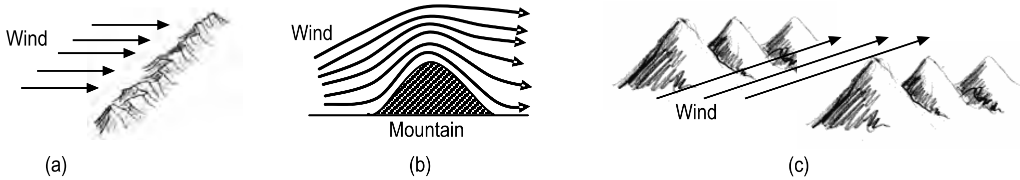


Figure 11.1 **Probable Windy Places:** Topographical maps help in identifying probable windy places: (a) Ridges; (b) Higher elevations; (c) Tunnel effect due to mountain passes.

Using appropriate wind sensors for at least a year and a half to collect data is a validation process. Since wind conditions can vary significantly from year-to-year, measurements are usually correlated with measurements taken from a nearby site or the meteorological office from where longer term records are available. These measurements are then correlated with the actual wind data collected by the wind project developer at that particular site and corrections are made for the long term trend. The layout of the WPPs is not only about technical optimization, but also related to economic, legal, environmental and social aspects.

After the indentification of a windy area the following activities have to be undertaken:

- Undertake a detailed assessment of the chosen site.
- Gather information from nearby monitoring sites.
- Examine government zoning and permitting regulations (governmental permits and environmental impact studies may be required in certain communities).
- Check for land compatibility as wind speeds are affected by the surrounding terrain and potential obstacles including nearby trees, vegetation and buildings. Since local conditions have a great impact on the wind, careful micrositing is also necessary. This can be done with the help of models which can be applied in the software developed for the wind power project.
- Undertake wind resource assessment with a 100–150 m and wind sensors at 10 m to 15 m intervals.
- Collect, validate and analyse data every month.
- See for proximity to electric transmission lines. Large farms require access to a transmission line with the capacity to evaluate the power output of the wind farm.
- If the wind farm is to be built on someone else's land, approval and compensation will be required. Also, political and community leaders and area neighbours may need to be educated about the proposed site to alleviate any potential concerns.

Micrositing, (also called *optimisation*) is the third stage of wind resource assessment. The main purpose is to quantify the small scale variability of the wind resource over the terrain whcih is under consideration. It is also used to position one or more WPPs on a site to maximise the overall energy output. Micrositing is also actual transfer of wind data to the exact WPP positions and hub heights.

The wind data which has been collected from the site in digital form for over a year or more, is to be taken to include all seasons of the year. Then, by using appropriate software some information including the following has to be generated to predict the wind generation potential at the site and also to arrive at the relevant type of WPP to be procured:

- Create wind rose.
- Calculate wind shear.
- Predict the annual electricity production.
- Estimate cash flow-inflow and outflow.
- Estimate economic feasibility.

EXAMPLE 11.2

At particular site, the wind speed is 6.1 m/s at 60 m above ground level (agl) and at 80 m height wind speed is 6.5 m/s. Determine the wind speed at 100 m height at that particular site.

Solution:

It is known that $\alpha = \dfrac{\log_{10}(v_2/v_1)}{\log_{10}(h_2/h_1)}$

$$\therefore \qquad \alpha = \frac{\log_{10} 6.5 - \log_{10} 6.1}{\log_{10} 80 - \log_{10} 60} = 0.221$$

When h_2 becomes 100 m, then corresponding v_2 will be:

$$\frac{v_2}{v_1} = \left(\frac{h_2}{h_1}\right)^{\alpha} \quad \text{or} \quad \frac{v_2}{6.1} = \left(\frac{100}{60}\right)^{0.221} \quad \text{or} \quad v_2 = 6.83 \text{ m/s}$$

So, the wind speed v_2 at 100 m height will be 6.83 m/s which is fairly a good site for a wind power project.

11.3 WIND RESOURCE ASSESSMENT SENSORS

Measurements of wind speed and wind direction are required for prediction of the wind power production. Typically, each wind parameter is scanned every 1 s to 2 s and the data points are averaged by a data logger mounted on the wind (or meteorological) mast (see Figure 11.2). Data is normally collected at ten minutes average intervals for at least a full year or even more. Various environmental factors affect the behaviour of the wind. Therefore, various other environmental parameters like the air temperature, atmosphere pressure, solar radiation, relative humidity and the rainfall measurements need to be analysed for arriving at more meaningful decisions regarding the various aspects to be considered for a wind power project. Some of the sensors mounted on a wind mast to measure the various environmental parameters that affect the wind resource are discussed below:

(i) Wind vane (to identify the direction of wind)
(ii) Anemometer (to measure wind speed)
(iii) Ambient temperature sensor (to measure temperature)
(iv) Barometric pressure sensor (to measure atmospheric pressure)
(v) Pyranometer (to measure solar radiation)
(vi) Relative humidity sensor
(vii) Data logger (to record the data from all the above sensors in digital form).

Figure 11.2 Tubular Meteorological Mast.
Picture by author.

Sensors that can monitor ambient temperature relative humidity and barometric pressure are useful to link to the wind speeds and direction, although it is not strictly necessary for all sites. An overall understanding of the working principle and main features of the sensors and data logger helps to choose the right type of devices to ensure the recording and storage of data reliably and accurately.

When evaluating the type of meteorological sensors to use, the following are the major parameters which are to be checked in the manufacturer's specifications:

- Operating temperature of the sensor (to check whether the sensor will function normally during hot and freezing temperatures)
- Response time (to check whether the short wind gusts will be recorded by the sensor)

- Accuracy and resolution (to check whether the accuracy and resolution are sufficient enough for arriving at decisions for the wind power project)
- Time interval of the data recording
- Number of days data could be recorded
- Durability of the sensor (to analyse the materials that make the sensor components and check the strength of the moving parts)
- Compatibility to data logger and deployment (to analyse whether there is any need for wiring or the sensor can be simply plugged into the data logger)
- Compatibility of software for analyzing the data
- Power back-up (to examine whether the sensor requires a power back-up both solar and battery)
- Technical lifetime (to determine for how long the sensor operate will without malfunctioning).

11.4 METEOROLOGICAL MAST

The correct choice of a WPP very much depends on the correct wind data of the site under consideration and its correct analysis. The meteorological assessment tools that directly and indirectly affect the wind are mounted on a wind mast which could be tubular (refer Figure 11.2) or lattice type. Data from the sensors are to be recorded for at least one year or more to calculate an annual representative wind speed frequency distribution.

To avoid measurement errors by the various sensors, it has to be ensured that the wind mast is also mounted absolutely perpendicular to the ground. The angle on the lower, reachable part of the mast is tested with suitable measuring tool (for example, the inclinometer) and then, the tower is checked from all sides if it is inclined. With experience, the human eye is pretty able to notice even little deviations.

Generally, using portable pulling and lifting equipment, the wind masts are erected by a gin pole (see Figure 11.3) and kept vertical by guy wires. For a tubular wind mast (as against lattice wind mast), the length of the traverse should be at least seven times of the tower diameter. If a slim lattice mast (width up to 30 cm) is used, a traverse length of about 1 m is to be chosen.

A thin lightning rod (thickness about 0.2 cm) on the top of the mast must be at a distance of at least 50 cm from the anemometer at an angle of 60° and it must be vibration-free.

All wind sensors must be mounted absolutely vertical on the wind mast booms. Even small deviations can lead to skewed winds resulting in wrong measurements.

To avoid interference, the anemometers and vanes have to be mounted far enough from the tower structure and other sensors. Booms carrying the sensors must be at the minimum distance from the tower to avoid shading which may influence the measuring negatively. Each sensor needs to have its own individual boom. Moreover, the booms should be fixed rigidly and should not swing which may otherwise affect the measurements and may also lead to the damage of rotating parts.

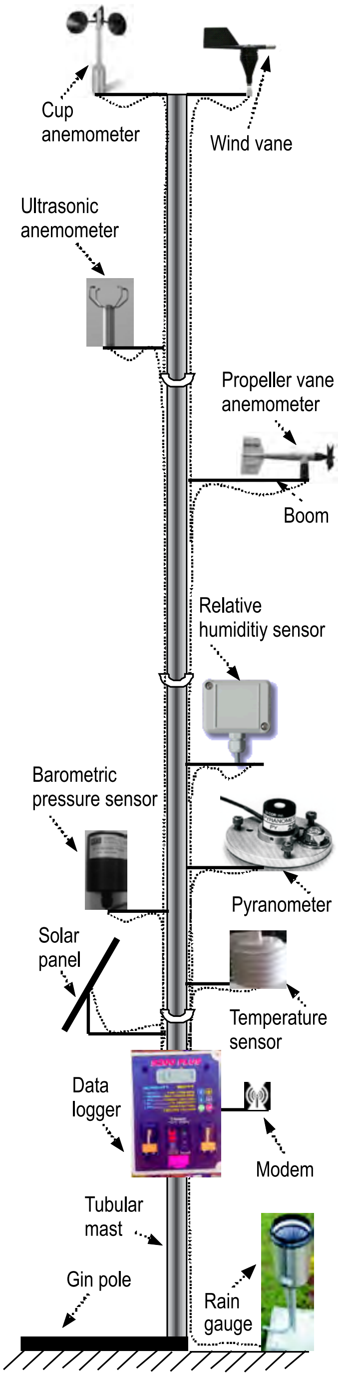


Figure 11.3 **Meteorological Mast and Sensors:** Sensors for assessing the data are mounted on booms.

Combined wind anemometer and wind vane on the same boom need to be avoided because the anemometer is not streamed on free. The nearness of the anemometer and the vane may have negative results on the measuring data.

Temperature and humidity sensors require solar radiation shields, as they shed rain water and operate in freezing conditions as well.

The solar panel and the GSM/CDMA antenna (for remote data collection) should also be securely fixed onto the mast.

The data logger (refer Figure 11.3 and 11.4) has to be securely housed inside a weatherproof, locked, tamper-resistant structure powered by rechargeable battery and also preferably, by solar PV panel. It should be mounted sufficiently high enough from the ground on the wind mast.

The dead weight of free hanging cables coming from the sensors to the data logger over 50 m length should not rub/touch sharp edges as non-stop working in the wind may damage them. The cables should be wrapped along the tower (refer Figure 11.3) and well secured with UV-resistant tape or ties and at the same time, allows sufficient slack.

11.5 DATA LOGGER

Data loggers (or data recorders) are digital electronic instruments (refer Figure 11.4) that record and store the ennvironment data from the all the sensors mounted on the wind mast. They are available in a variety of types and have evolved from simple strip chart recorders to the integrated electronic onboard cards for personal computers. The data logger needs to be electronic and compatible with different types and number of sensors for desired sampling and recording intervals. It should also accept third party sensors.

Figure 11.4. Data Logger: The wind data of every month of about 10 minutes intervals is stored in a digital chip. Every month a new memory chip can be replaced by the earlier one which is taken out for analysis.
Picture by author.

But modern data loggers come with cards that can store data for more than 18 months. Data loggers calculate and record ten-minutes mean wind speed which is standard for most wind energy analysis software. For a greater accuracy, for about 18 months, wind data of the site under consideration are gathered, stored and analysed using appropriate software based on which the wind power projects are designed and developed. Usually, after every month, the flash memory cards (32 MB or more) in which the data is stored is taken out for analysis and replaced by a new one. It needs to be mounted in a non-corrosive, water tight, lockable electrical enclosure to protect itself and powered by a rechargeable battery with solar panel options as well.

11.5.1 Data Communication Options

There are two options for downloading data from the data loggers:

- Manual download
- Remote communications.

Manual download is a less costly option, though it has some limitations. Technicians must visit the data logger to replace the flash cards or download the data onto a laptop and there may be no way to know about malfunctions (if any) of the sensors until data has been examined.

Remote communications (cellular or Wi-Fi) allow for real time internet-based access to data from the data logger. The user logs onto the website to view and download the data, reducing the chance of data gaps due to equipment malfunction. By this method of cellular phone and e-mail alarm, notifications can be set when sensor parameters are out of a set range or if the instrument fails or if the battery power is low. This helps to fix the problem at the earliest.

11.6 WIND VANE

Basically, the wind vane (see Figure 11.5) (also called the *wind flag*) consists of an asymmetrically shaped object with a fin connected to a vertical shaft. The design of wind vane is such that the weight is evenly distributed on each side of the axis of rotation but the surface area is unequally divided so that the pointer can move freely on its axis. The side with the larger area is always blown away from the wind direction. The wind vane constantly seeks a position of force equilibrium by aligning itself into the direction of the wind.

Knowing the wind direction for a WPP is crucial because all upwind wind turbine rotors have to face the wind perpendicularly and it is achieved by the yawing action. Wind direction frequency information is important for identifying preferred terrain shapes and orientations as well as for optimising the layout of WPPs within a wind farm. Wind direction data are collected at the same heights as the wind speed begins from the hub height and preferably at every 10–15 m distances as well.

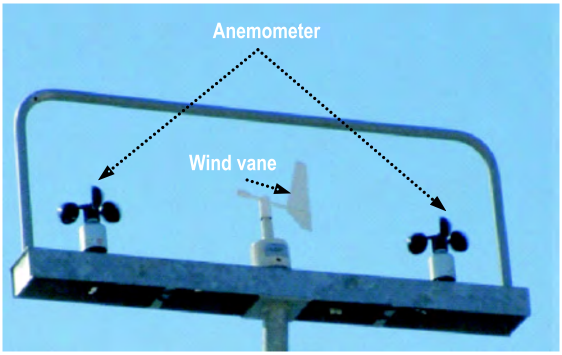


Figure 11.5 **Wind Sensors:** Three-cup anemometer for wind speed and wind vane for direction. *Courtesy: Riaan Smit, South Africa.*

As the wind direction changes, the wind vane oscillates in the wind and comes to an equilibrium as the wind direction steadies out. For determination of the wind direction potentiometric (rotary potentiometer) transmitter is used more and more because the resolution (1°) is very excellent and it needs only little power consumption. Usually, a good vane is connected to a four-core cable. This compensates the cable resistance of the connection so that even long cables do not lead to wrong measuring results. Modern wind vanes use optocouplers, the output of which is the electronic digital signal pulses.

This signal is transmitted to a data logger and relates the vane's position to a known reference point (usually true north). The standard deviation is determined in the data logger for both wind direction and wind speed and defined as the true population standard deviation σ for all the 1 s to 2 s samples within each averaging interval.

It is to be checked that the data logger has suitable software for the averaging of the results so that the north jump at changing wind directions can be taken into consideration; the average of 350° and 10° should result in north and not 180°. Therefore, the alignment (or orientation) of the wind vane to a specified reference point is important.

When buying a wind direction vane, it is important to check the resolution of the vane so that the data output is in small enough units of assessment. Some divide a complete 360° rotation into 16, i.e., 22.5° segments. The open deadband area of the potentiometer should not exceed 8°. Also, the maximum wind speed is considered especially whether the vane is designed to withstand typical and maximum wind speeds at the site under consideration. Moreover, the expected lifetime and the materials of which the components are constructed are also considered.

11.7 ANEMOMETER

The single-most important characteristic of a site is its wind speed and the performance of a WPP is very sensitive to uncertainties and errors in the basic wind speed estimate. Therefore, the wind speed measurement is of utmost importance.

An *anemometer* (refer Figure 11.5) is the device for measuring the wind speed. Ideally, anemometers need to be placed at three locations on a tower, i.e., the proposed turbine's hub height, the height of the highest blade tip and the height of the lowest blade tip. But due to budgetary restrictions, sometimes, shorter towers are used than the proposed turbine blade tip. Multiple measurement height of generally 10 m to 15 m intervals of the wind mast are used for determining the site's wind shear characteristics. However, by using some numerical models, the input data from these lower tower heights can be used to extrapolate the wind speed for higher hub heights.

In complex terrain (defined by the IEC as having a slope of more than 10% within a distance of twenty times the hub height from WPPs), it is recommended that vertical anemometers (such as propeller anemometers) capable of measuring the vertical wind speed can be used in conjunction with the standard instruments. As vertical motions are often very small, a highly sensitive anemometer would also suffice. Since vertical winds can vary greatly with height above the ground, it is better to place the anemometer as close to hub height as possible without causing interference with other sensors. A vertical separation of 1 m to 2 m between sensors on the boom is enough.

The height of a typical tall tower anemometer ranges from 50 m to 150 m. When comparing data from different locations, all wind speeds should be extrapolated to a common reference height (e.g. 90 m, a typical WPP hub height). Wind speeds can be adjusted to another height using the power law equation, i.e., $v_2 = v_1(h_2/h_1)^{\alpha}$. The multiple height data serves as a valuable backup if any sensor at one-height fails. For a 50 m wind mast, normally, the measurements are taken at 10 m, 25 m, and 50 m. For a 60 m tower, measurements are at 10 m, 30 m and 60 m. Preferably, one anemometer should be top mounted (on a pole exceeding the mast height) to avoid flow distortion. A comparison of an international anemometer calibration group revealed that uncertainties ±3.5% occurred due to the calibrations in different wind tunnels. This translates about 10% uncertainty in energy yield prediction.

11.7.1 Cup Anemometer

The cup-anemometer is the most common wind speed measurement tool in the wind industry utilised for measuring the mean wind speed data as it is reliable and comparatively cheap. It consists of three hemispherical or conical cups (refer Figure 11.5) that rotate around a vertical shaft. The aerodynamic shape of the cups converts the wind pressure force to the rotational torque for turning the spindle to which they are attached.

All rotational anemometers have a threshold start-up speed. This is usually between 0.5 m/s and 2.0 m/s. The response of the instrument to changes in wind speed is described either by a distance constant or a time constant.

A *distance constant* is the distance the air travels past the anemometer during the time, it takes the cups to reach 63% of the equilibrium speed after a step change in the wind speed and it depends only upon the air density. This is the response time of the anemometer to a change in wind speed. The *time constant* is

the time taken by the anemometer to respond to 63.2% of the step change and varies inversely with the wind speed. Consequently, cup anemometers tend to overestimate a decelerating wind (overrun error).

The cup rotation is almost linearly proportional to the wind speed over a specified range. A transducer in the anemometer converts this rotational movement into an electrical signal by a varying voltage or by a series of pulses from an optocoupler and sent to a data logger by cable or to a computer by wireless modem. Therefore, counting the turns of the cups over a set time period gives the average wind speed for a wide range of speeds. The data logger then uses known multiplier (or slope) and offset (or intercept) constants to calculate the actual wind speed.

Only the uninfluenced, horizontal component of the wind stream has to be measured because only this one is relevant to energy transformation. Wind transmitter with small cups and an sharp-edged body are often very sensitive to skew winds and turbulences which are caused by tower and traverses. Since they are mechanical, many parts eventually wear out, although most have special long life (two years plus) bearings.

All anemometers are initially calibrated in a wind tunnel. However, if the data collection is to continue for a longer time, it will be better to perform on-site calibrations using a reference anemometer. If care is not taken, the anemometer reading could be affected by the distortion of the wind flow due to the wind mast (refer Figure 11.3) or other instruments. Hence, the wind mast should be carefully oriented to restrict this disturbance to the least frequent wind direction.

These cup anemometers often have comparatively better response characteristics. When selecting a cup anemometer, the reliability and maintenance should be checked, as there is considerable number of manufacturers.

11.7.2 Propeller Vane Anemometer

The propeller vane anemometer (see Figure 11.6) indicates both the wind direction and the wind speed. This type of anemometer which is relatively less expensive, is simple and reliable to operate and so has proven to be popular both for measuring the mean flow and the air turbulence as well.

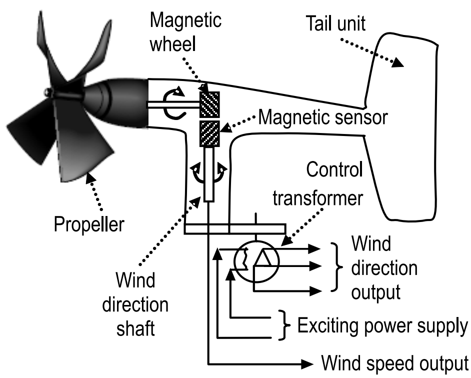


Figure 11.6 Working Principle of Propeller Vane Anemometer.
Courtesy: www.campbellsci.com

This device consists of a propeller (or prop) mounted on a horizontal shaft that is always oriented into the wind because of the tail vane. The nose of the prop points towards the direction from which the wind blows and the rotation of the propeller measures the wind speed. The wind moves the propellers connected to a shaft with a magnetic wheel, creating variable current of frequency proportional to wind speed in a coil. The coil is placed in a motionless part of the meter. The signal's frequency is measured by using the microprocessor sensors.

Alternatively, the propeller shaft is coupled to an optocoupler with light pulses or a DC generator and the output is a millivolt level DC voltage proportional to wind speed. The device is equipped with a digital current interface of time courses similar to RS-232C standard.

The wind direction gets carried onto a potentiometer's slide placement where voltage is measured using an analogue to digital converter integrated with the microprocessor. The electric signals from the sensors are counted in the microprocessor taking into consideration the calibration factors saved in the program memory. These results are sent from the device in a digital form to a supervisory system of the data collection.

11.7.3 Ultrasonic (Sonic) Anemometer

Compared to the cheaper cup anemometer and the propeller vane anemometer, the sonic anemometer (refer Figure 11.3) is also becoming popular because of more accurate measurement. This anemometer is relatively maintenance-free and error-free, as it does not have any moving part.

Ultrasonic waves (high frequency sounds which are not sensed by human ears) propagate straight through the air in the same way as sonic waves and the propagation speed is almost kept constant at about 340 m/s. However, the speed changes more or less when the air flows. If the ultrasonic wave propagates in the forward direction to the wind, its speed becomes higher by the wind speed component and if it propagates in the reverse direction, its speed becomes lower by the wind speed component. It is capable of measuring wind velocity in the x-axis, y-axis and z-axis.

Transducers are fitted at the tip of each arm emitting acoustic signals which travel up and down through the air. Speed of sound S_s in moving air is different from the speed in still air. Two ultrasonic transducers (heads) are mounted opposite to each other at a fixed distance to transmit ultrasonic pulses to each other, alternately and repeatedly at certain intervals. Since sonic anemometers can take measurements with very fine temporal resolution (20 Hz or better), they are better suited for the inertia-free measurement of gusts, peak values and turbulence measurements as well.

If both the sound and wind is moving in the same direction, then the resultant speed S_1 of the sound wave is:

$$S_1 = S_s + v \tag{11.1}$$

If the sound wave moves in the opposite direction to the wind, then:

$$S_2 = S_s - v \tag{11.2}$$

From Eqs. (11.1) and (11.2):

$$\text{Wind speed } v = \frac{S_1 - S_2}{2} \tag{11.3}$$

Lack of moving parts (hence, lower maintenance) is a major strength of such sonic anemometer. Their main limitation is the distortion of the wind flow itself by the structure supporting the four transducers.

11.7.4 SODAR

The other state-of-the-art instrument is the ground-based SOnic Detection And Ranging (SODAR) by which the wind speed can be measured remotely from the ground. A SODAR (see Figure 11.7) system installed on the ground can get measurement data not only from a point, but also from a three-dimensional space. SODAR systems measure the wind profile by emitting audible pulses in three directions.

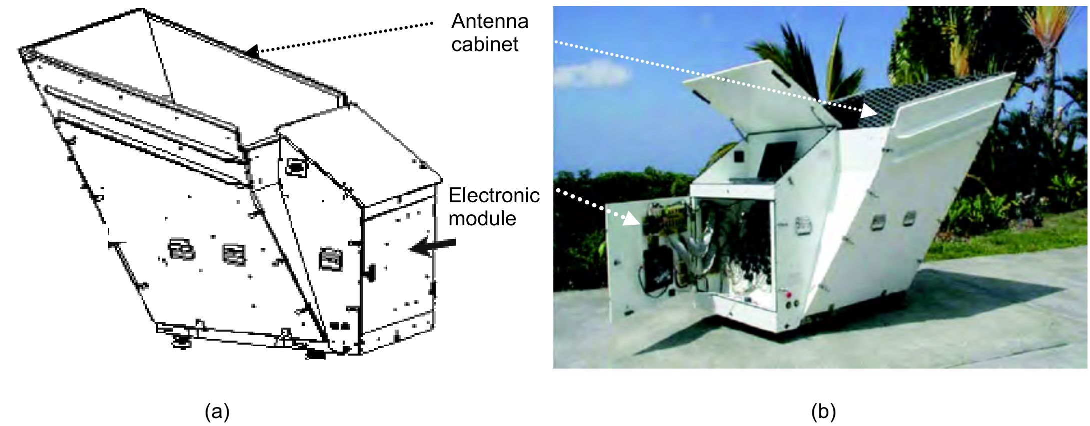


Figure 11.7 **SODAR:** (a) Schematic diagram of SODAR; (b) SODAR being installed and commissioned. *Courtesy: www.sodar.com/about_sodar.*

As the sound propagates through the air, it is scattered by small changes in air density and some of the emitted sound is returned to the SODAR. The change in the received frequency from the transmitted frequency is known as the *Doppler shift* and that shift is proportional to the observed wind speeds and their directions.

SODARs have not replaced measurement masts, but are often used as a complement to get data from additional heights and nearby sites in an area or to get data on the turbulence in complex terrain. SODAR measurements are more time intensive in terms of resources needed for data quality checking and analysis. Hence, it is not used for long term monitoring of wind energy sites but for the intensive campaigns of a few weeks to few months in order to get a clearer picture of the wind regime to reduce the risk related to overestimation due to wind mast extrapolations for large wind power projects.

11.7.5 LIDAR

Lately, other types of wind sensor equipment such as the LIght Detection And Ranging (LIDAR) is being tested in the wind industry. It seems to be more economical for onshore megawatt range as well as for offshore WPPs, as it can measure the wind parameters at any height between 10 m and 200 m LIDAR (see Figure 11.8) can not only measure the wind speeds but also the temperature, pressure, humidity as well as trace gases, aerosols and cloud.

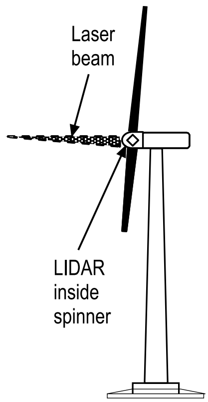


Figure 11.8 LIDAR inside Spinner of a WPP.

LIDAR is similar to radar that sends out electromagnetic waves (radio waves) and then analyses those electromagnetic waves that bounce back to determine the position and movement of objects. Radio waves have long wavelengths and therefore, reflect only from large objects. On the other hand, LIDAR uses light waves that have a much shorter wavelength (e.g. infrared light with wavelength of 1.55 μ) and is readily reflected from relatively much smaller objects one reason that human vision relies on it. This reflected light can be detected by the devices that are so sensitive that they can pick up even one returning photon (the quantum–mechanical particles of which light is composed) out of every thousand billion fired by a laser.

LIDAR can be used for power curve assessment without much difficulty because it can be ground based like SODAR, as no construction permission is required, thereby avoiding the difficult use of taller and taller wind masts as regards megawatt size WPPs. Another application of LIDAR is that it can be placed in the hub or mounted in the centre of the nacelle of WPP where the beam of laser is focused on the desired measurement distance in front of the WPP in order that it will be able to see the wind before it hits the blades, so that they can be adjusted to use the wind more efficiently. It can also be mounted on the nacelle behind the rotor (see Figure 11.9) to measure inflow and wind wake fields as well.

Light pulses produced by the LIDAR are transmitted 200 m to 300 m in front of the wind turbine into the atmosphere. They are scattered and attenuated during

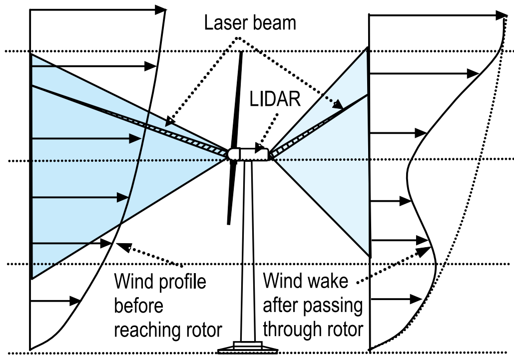


Figure 11.9 Wind Assessment with LIDAR: Measures wind inflow and wind wake also after has passed through the rotor.

their propagation as they encounter various airborne aerosols, like water droplets dust, pollen and salt crystals that drift along at the precise speed of the wind.

A small fraction of the scattered light is directed backwards to the LIDAR. This back scattered light which contains information on atmospheric properties is collected by a telescope and analysed by the computer connected to the motors that adjust the pitch of the rotor blades in order to maximise energy production and reduce damage. Due to this pre-emptive measure it is expected to improve electric power production by about 5%. This may not sound much, but for a single 4 MW WPP this saving will be around ₹ 17,10,000 every year.

Table 11.1 provides a comparison of different wind sensor technologies.

11.8 TEMPERATURE SENSOR

The ambient temperature is an important descriptor of a wind farm's operating environment, normally measured either near ground level at 2 m to 3 m or near hub height. It is also used to calculate the air density, a variable required to estimate the wind power density and WPP's power output. The daily maximum and minimum values should be determined for wind speed and temperature.

The typical ambient air temperature sensor consists of a transducer and a matching interface device (refer Figure 11.3). Generally, it is a thermistor or a resistance temperature detector (RTD) with a Gill type six-plate multilayer, passive radiation shield to guard it from direct solar radiation. It stops the sensor to heat up (even when the sun hits it directly) and without causing an air jam. This also renders the fitting easier to the wind mast.

The interface connects the transducer with the data logger. The resistance value is measured by the data logger which uses a known equation to calculate the actual air temperature. All the data measured by the sensors are recorded, stored and displayed usually, in digital form and are available at the tap of a key on the data logger.

Table 11.1 Comparison of different Wind Sensor Technologies

S.No.	Type of wind sensor	Measurement method	Remarks
1.	Cup anemometer	Wind speed related to rotation speed of cups	• Proven, robust, reliable and inexpensive • Difficult to extrapolate in complex terrain • Maintenance intensive
2.	Propeller vane anemometer	Wind speed related to rotation speed of propellers	• Need to be aligned into wind and is done so due to the vane • Faster response time than cup anemometer • The oscillating pendulum movement when the wind (often changes) influences the accuracy of the measurement
3.	Sonic anemometers	Wind speed related to time of flight of sonic pulses between transmitter and receiver.	• Since no moving parts, better suited for the inertia-free measurement of gusts, peak values and turbulence measurements as well • They are capable of measuring wind velocity in *x*-axis, *y*-axis and *z*-axis • But calibration is difficult, since it must be done depending on the wind direction • Needs strong energy source
4.	SODAR	SODAR systems emit audible pulses in three directions. The sound is scattered by the small changes in air density and reflected sound is measured by the SODAR.	Sends sound pulses up into the air to measure wind speed and its direction up to 140 m.
5.	LIDAR	LIDAR systems detect wind speed and direction based on the time delay of the laser beam reflected by airborne aerosols.	• Can measure at any height between 10 m and 200 m • Errors on the measured wind velocity due to an angle between the wind direction and the laser beam

11.9 BAROMETRIC PRESSURE SENSOR

Generally, the air pressure (measured in millibar or mb) also plays a part in wind energy. It has been seen that the power of the wind ($P = 1/2\ \rho A v^3$) also depends on the density of the air which varies with temperature. Barometric pressure (or atmospheric pressure) is used with air temperature to determine the air density. It is the force per unit area exerted against a surface by the weight of the air molecules

above that surface. Normal variations in pressure at the same temperature can affect air density by about 1%. Air density varies with temperature and pressure about 10% to 15% seasonally. A wind speed say 7 m/s will have a higher power density and energy content at the coast in northern Europe (with annual average temperature of 6°C), than at the coast of Tamil Nadu in southern India, where the temperature at sea levels varies from 20°C to 37°C.

In most cases, the impacts of these differences in air density are negligible but in tropical climate and at heights of 500 m or more above the sea level, the air density should be considered in the calculations. A typical barometer (refer Figure 11.3) uses a piezoelectric transducer (powered externally) that gives a standard output that can be fed to a data logger.

$$\text{Air density } \rho = \frac{P}{RT} \tag{11.4}$$

where,

ρ = Air density in kg/m^3
P = Pressure in mb
R = Specific gas constant for air (287.05 J/kg/K)
T = Air temperature in degrees Kelvin (273+°C).

11.9.1 Impact on Wind Power due to Height above Sea Level

The air density also decreases with the height above the sea level (asl). Therefore, on a mountain range in Himalayas, the air density is less than at sea level. As compared to a windy site at sea level with an average temperature of 15°C (1.225 kg/m^3), air density will be 5% higher at 0°C and 5% lower at 30°C. With a constant temperature and a different height above the sea level, the air density will be 5% less on 500 m above the sea level and 10% less on 1000 m above the sea level. Temperature usually decreases with the height above the sea level. So, these two factors often compensate each other to some extent.

EXAMPLE 11.3

Calculate the air density for the given pressure of 995.2 mb at 25°C temperature.

Solution:

Given:

$$P = 995.2 \text{ mb}$$
$$R = 287.05 \text{ J/kg/K}$$
$$T = (273 + 25) = 298 \text{ K}$$

Using the above mentioned formula,

$$\rho = \frac{P}{RT}$$

$$\rho = \frac{995.2}{287.05 \times 298} = 1.163 \text{ kg/m}^3$$

11.10 PYRANOMETER

A pyranometer (refer Figure 11.3) measures the global or total solar radiation which combines direct sunlight and diffused short-wave radiation from the sky. Solar radiation is used in conjunction with the wind speed and time of day and is measured in watt per square metre. It is an indicator of atmospheric stability and used in numerical wind flow modelling.

Typically, a pyranometer consists of a photodiode that generates a small voltage (millivolts) across a fixed resistance proportional to the amount of solar radiation (insolation). The output current from the photodiode (microamps or less) is amplified by a signal conditioner to be fed to the data logger that uses a known multiplier and offset to calculate the global solar radiation.

Another type of pyranometer sensor is a thermopile type that consists of a group of thermal sensors that react to radiant energy to produce a voltage proportional to temperature.

To measure accurately, the pyranometer must be located above any obstruction and horizontally mounted on a boom arm extending southward (in the northern hemisphere) to prevent or minimise any shading about 3 m to 4 m above the ground.

11.11 RELATIVE HUMIDITY SENSOR

The use of a relative humidity sensor can improve the accuracy of air density estimates. The addition of water vapour to air reduces its density, thereby decreasing the wind's kinetic energy. Commonly used relative humidity meter (refer Figure 11.3) are electronic sensors, either capacitive or resistive. The capacitive sensors sense water by applying an AC signal between two plates and measure the change in capacitance caused by the amount of water present. The resistive sensors use a polymer membrane which changes conductivity according to the absorbed water.

11.12 MODEM

When it comes to remote viewing/collection of data of the various sensors through the data logger, a GSM or CDMA compatible modem (refer Figure 11.3) is required which is generally supplied by the data logger manufacturers compatible with their equipment. This may also be a part of the supervisory control and data acquisition (SCADA) system bundled along with modern WPPs.

EXAMPLE 11.4

A WPP can generate 2MW at the rated speed of 10 m/s at atmospheric pressure and temperature of 25°C. Determine the change in output power of the WPP if it is operated at an altitude of 2000 m above the sea level at 8°C and wind speed of 12 m/s and pressure of 0.9 atmosphere.

Solution:

$$\rho = \frac{P}{RT}$$

where,

P = Pressure in pascals

T = Temperature in degree Kelvin

R = Specific gas constant for air (287 J/kg).

Air pressure at 1 atmosphere = 1.01325 × 105 Pa

At 2000 m air density $\rho = \dfrac{0.90 \times 1.01325 \times 10^5}{281 \times 287} = 1.13$

$$P = \frac{1}{2}\rho A v^3$$

$$\therefore \quad 2000 \times 1000 = 0.5 \times A \times 10^3$$

$$\therefore \quad A = 4000$$

At 2000 m, power generated is

$$P = 0.5 \times 1.13 \times 4000 \times 12^3$$

$$= 27120 \text{ W} = 3905280 \text{ W}$$

$$= 3905.2 \text{ kW}$$

11.13 AREA REQUIRED BY WPP

Modern large WPPs require a large area around them which should be clear of trees and other WPPs to maximise the effect of the wind. They should have about seven rotor diameters (7 D) of clearance in the direction of the wind and five rotor diameters (5 D) in every other direction. As a rule of thumb, the area required by a 1 MW WPP is about 5 acres. A typical wind farm of 20 WPPs might extend over an area of 1 km^2 but only 1% of the land area would be used to house the WPPs, electrical infrastructure and access roads. The remainder can be used for other purposes such as farming or as natural habitat.

11.14 SOFTWARE ANALYTICAL TOOLS

Wind power developers use various types of software applications to analyse all the wind data collected from the wind mast over a period of $1^1/_2$ to 2 years. Most of the data logger manufacturers offer data retriever software that is compatible with their own loggers such as NRG Systems, SecondWind, Kintech Engineering or Campbell Scientific. Many of the wind data analysis software such as WAsP, WindPRO, Windographer, GH Windfarmer, Openwind and others also assist the user in removing measurement errors from wind data sets and perform specialized statistical analysis. These analyses result in the form of bar graphs, pie diagrams,

tables, wind rose, Weibull distribution curves (discussed in chapter 2) and layout of wind farms. Through all this exercise, the annual energy output is also predicted.

For the majority of prospective wind farms, the wind project developer must undertake a wind resource measurement and analysis program in order to get a robust prediction of the expected energy production over its entire lifetime. The regional wind maps are valuable tools for finding a suitable site by the wind project developer but are not accurate enough to justify the financing of large wind power projects. For large wind power projects, even though wind data may be available from different sources such as wind maps and weather stations, it is necessary to countercheck by putting up a wind mast for at least a year and half to predict the amount of wind energy (refer Figure 11.10) at the proposed windy site and calculate the expected wind production during its entire lifetime.

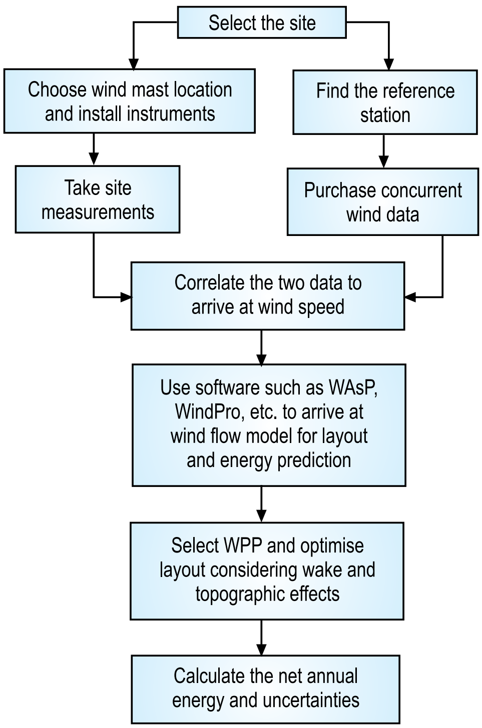


Figure 11.10 Wind Energy Prediction Model for a Proposed Site.

SUMMARY

Wind resource assessment helps in estimating the future energy production of a wind farm. An accurate wind resource assessment is crucial for the choice of windy sites and selection of most appropriate WPP for the site under consideration and the successful development of the wind farms. In this context, all the meteorological assessment tools have been discussed here for their appropriate application.

EXERCISES

11.1 Justify the importance of an accurate wind resource assessment.

11.2 Describe the three major steps for siting a WPP.

11.3 At a particular place, the wind speed is 4 m/s at height of 15 metres in a particular month. If a WPP with a hub height of 90 m is to be installed at that place, extrapolate the wind speed at that height.

11.4 Explain the need for micrositing.

11.5 Discuss the method of mesoscale modelling.

11.6 Compare the six major meteorological sensors with regard to wind project development.

11.7 Describe at least eight major criteria based on which the specifications of the meteorological sensors have to be evaluated.

11.8 To avoid measurement errors, describe some of the techniques in the installation of the sensors on the meteorological masts.

11.9 Explain the working of a propeller anemometer.

11.10 Describe the working principle of ultrasonic anemometers.

11.11 Compare the merits and demerits of cup anemometers, propeller anemometer and ultrasonic anemometers.

11.12 Justify why SODAR and LIDAR are not used in WPPs.

11.13 Calculate the air density for a given pressure of 995.2 mb at 25°C temperature.

11.14 Justify the importance of pyranometer measurement for wind power projects.

11.15 A WPP can generate 2.5 MW at a rated speed of 11 m/s at atmospheric pressure and temperature of 25°C. Determine the change in output power of the WPP if it is operated at an altitude of 1500 m above the sea level at 30°C and wind speed of 11 m/s and pressure of 0.9 atmosphere.

11.16 Is relative humidity necessary for wind resource assessment? Comment.

11.17 Calculate the total wind power in an area where the average wind speed is 7 m/s, using a WPP with a 450 m rotor diameter. Assume air temperature is 25°C with a density of 1.225 kg/m^3.

12

Design Considerations of Wind Power Plants

Then a wind from the LORD sprang up.
—Numbers 11:31

Learning Outcome

On studying this chapter, you will able to consider some of the cardinal issues in the design of horizontal axis wind power plants.

CHAPTER HIGHLIGHTS

12.1 INTRODUCTION

This chapter discusses the design aspects of horizontal axis WPPs that are based on many of the concepts discussed in earlier chapters. Through all the discussions so far, it is seen that a modern WPP is fully automatic (see Figure 12.1) and its components are related to mechanical, electrical, civil, electronics, instrumentation and computer engineering and their integrated working converts the wind energy into useful electric energy. Therefore, the design of its various components is undertaken by a team of specialists from these branches of engineering to finally zero down for a final design of WPP. The leading WPP manufacturers are mostly focusing on bigger and bigger WPPs, as they believe that it would bring down the cost of wind energy.

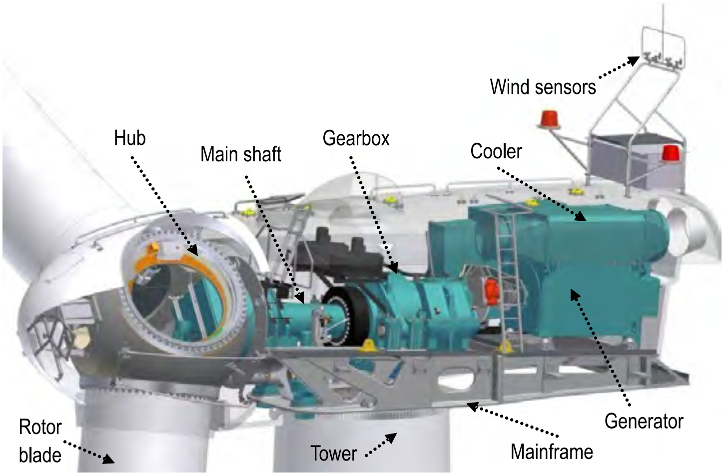


Figure 12.1 **WPP Components:** The design of different components of a WPP is undertaken by team of specialists from different branches of engineering and also using different software for modelling, simulation and analysis.
Courtesy: Suzlon Energy Limited.

The optimum design for a modern WPP is not simply dictated by technology alone. In fact, the optimum is a compromise between the technology and the economics. A WPP engineer has to aim at building a WPP that delivers electric power for the lowest cost per kilowatt hour (kWh) of energy. The single important factor driving new technologies is the need to reduce life cycle based cost of energy (CoE) using clever designs (discussed in preceding chapters) to boost the system performance with higher reliability, reduced loads, lower investments and operating costs.

Various softwares are now available for designing WPPs such as *OpenWind* and others. It is wind farm design software for engineers and scientists. It is an open source and free to download and use. However, this chapter is not intended to develop these design skills (which is beyond the scope of this book) but it aims to discuss the major design considerations of the WPP and its components, thereby creating an interest and motivation in the design of WPPs.

12.2 WPP DESIGN PROCESS

In practice, the design process is undertaken iteratively to arrive at the most optimum design. Every WPP manufacturer employs some custom designed computer software (usually, a closely guarded secret from business point of view) using computer-based modelling and simulations for arriving at optimised designs. For a typical WPP design process, the following major steps are generally adapted:

- (i) Analysis of the available wind resource data (refer to Chapter 2)
- (ii) Determination of application, i.e., onshore, offshore and others (refer to Chapter 3)
- (iii) Decision of the power P expected from the WPP (refer to Chapter 4)
- (iv) Rotor orientation, i.e., upwind or downwind (refer to Chapter 3)
- (v) Yaw control, i.e., forced yaw, free yaw or fixed yaw (refer to Chapter 3)
- (vi) Type of hub, i.e., rigid, teetering or hinged (refer to Chapter 3)
- (vii) Rotor power control, i.e., stall, pitch or active-stall (refer to Chapters 4 and 5)
- (viii) Rotor speed, i.e., constant or variable (refer to Chapter 6)
- (ix) Electric generator (refer to Chapters 6 to 8)
- (x) Geared, direct-drive or hybrid (refer to Chapter 8)
- (xi) Grid codes to be adapted (refer to Chapters 9 to 10)
- (xii) Consideration of all the types of loads
- (xiii) Evolving a basic WPP design
- (xiv) Determination of the cost of energy for the chosen design
- (xv) Building and testing the WPP prototype for at least one year or more and addressing the feedback data
- (xvi) Series production of the WPP

Generally, all large WPP manufacturers design WPPs to produce maximum power output around 12 m/s to 15 m/s, as it is uneconomical to design beyond this wind speed because higher wind speeds are not that common. Beyond 25 m/s wind speed which is still rare, the WPP is designed to completely halt so as to prevent damage to it due to overloading.

Every WPP design engineer has also to consider the strength of the structure to withstand the forces which will act upon the WPP. A WPP designer has to consider the climate (temperature, humidity), turbulence and 3 s gust (maximum wind speed measured in any 3 s period) of a wind regime so that an appropriate class of WPP can be determined (refer to Chapter 3). The lower the class value, the greater will be the structural strength. The strength of a WPP is a function of its geometry and the materials with which it is manufactured. The effects of time are fatigue and corrosion-mainly determined by material properties.

Based on these decisions, the WPP design process begins. Prediction of the stresses on all of the different components is necessary, as the nacelle weighing tens of tons mounted on the tower at a great height is a cantilever load. This is a specialist field to calculate the forces which act on a WPP structure and its components. Fundamentally, there are two ways to handle WPP structural loads—either design to rigidly endure loads or design to flexibly respond to dissipate the loads. The former

is relatively easy from a design standpoint, i.e., just make the components bigger. The amount of vibrations, bending and stretching of the WPP both individually and as a whole, needs to be calculated in advance which is structural dynamics.

In this context, it is worth mentioning that the WPP design engineer should also be aware of the following IEC standards related to WPP:

- IEC 61400-1: Design requirements
- IEC 61400-2: Design requirements for small wind turbines
- IEC 61400-3: Design requirements for offshore wind turbines
- IEC 61400-4: Gears
- IEC 61400-5: Wind turbine rotor blades
- IEC 61400-11: Acoustic noise measurement techniques
- IEC 61400-12: Wind turbine power performance testing
- IEC 61400-13: Measurement of mechanical loads
- IEC 61400-14: Declaration of apparent sound power level and tonality values
- IEC 61400-21: Measurement and assessment of power quality characteristics of grid connected wind turbines
- IEC 61400-22: Conformity testing and certification
- IEC 61400-23: Full scale structural testing of rotor blades
- IEC 61400-24: Lightning protection
- IEC 61400-25: Communication protocol
- IEC 61400-27: Electrical simulation models for wind power generation (committee draft).

The instantaneous forces which act upon a WPP during average day-to-day operation is referred to as *dynamic behaviour*. The loadings experienced by a WPP are important for arriving at two major areas—ultimate strength and fatigue of the WPP as whole and also of the individual components. This leads to the considerations of different kinds of loads which the entire WPP structure has to withstand:

- *Static load* (non-rotating) is constant and proportional to its stiffness. A steady wind blowing on a stationary WPP induces static loads on its various components.
- *Mechanical loads* are due to the mass or momentum of the WPP's structure
- *Dynamic or aerodynamic load or steady load* (rotating) is due to somewhat predictable wind force. This could also be due to the wind gust, differential wind speed in upper and lower positions of the rotor blade as well as due to the gravitational acceleration of the blade mass while in operation, causing gyroscopic effect. Aerodynamic loads may also result from the orientations of the wind turbine rotor structure which are out of alignment with respect to the direction of the wind and the bending of the rotor blades in high winds which introduces centrifugal loads that act against aerodynamic steady thrust loads, thus reducing mean blade loading.
- *Impulsive loads* are time varying loads of comparatively short duration such as those experienced by the blade of a downwind rotor passing through the tower shadow for which a teetering hub is to be selected.

- *Cyclic loads* are caused by the rotation of the rotor which arise due to weight of the blades, wind shear, yaw motion and also may be due to vibration of the components and WPP structure.
- *Stochastic load* is due to the unpredictable nature of the wind. The mean value may be relatively constant but there can be significant fluctuations from that mean. They may be cyclic, transient or impulsive loads.
- *Transient loads* are of temporary nature and may result in fatigue and later damage, if applied more often. This is generally due to:
  - Resonant vibration due to the natural frequency of the tower
  - Wake induced cross wind oscillations of cylindrical shell type towers
  - Stiffness reduction because of bolt snapping or pullout at tower section joints
  - Application of sudden brakes
  - Blocked pitch (accidental) or yaw mechanism either during operation or high winds
  - Higher order blade frequencies which might trigger tower resonance
  - Grid disconnection or rotor jamming with gearbox during operation.

12.3 GENERALISED ROTOR DESIGN

The rotor is one of the most crucial parts which play a significant role in the energy transition from wind to the electric energy. Due to ease of construction, old windmills used four rectangular blades covering about 20% of the swept area. The multi-bladed water pumping windmills cover almost the whole swept area. However, the modern efficient WPPs use two or three slender blades that cover not more than 3% to 4% of the swept area.

The principles of fluid mechanics, structural dynamics, material science and economics are to be applied in the design. In rotor design, an operating speed or operating speed range is normally selected first, considering the issues of acoustic noise emission (refer to Chapter 4). After the speed is chosen, it follows that there is an optimum total blade area for the maximum rotor efficiency. Depending on the blade planform area, the number of blades can be decided, i.e., one, two or three.

The nominal power of the WPP is directly related to the driving torque which is determined by the wind speed and the amount of air that passes over the rotor blades. So, increasing the rotor diameter has a direct impact on the performance of the WPP (refer to Chapter 4). Increased rotor diameters catch more wind. Increased hub heights bring the rotor in the air layers that are laminar and also with winds of higher wind speeds (refer to Chapter 2).

A typical WPP can be modelled as a rotating mass with a large inertia, which represents the rotor and a rotating mass that represents the drive train (see Figure 12.2). To this mechanical model, these torques are applied—aerodynamic torques acting on the rotor, the electromagnetic torque acting on the generator the possible torques are applied to the shaft by mechanical brakes. Below the rated wind speed, the control systems act to maximise the aerodynamic wind turbine

torque (affecting the power output), whereas, above the rated wind speed, the control systems modulate the electric generator torque to keep the RPM within the acceptable limits.

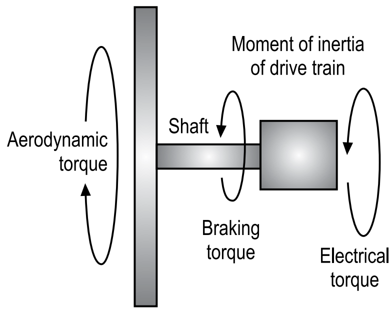


Figure 12.2 Mechanical Modelling of WPP.

In a constant speed WPP, the generator torque is a function of the aerodynamic torque and it is the only way is to control the generator torque (and consequently, the power output). The aerodynamic torque can be controlled by acting on the rotor geometry, by regulating the pitch over the length of the blade or by changing the geometry of a part of the blade of a stall controlled WPP.

However, in variable speed WPPs, the generator torque and the aerodynamic torque can be independently changed and consequently, the rotor speed can be controlled, thus affecting the acceleration or deceleration of the generator rotor. Changes of the generator torque are done in the PEC by regulating the phase and frequency of the current flowing through the generator windings.

If the power of a WPP is known, to arrive at the approximate diameter of the rotor by rule of thumb, the rated power of the WPP (in kilowatts) is multiplied by a factor 0.12.

EXAMPLE 12.1

Determine the approximate rotor diameter of 150 kW wind power plant. For 6 MW wind power plant, find the rotor diameter.

Solution:

The rotor diameter of 150 kW wind power plant will be:

= 150 × 0.12 = 18 m (multiplying factor is 0.12 for submegawatt WPPs)

The rotor diameter of 6 MW wind power plant will be
= 6000 × 0.023 = 138 m (multiplying factor is 0.023 for megawatt WPPs).

The blade design process begins by deciding the primary aerodynamic factors that affect the rotor with a best hunch, i.e., a compromise between aerodynamic and structural efficiency. The following parameters are considered:

- Power *P* expected from the WPP
- Tip speed ratio TSR λ—which could be 6 to 8 for a three-bladed and 8 to 12 for two-bladed WPP respectively (refer to Chapter 4).

- Number of blades n–which is generally 3 or 2 for electricity generating WPP
- Solidity σ—around 4% of the swept area
- Lift coefficient C_L
- Angle of attack α
- Aerofoil shape.

The lifetime of a wind turbine rotor depends on the variable loads and environmental conditions that it experiences at that location. Therefore, the rotor's inherent mechanical properties and design affect its useful technical life. The speed at which the rotor rotates is also a fundamental choice in the design of a WPP and it defines the TSR. High TSR means that the aerodynamic force on the blades (due to lift and drag) is almost parallel to the rotor axis. The lift-to-drag ratio can be affected severely by dirt or roughness on the blades. Even small variations in the outboard aerofoil camber (±0.5% of chord) or twist (±0.5°) can lead to substantial aerodynamic imbalance of rotor and WPP life reduction.

12.3.1 Hub Choice

The hub serves two aerodynamic purposes. Firstly, it serves as a structural function in connecting the blades and secondly, it imparts a rotation to them and transmits the useful energy to the drive train to be converted into electrical power. The choice of the hub for the WPP depends on the different types of hub options which are as follows:

(i) Fixed blades and rigid hub [see Figure 12.3(a)].
(ii) Pitching blades and rigid hub [see Figure 12.3(b)].
(iii) Hinged (or flapping) blades and hub [see Figure 12.3(c)].
(iv) Fixed blades and teetering hub [see Figure 12.3(d)].
(v) Pitching blades and teetering hub

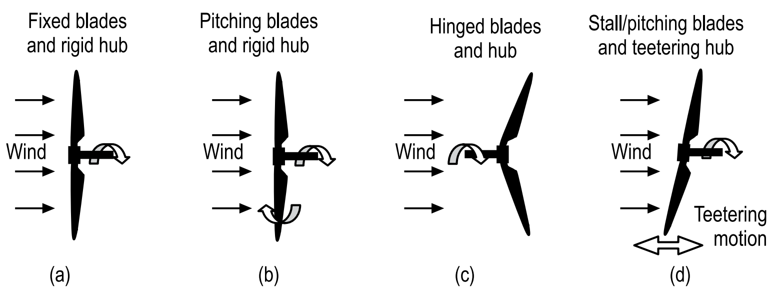


Figure 12.3 **Hub Choice:** (a) Has to bear high loads by WPP shaft and alternating bending moments at blade roots, leading to greater fatigue. (b) Frees all WPP components from loads even in high winds. (c) Frees blade roots of alternating bending moments and WPP rotor shaft of bending loads. (d) While freeing the WPP rotor shaft of alternating bending moments, they are reduced at the blade root, especially for 2-bladed WPP.

12.3.2 Rigid Hub

A *rigid hub* [see Figure 12.3(a)] is one which is quite heavy and has all major parts fixed relative to the main shaft. It has to bear all the high loads on WPP rotor shaft and alternating bending moments at blade roots. Due to the rigid junction, there is relatively high stress on the rotor blades and other components. This includes the aerodynamic loads on the blades and dynamically induced loads due to blade rotation and yawing motion.

This type of hub is a common choice for three-bladed WPP, which includes hubs where the blade pitch can be varied in real time (i.e., when the wind is blowing and the rotor is rotating) and also the stall regulated WPPs [see Figure 12.3(a)] where blade angles cannot be varied. Pitching blades [see Figure 12.3(b)] have bearings at the root to secure all the other motions except pitching. It frees all wind turbine components from loads in high winds. Although this hub does not allow movement in the edgewise and flapwise direction, it is low on wear, manufacturing and maintenance costs.

12.3.3 Hinged Hub

Hinged (or flapping) blades and hub [see Figure 12.3(c)] used in some downwind WPPs and some two-bladed WPPs, have hinges for the blades that allow them to move in and out of the plane of rotation independently of each other. Since the blade weights do not balance each other, some mechanism is provided to avoid flapping during starting, stopping and low rotational speeds. This design frees the blade roots of the alternating bending moments and rotor shaft of bending loads. However, this design is not so popular for large WPPs.

12.3.4 Teetering Hub

If it is an upwind two-bladed WPP, a teetering hub [see Figure 12.3(d)] is generally the natural choice (refer to Chapter 4). This allows the blade and hub system to adjust to differential loading across the rotor from wind turbulence, shear or tower shadow. The teetering hub reduces the loads due to dynamic imbalance as it is mounted on bearings during normal operations. As the blades rotate, they incur different loading patterns in their path. A teetering hub allows the blades to adjust to this condition rather than forcing the hub and gearbox bearings to absorb it. A teeter design prevents these load impulses from being transferred into the gearbox and drive train as bending loads.

12.4 AERODYNAMIC REGULATION CHOICE

When the blades are upscaled, the THM increases cubically faster than the WPP capacity and performance. WPPs are subjected to large variations in the aerodynamic torque due to the turbulence of the incident wind including the rotor tilt, partial

blockage of the wind flow by the tower, wind shear and yaw error. The pitch control system can, at best, only removes the lower frequency part of these variations and normally, is inoperative below the rated wind speed.

Hence, the careful design of the blade and a combination of experimental, numerical and simulation studies are to be employed to study the behaviour of the blades for different aerofoil designs. WPPs can go in for active or passive aerodynamic power regulation, as the power is derived from the uncontrollable wind. Following three methods of aerodynamic control (refer to Chapter 5) also need to be considered when designing a WPP blade:

- Stall control
- Pitch control
- Active-stall control.

12.4.1 Design of Stall Controlled Blades

The basic advantage of stall controlled (regulated) WPP is that moving parts of the rotor can be avoided. But stall control represents a very complex aerodynamic design problem and related challenges in the structural dynamics of the blade, e.g. to avoid stall induced vibrations. Stall controlled WPPs with a fixed blade angle, is hard to get started in slow winds if they are twisted to attain optimum efficiency at their constant RPM. A part of the blade is, therefore, designed with a blade angle that gives enough lift to get the rotor to start rotating at a wind speed of 3 m/s to 5 m/s.

If the rotor rating (in kW/MW) is designed for higher than the electric power rating of the electric generator (in kW/MW), the blade will stall and never reach its designed TSR value and never produce the optimum power that can be harnessed at that designed rated wind speed. Whereas, if the WPP rotor rating is designed for a lower rating than the rated power of the electric generator, then the rotor will start to spin faster to reach upto the generator load. In doing so, there could come a point where the rotor may work at runaway speeds and stall.

In another situation, if the electric generator draws more power than that for which the rotor is designed, then the rotor slows down and stalls. Hence, the blade design is only 'optimum' for one particular value of TSR, when:

- TSR value is between 6–8 (to match the speed of the generator)
- Lower solidity of about 10%
- Higher TSR means lower blade angle (blade tip is flat to the plane of rotation).
- Lower TSR means higher blade angle (feathered).
- Large chord and large twist near hub—the blade gets thinner nearer to the blade tip.

Increased interest in variable speed coupled with the uncertainty about how variable speed stall control machines will operate has reduced the interest in stall WPPs when large capacity WPPs are considered. However, lower price and less risk for technical problems makes it still a viable option for sub-MW wind project investors.

12.4.2 Design of Pitch Controlled Blades

Pitch controlled WPPs can turn their blades about their longitudinal axes to get the WPP started to rotate after a calm period. The pitch control is generally applied to control the power when the wind speed is above the rated wind speed. Pitch controlled WPPs can use different types of aerofoils, since they don't depend on the stall phenomenon. The aerodynamic blade design of a pitch regulated WPP is not that critical (and hence, less complex) compared to stall regulated WPP because of the higher controllability due to the pitching action. The blades could vary the blade angle continuously to adapt it to the wind speed.

However, this strategy has also its drawbacks, since the wind speed changes quite frequently and it becomes difficult for the pitching mechanism to respond quick enough. The components are worn out very soon. The components of the pitching mechanism wear out fast and it is also hard to repair or replace without dismantling the complete rotor. An innovative concept has been developed in Regenpowertech direct drive WPPs (refer Chapter 8), using a belt to pitch the blade instead of gears.

Following two concepts of pitching are possible:

- Single blade adjustment
- Uniform blade adjustment.

The *single blade adjustment* allows independent adjustment of individual blade angle of attack and also operates as a redundant brake system. This can be achieved either by electric pitching motors or hydraulic pitching mechanisms.

In *uniform blade adjustment*, all the blades are adjusted simultaneously to turn in the same angle of attack, in and out of the wind when the power output crosses the rated capacity. After the cut-out wind speed drops, all the blades are commanded to resume normal production of the electrical power.

12.4.3 Design of Active-stall Controlled Blades

In winter a stall controlled WPP with nominal power of 1 MW can produce 1.1 MW, which is not good for the generator. In summer, the opposite applies so that the WPP cannot utilise its full capacity. By pitching the stall blade angle, the WPP can be adjusted to be optimised in all weather conditions. The power output can also be controlled to stay at the rated power level when the wind speed is stronger than the rated wind speed. To solve this problem of the simpler stall controlled WPPs, some manufacturers developed the active-stall topology (refer Chapter 5), as it is simpler than a pitch controlled WPP, but having all its advantages.

12.5 BLADE NUMBER

As a WPP is subjected to high wind speeds, it is under massive amount of stress and to reduce the impact speeds without affecting efficiency, the rotors are built with fewer and narrow blades as practical as possible. Fewer blades with higher

RPM also reduce the peak torques in the drive train, resulting in smaller gearbox and generator costs. However, fewer the number of blades, the higher will be the RPM as compared to a WPP of same rating with more blades. Especially for upwind WPPs, this has a bearing on the blade stiffness and the thinness of the blades to avoid tower hits. Fewer the number of blades, lower will be the material and manufacturing costs of the rotor and drive train.

It is reported that increasing the number of blades from 1 to 2 yields about 6% increase in aerodynamic efficiency, whereas increasing the blade count from 2 to 3 blades yields only an additional 3% in efficiency. Increasing the blade count further yields minimal improvements in aerodynamic efficiency and sacrifices too much in blade stiffness as the blades become thinner.

The deflection of blades in a downwind WPP results in increased tower clearance.

The choice of rotors therefore depends largely on various factors (see Table 12.1) and ends up in a trade-off, considering the economics, technology, maintenance and safety.

TABLE 12.1 Choice of Rotors

Type	Speed	Torque	Power coefficient C_p	TSR	Solidity (%)	Application
Horizontal Axis Wind Turbine						
Multibladed water pumping wind mill	Low	High	0.12 to 0.17	1	50–80	Water pumping and grinding grain
Four-arm Dutch wind mill	Low	High	0.18 to 0.22	2–3	30-50	Water pumping
Three-bladed WPPs	High	Low	0.32 to 0.48	8–9	Less than 5	Electric power production
Two-bladed WPPs	Higher	Lower	0.32 to 0.40	7–10	Still lower	Electric power
Shrouded rotors	Highest	Lowest	1.0 to 1.15		Lower	Electric power
Vertical Axis Wind Turbine						
Savonius	Low	Medium	0.2	1	About 50	Mechanical power
Darrieus/H-rotor	Moderate	Very low	0.25 to 0.37	5–6	10–20	Electric power

12.6 BLADE DESIGN

The strength of the lift force depends on the aero-shape and thickness of the blade aerofoil. Therefore, the design of the blade is of utmost importance to optimise the capture of the energy in the wind. The blade profile is compromised properly between the aerodynamic performance and the mechanical strength by making sure that the ratio of thickness to chord length is about 40% at the position for the maximum chord length. Efficient design of WPP blades requires solving several equations involving the lift coefficient, drag coefficient, angle of attack and several other factors (refer Chapter 4). Modern WPP blades have evolved the current shapes through specific design efforts. Now, they have higher lift-to-drag ratio and power coefficient of around 0.5, an increase by about 20% from the older blade designs.

One of the most important goals when designing longer blades is to keep the weight under control. Since blade mass scales up as the cube of the rotor radius, loading due to gravity becomes a constraining design factor for systems with longer blades. Because of the wind gusts, the blades almost never rotate smoothly. In response to wind gusts, while rotating, they move around with side loading and torsional loading. A blade profile is designed to have several thicknesses along the length of the blade. Finite element method (FEM) is also a good tool for blade design. It is known that:

$$P = \frac{1}{2} C_p \rho A v^3 = \frac{1}{2} C_p \eta_d \eta_a \ \eta_{\text{pec}} \rho \pi \frac{D^2}{4} v^3 \tag{12.1}$$

where,

C_p = Power coefficient (say 0.4)
η_d = Efficiency of drive train (say 0.90)
η_e = Efficiency of electrical generator (say 0.98)
η_a = Efficiency of auxiliary services (say 0.97)
η_{pec} = Efficiency of power electronic converter (say 0.98)
ρ = Air density (1.225 kg/m^3)
A = Swept area
D = Blade diameter in metres
v = Wind speed in m/s.

$$\therefore \qquad D = \left(\frac{8P}{C_p \eta_d \eta_g \eta_a \eta_{\text{pec}} \rho \pi v^3} \right)^{1/2} \tag{12.2}$$

EXAMPLE 12.2

Design the rotor blade for a 3 MW WPP without power electronic converter at a wind speed of 12 m/s. NACA 4412 aerofoil may be used. The assumptions could be the same as given for Eq. (12.2).

Solution:

It is known that $D = \left(\frac{8P}{DC_p \eta_d \eta_e \eta_a \rho \pi v^3} \right)^{1/2}$

$$\therefore \qquad D = \left(\frac{8D \times 3 \times 1000 \times 100}{0.4 \times 0.9 \times 0.98 \times 0.97 \times 1.225 \times 3.14 \times 12^3} \right)^{1/2} = 32.48 \text{ m}$$

For a given diameter of a WPP and given values of available wind power and power coefficient C_p, it is possible to have different values of rated power P_{rated} as a function of the onerousness of sizing. For example, for a WPP with a rotor diameter of 90 m, rated powers of 2 or 3 MW are also possible.

Note: *For Darrieus vertical axis WPP, the definition of the rotor dimensions is more complex, since it implies solving elliptical integrals. However, on comparing the shape of the blades to a parabola, the equation to find the diameter can be expressed as:*

$$A = 2/3\ WH \tag{12.3}$$

where,

W = Maximum width of the rotor (diameter)

H = Rotor height.

The streamlined shape of the WPP blade is the first step towards the design as the aero-shape has a distinct influence on the transition efficiency of wind energy. Figure 12.4 depicts the typical cross sections of a blade. The aerofoil twists along the entire length and the selection of different sections and the distribution of chords along its length are pivotal.

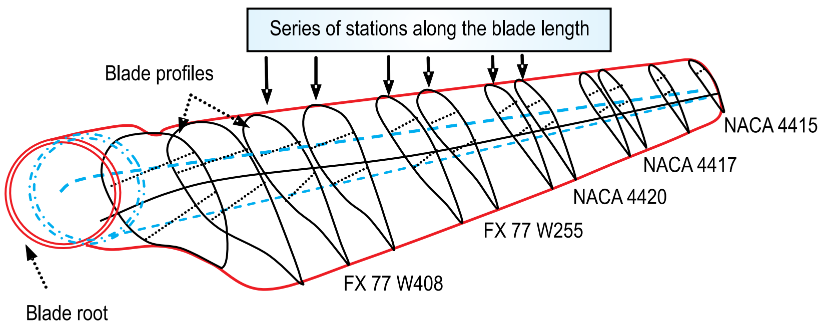


Figure 12.4 Typical Blade Profile.

In early years of 1970s and 1980s, blade profiles were adapted from the readily available catalogue of aircraft aerofoils used by National Advisory Committee for Aeronautics (NACA), USA with low lift-to-drag ratio and moderate power coefficients of the rotor. For example, NACA 230xx and 44xx series were more popular, as they had maximum lift coefficients C_L, low drag coefficients C_D and low pitching coefficient C_M. Many WPP manufacturers used modified versions of NACA aircraft wing profiles such as NACA 63 series in which most of the aerodynamic force produced was distributed between 68% and 100% of the blade outer to maximise the energy capture from the wind.

The blade profile numbers give some idea of the profile, e.g. in NACA 6312, the first digit 6 indicates the maximum values of the mean camber line (refer Chapter 4) ordinate in percentage of the mean value of the chord length. The second digit 3 indicates the distance from the leading edge to maximum camber in tenths of the chord length. The last two digits, i.e., 12 give an idea of the relative thickness (in relation to the width of the blade) in percentage, i.e., here, it is 12% of the thickness.

From 1990s, aerofoils developed specially for WPPs have been used. Every blade is designed with three different aerofoils, a very thick one close to the hub, an aerofoil with average thickness in the middle part of the blade and a very thin one close to the tip.

For a WPP a faster RPM is required and hence, TSR is high, maybe around 6 to 8. Angle of attack α and corresponding lift coefficient C_L can be taken from the

performance data of the aerofoil used in the design. Then, the chord length C and the blade angle β at different sections of the aerofoil have to be computed.

The load of a WPP is the electric power produced by the electric generator. If the WPP gets disconnected from the grid due to a blackout, for example, the load disappears and the generator accelerates to runaway speed, the wind turbine rotor will accelerate very fast to its maximum TSR. The TSR and the C_p are taken care by the blade designers for the most optimum value between stalling and runaway speed of the electric generator. For example, for a three-bladed WPP, the TSR rapidly increases to 18 before it loses its power due to the stalling process that will set in. For example, the rotor blade of a WPP with 50 m rotor diameter will have a tip speed of 180 m/s (650 km/h) even with only a wind speed of 10 m/s. This is more than any blade can manage and may destroy the WPP and therefore, it must have a control mechanism to stop it.

Several computational models are available for designing aerofoils like FOCUS and also open source software such as Qblade. This software allows the user to develop/import aerofoil shapes, simulate them and use them for the design.

12.6.1 Blade Design Theories

Different theories are adopted for blade design of horizontal axis WPPs:

(i) *Axial moment* theory propounded by Rankine and improved by Froudes for marine propellers
(ii) *Blade element momentum* (BEM) theory propounded by Froude and Taylor
(iii) *Strip theory* is a combination of momentum theory and blade element momentum theory
(iv) *Biot–Savart* law
(v) *Reynolds-averaged Navier-stokes* (RANS) model
(vi) *Finite element method* (FEM).

Axial moment theory assumes the air flow to be incompressible, homogenous with static pressure in front and behind the rotor equal to atmospheric pressure. The rotor is considered to be made of infinite number of blades. However, frictional drag over the blades and wake behind the rotor is neglected.

In *BEM theory*, the blade is assumed to be made up of a number of strips arranged in the spanwise direction having infinitesimal thickness. The theory assumes that the air which passes through the rotor undergoes an overall change in velocity and rate of change of momentum is equal to the overall change in velocity times the mass flow rate. It is also assumed that the fluid flow at a given annulus does not affect the flow at adjacent annuli. This theory uses both axial and angular momentum balances to determine the flow and the resulting forces on a blade. This theory gives a better understanding of the aerofoil properties.

The *strip theory* or *blade element* can also be used in the design of the rotor blade. In this, the forces acting on the blade elements rotating at distance r from the rotor axis are calculated. The blade element is formed by the rotor blade chord and the radial extent of the element dr.

Biot–Savart law is another method that can be used for blade design. The law assumes that the wind turbine rotor is shedding a continuous sheet of vortices at the tip and sometimes, at the root or along the blade as in lifting line theory. This law is applied to determine how the circulations of the vortices induce a flow in the far field.

Still another method is the computational flow solvers based on *Reynolds–averaged Navier–Stokes* (*RANS*) model and other similar three-dimensional models. This is primarily due to the shear complexity of modelling wind turbines.

The process of determining the best lift and thereby, the most optimal blade profile is known as the *finite element method* (*FEM*) or *finite element analysis*. This process looks at what each bit of the blade should do when facing the wind.

12.6.2 Blade Root Design

The blade root is the most critical part of the rotor blade, as it experiences the highest loads and has to transmit energy captured by the GRP blade section to the metallic portion of the blade for onward transmission to the hub, main shaft, gearbox (for geared WPPs) and/or electrical generator.

The part closest to the hub has to be thick and strong to make a solid connection of the blade to the hub. This part of the rotor blade is very thick and almost round like a pipe. This innermost part of the rotor has a small area and does not contribute much to the power production. The root and the laminar joints of the moving rotor experience maximum fatigue stresses and so have coned blades and tilted nacelles. This load can also be out of the rotor plane resulting in flapwise bending. Yaw (gyroscopic) forces are significant in free yaw machines as in downwind WPPs where instantaneous yaw velocities can cause severe flapping of the rotor blades. The root bending moment M_{root} of the blade can be given as:

$$M_{\text{root}} = g\int m(r)\sin\psi\, dr \tag{12.4}$$

where,

g = Gravitational constant

m = Effective mass of the rotor blade in kilograms

r = Distance from the root in metres

ψ = Angle of the blade from the vertical.

12.6.3 Noise Reduction in Blade Design

WPPs can cause two different types of noise—mechanical noise from the nacelle (gear box, generator and other moving mechanical components) and aerodynamic noise from the rotating rotor blades. The mechanical noise from inside the nacelle is reduced by sound absorbant materials on the nacelle walls.

It has been seen that the rotor blades work by braking the wind. Part of the kinetic energy of the wind is transferred to the blade which turns the blade and slows the wind. Some part of this energy is converted into swishing aerodynamic noise, sometimes called the *white noise*.

As the blade surface is very smooth (for aerodynamic reasons), the surface itself will vibrate at a high frequency and itself emits some (although very little) of the noise. Everything else being equal, the volume of sound increases on a scale of the fifth power of the blade speed relative to the air. Most of this noise generated comes from the trailing edge of the blades, as the air is stirred by the leading edge of the blades.

The level of sound emission from a WPP is decisive for the distance to neighbouring houses which should be around 45 dB at 330 m distance from the nearest WPP. This is the measurement from the centre of the rotor when the wind speed is at 8 m/s at 10 m height above the ground for a WPP sited in an open landscape with roughness class 1.5 (roughness length 0.5).

The noise levels also depend on the speed of the blade tip. The way in which the air flows around the blade tips is far more complex, even when compared to how the air flows over other parts of the blade and research and development is constantly being undertaken about this with computational fluid dynamics (CFD) and other techniques, as manufacturers seek greater performance from their WPPs. By careful design of the trailing edge shape and careful balancing of the rotor blades during manufacture and installation, this noise can be reduced drastically. The difference between the sounds from big or small wind turbines is not substantial.

12.7 BLADE MANUFACTURE

The blade which is hollow is manufactured by moulds. The mould in two halves is like a clam shell aerodynamically shaped. Basically, the hollow blade has three components (see Figure 12.5)—web, spars and skin. The GRP web and spars give strength and the skin renders the required aerodynamic shape. After applying a coat of paint which acts as a protective coating on the blade, glass fibre is used to manufacture the shells. Layer after layer of fibreglass cloth with polyester or epoxy resin between each layer is laid in the two shells and glued together to form a complete blade.

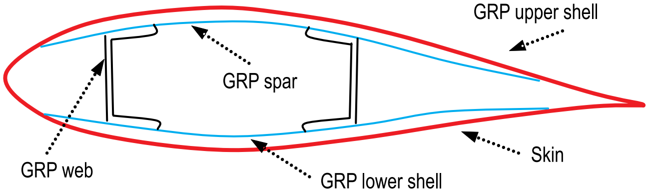


Figure 12.5 **Blade Construction:** To reduce the wind turbine blade weight to the minimum, it is kept hollow and is made of GRP to render it strong and durable for many years. The GRP skin, shells and spars provide the requisite aerodynamic shape to the whole blade.

The upper and lower shells are bonded by supporting spars. The load transmission from the GRP to the metal flange of the blade root requires steel spars to be

covered by GRP for upper and lower shell. The spars give the strength. There are no glue joints between spars and shells, no weak points, no easy access for water or lightning. Once the two shells are finished, the glue beam (made of spars and webs) between the two shells is assembled.

The manufacture of fibreglass (such as resin infusion moulding) is a painstaking operation. The hollow rotor blades are usually made of lightweight matrix mats of glass fibre reinforced with polyester or epoxy. The GRP skin made of fibreglass mat and resin inside a mould renders the required aerodynamic shape.

The load transmission from the blade to the metal flange of the blade root at the hub is complicated. Apart from wear and tear to the materials, vibration reduces efficiency of the WPP rotor.

12.7.1 Blade Materials

The choice of blade materials and the manufacturing process have also an influence on how the blade can be designed. The cheap and easily available wood and canvas sails which were originally used in early windmills had a relatively high drag (low aerodynamic efficiency) for the force they capture and hence, superseded with solid aerofoils. The main forces acting on the blade of a WPP are primarily aerodynamic and centrifugal. The rotor blades are subjected to repeated bending. This flexing and relaxing eventually cause cracks to appear in the blades which can ultimately lead to the component breaking. Therefore, the modern WPP rotor blades need to have the following design requirements:

- Low density
- Good mechanical properties, fatigue life to accommodate 30-year extreme wind conditions
- Good corrosion resistance
- High strength-to-weight ratio
- Tailorability of material properties
- Ease in the formation of the aerodynamic shape-versatility of fabrication methods
- Lower cost
- Stiffness to avoid resonance and aero-elastic stability.

WPP manufacturers are well aware of metal fatigue and so, metal is not used for rotor blades, as there are other more suitable materials that can withstand this repeated flexing due to the fluctuating wind speeds.

Of all the materials that can be used for blade manufacture, glass fibre, carbon and aramid (like Kevlar) fibre reinforced composite materials possess the overall requisite mechanical properties such as greater strength, torsional stiffness, light weight and greater longevity. These composite fibres are available in different forms. The commonly available fibre preforms are unidirectional tow, woven cloth, knitted fabric, continuous strand mat, chopped strand mat and braid as well as chopped fibres in sheet and bulk moulding compounds.

When high strength is required, unidirectional bundles of fibres known as tows can be used. Woven cloths and knitted fabrics are easier to use especially over complex contours of the rotor blade profiles.

Glass fibre, while strong enough, has a low modulus that leads to large angular deflections and consequent problems with bearing alignment. They have high aero-elasticity that contribute towards a soft or flexible structure that can more easily absorb high dynamic loads. They have proved to have the combination of strength and less material and fabrication costs required for competitive blade manufacture.

The structural material for glass fibre blade construction which is unidirectional roving is comparatively cheaper. They are usually made of lightweight glass fibre matrix of reinforced (GFRP or GRP) mats with polyester or epoxy. Since GRP is quite versatile in forming, the matrix is laid up in female half-moulds (using glass fibre mats soaked in a polyester or epoxy resin) before the two aerofoil halves are glued together as a whole blade.

Carbon fibre has more stiffness, strength and fatigue endurance than glass fibre, while the new resins provide higher toughness and shorter process cycle time. But it is relatively more expensive. Still, it is being considered, as its fatigue strength is three times higher than GRP and also comparatively lighter. The carbon glass fibres in the blade reduce the weight by about 20% as compared to the metal and the high stiffness characteristics of carbon also reduce the possibility of blade bending in high winds and therefore, positioned safely nearer the tower. Further, the carbon helps to twist couple the blades during manufacture in order to improve the aerodynamic blade performance for quick response to wind gusts.

The *aramid* group of materials is a cheaper option than carbon with material properties that is somewhat a compromise between relatively expensive carbon and cheaper glass. Unlike carbon, the aramids are non-electrically conducting which is an advantage in locations where galvanic corrosion can occur such as the blade root or hub junction, thereby preventing the need for protection against lightning strikes.

12.7.2 Blade Manufacturing Technologies

For greater longevity of the blades, the fatigue life and reliability of the blades need to be good. Fatigue life of materials has been greatly improved by the advancements in material science. Reliability can be improved through carefully controlled mechanised manufacturing processes. Following are some of the methods for manufacturing composite blades:

(i) Wet lay-up
(ii) Prepreg lay-up
(iii) Filament and tape winding
(iv) Pultrusion
(v) Fibre placement.

Of these five manufacturing processes, the first three are more manual labour-based processes and the last two processes are the combination of manual and mechanised processes.

Wet lay-up is a labour intensive process where the fibre (in the form of fabric, mat or roving) is placed in the shell die of the blade and impregnated with the resin by hand. In this relatively cheap method, quality can vary depending on the skill and keenness of the worker. As it is laid by hand, resin content is difficult to control but the vacuum bag rub-out can improve uniformity of resin distribution and laminate quality.

Prepreg lay-up is another manual process where the fibre form is impregnated by a supplier but it assures a better control of resin content. Due to the heat and pressure required for curing, the cost of this process goes up slightly than that of the wet lay-up process.

Tooling requirements are reduced for both these processes except where an autoclave is required for cure. A mixture of polyester resin and some form of talc are used as a filler in the joining operations. Blade skins are laid up in both halves of the die shell that are trimmed at the mating plane after the skins are cured. Bonding of the skins and spars is achieved by using paste adhesives. Sometimes, both halves are cured as one piece in cavity-bonded tools using an internal bag to press the material out against the tool.

The *filament and tape winding process* is relatively less manual labour intensive and with greater uniformity in quality. The spars are first wound, followed by the addition of leading and trailing edge mandrels and winding is continued to completion. A tape laying equipment lays the tape on the tubular spars for structural strength together with a lighter aerodynamic surface covering. The blade skin on the two halves and the spar are bonded together with a filled epoxy.

The mechanised *pultrusion process* is almost free of manual labour and the quality of the laminate is, therefore, good, giving a consistent product at reasonable costs. In this process, a continuous dry preform is pulled through a matched die while resin is injected under high pressure. After this, it is first heated for cure and then cooled in the die to a temperature where it possesses sufficient strength to support the pulling clamp pressure. The limitation is that some part must be constant in cross section to reduce aerodynamic and structural efficiencies.

In *fibre placement process*, the raw material is towed rather than taped (as in filament winding). The roller equipment places the fibre mats on any tool surface in any direction to produce a quality laminate. A roller equipment sticks the ply to the tool or prior ply. This process offers the design freedom of uniform quality of machine fabrication and manual lay-up as well. By and large this process also offers optimum aerodynamic and structural efficiency.

12.8 NACELLE DESIGN

The nacelle designs are different for geared, direct-drive and hybrid WPPs. The choice of shaft, type of gearbox adapted, type of generator selected and type of couplings are planned. The choice of the towers also influences the nacelle design.

12.8.1 Geared WPP Main Shaft Design

The purpose of the main shaft is to transfer the loads to the fixed system of the nacelle. Other than the aerodynamic loads from the rotor, the main shaft has also to bear the gravitational loads and reactions from the bearings and the gearbox. It is subjected to large transient loads and also torsional vibrations in the drive train. Therefore, structural analysis of all loads have to be undertaken in the design stage to verify whether the shaft would be able to withstand the loads to which it will be subjected.

The shaft acts as a spring connecting two rotating masses (the blades on one end and the generator on the other end) and this system can oscillate in a torsional mode. The shaft (see Figure 12.6) can be thought of as a spring with a torsional spring constant k_T. A large value of k_T means a more rigid (stiff) shaft, whereas a small value means a relatively more flexible (soft) shaft and is given by

$$k_T = \frac{T}{\theta} \tag{12.5}$$

where,

T = Torque

θ = Total twist directly proportional to T till the material is in its elastic range.

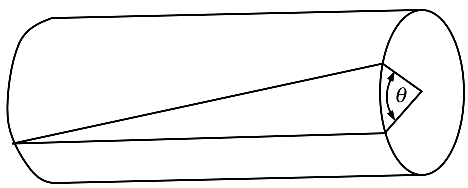


Figure 12.6 Torsional Twist of a Typical Shaft: The twist θ should be within the elastic range of the material.

If the oscillation frequency of the shaft is supposed to be the same as that of the pulse from the tower shadow, the oscillations will amplify until the shaft twists and breaks or some protective circuit shuts down the WPP. This means that if a shaft is not designed properly for safe operation, the WPP may fail catastrophically at resonant frequency. Hence, the frequency of oscillation has to be known at the design stage itself.

Just like in a compressed spring, a twisted shaft contains potential energy U which is given by:

$$U = \frac{k_T \theta^2}{2} J \tag{12.6}$$

The polar area moment of inertia J is used to study the mechanics of materials, normally in a static or stationary mode and for a shaft with radius r_o it is given by the following equation:

$$J = \frac{\pi r_o^4}{2} \tag{12.7}$$

Its unit is m^4.

A potential energy U has to be supplied to the WPP shaft for start-up and is delivered back to the system during shutdown. During a wind gust, part of the extra power go into shaft potential energy rather than instantly appearing in the electrical output. This stored energy then goes from the shaft into the electrical system during a wind lull. Thus, it can be seen that a shaft helps to smooth out the power fluctuations in the wind.

EXAMPLE 12.3

Find the twist angle θ and the energy stored in the high speed shaft of a WPP (refer Figure 12.6). The length is 1.95 m, torque is 1250 Nm/rad, angular velocity is 198.5 rad/s, diameter is 0.05 m and the shear modulus of 78 GPa.

Solution:

$$J = \frac{\pi r_o^4}{2} = \frac{\pi(0.05/2)^4}{2} = 6.135 \times 10^{-7}\ \text{m}^4$$

k_T is also given by:

$$k_T = \frac{JG}{L} = \frac{(6.135 \times 10^{-7})(78 \times 10^9)}{1.95} = 245.4 \times 10^2 = 24540$$

where,

J = Polar moment of inertia
G = Shear modulus (for steel, it is 83 GPa or 83×10^9 Pa)
L = Length of the shaft

$$\theta = \frac{T}{k_T} = \frac{1250}{24540} = 0.050937\ \text{rad} = 2°55'6''$$

This twist is not large and hence, it is a safe operation.

Potential energy U is given by:

$$U = \frac{k_T\,\theta^2}{2}\ J = \frac{24540 \times 0.0509^2}{2} = 31.79\ \text{J}$$

The potential energy is not large and hence it will safely operate.

The main bearing is that which supports the main shaft and transmits the reactions from the rotor loads to the mainframe mounted onto the tower. There are different concepts for integrating the main shaft in the nacelle:

- Main shaft on single main bearing [see Figure 12.7(a)]
- Main shaft on two-main bearing [see Figure 12.7(b)]
- Main shaft on fore-bearing and gearbox bearing [see Figure 12.7(c)]
- Integrated main shaft with gearbox [see Figure 12.7[d)].

(a) Main Shaft with Single Main Bearing

In this configuration [see Figure 12.7(a)], main shaft rests on single broad bearing housing with self-aligning roller bearings inside it. These are designed for high axial

and radial loads consisting of two rows of symmetric barrel rollers and a hollow spherical runway of the outer ring which allows turning around their radial axes and prevents power transmission from bending or torsion. The rotor thrust is completely absorbed by the main bearing. However, a limitation of this kind of bearing is that bending moments must be provided at the entrance area of the gearbox.

(b) Main Shaft on Two Main Bearings

In this case [see Figure 12.7(b)], the main shaft is mounted on the fore-bearing and aft-bearing. By this, the bending moments and rotor thrust are absorbed by either of the two bearings. Only the drive torque is transmitted to the gearbox which is the best advantage of this topology. The bearings are designed as self-aligning barrel roller bearings. The fore-bearing is mounted as close as possible to the rotor hub to minimise the gravity moment due to cantilever rotor mass to reduce the shaft fatigue.

(c) Main Shaft on Fore-bearing and Gearbox Bearing

In this strategy [see Figure 12.7(c)], the hub-end of the main shaft rests on the fore-bearing and aft-end in the gearbox, thus saving the need of the additional aft-bearing. But then a part of the rotor thrust is absorbed by the gearbox bearing.

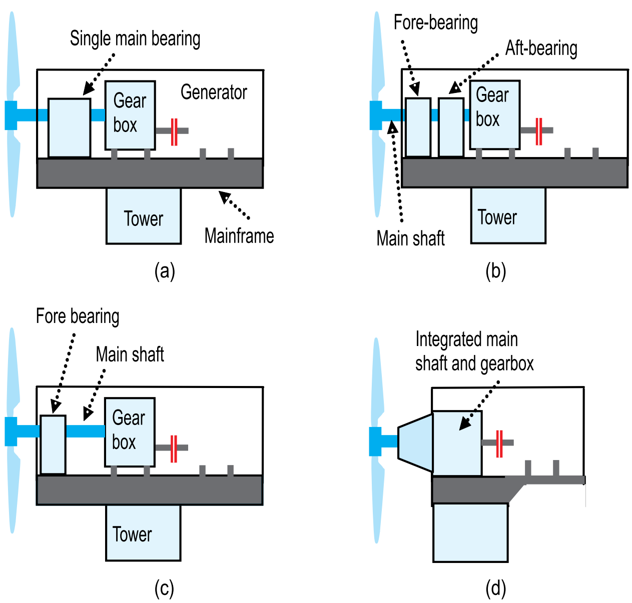


Figure 12.7 Different concepts for Integrating Main Shaft in Nacelle: (a) Main shaft single main bearing; (b) Main shaft on two-main bearing; (c) Main shaft on fore-bearing and gearbox bearing; (d) Integrated main shaft and gearbox.

(d) Integrated Main Shaft with Gearbox

In this design [see Figure 12.7(d)], the long main shaft concept is avoided by integrating the bearing into the gearbox. However, due to the high bending moments, this type of bearing is mainly adapted for smaller capacity WPPs.

EXAMPLE 12.4

A solid steel shaft has a radius of 0.2 m and a length of 1.2 m. Find the area moment of inertia J and the mass moment of inertia I. Assume the volume density of steel to be 7800 kg/m^3.

Solution:

The polar area moment of inertia J is used to study the mechanics of materials, normally in a static or stationary mode and for a shaft with radius r_o it is given by the following equation:

$$J = \frac{\pi r_o^4}{2}$$

$\therefore$ Area moment of inertia $J = \frac{\pi (0.2)^4}{2} = 0.00251 \text{ m}^4$

The polar mass moment of inertia I is used to determine the dynamics of rotating structures and is obtained by:

$$I = J\rho_a$$

where,

ρ_a = Area density in kilogram per square metre

The area density ρ_a is obtained by multiplying the volume density by its length.

$$\rho_a = 7800 \times 1.2 = 9360 \text{ kg/m}^2$$

$\therefore$ Mass moment of inertia $I = 0.00251 \times 9360 = 23.493 \text{ kgm}^2$

EXAMPLE 12.5

Determine the diameter of a geared WPP of 1500 kW capacity. The low speed shaft rotates at 20 RPM and the high speed shaft rotates at 1500 RPM. The gearbox efficiency at rated conditions is 0.96 and the generator efficiency is 0.94. Solid steel shafts are available with recommended maximum stresses of 55 MPa.

Solution:

The angular velocity ω_m is determined by the RPM through the equation:

$$\omega_m = \frac{2\pi N}{60}$$

$\therefore$ Angular velocity of high speed shaft, $\omega_e = \frac{2\pi \times 1500}{60} = 157 \text{ rad/s}$

$\therefore$ Angular velocity of slow speed shaft, $\omega_g = \frac{2\pi \times 20}{60} = 2.093 \text{ rad/s}$

Power in high speed shaft, $P_e = \dfrac{1500 \times 1000}{0.94} = 1595744$ W

Power in low speed shaft, $P_g = \dfrac{1595744}{0.96} = 1662234$ W

The torque is given by $T_m = \dfrac{P_m}{\omega_m}$

∴ Slow speed shaft torque, $T_g = \dfrac{1662234}{2.093} = 794187$ N-m/rad

∴ High speed shaft torque, $T_e = \dfrac{1595744}{157} = 10163.97$ N-m/rad

Polar moment of inertia J of the shaft is given by

$$J = \frac{\pi r_o^4}{2}$$

where, r_o is the shaft radius

The shearing stress varies with the distance from the shaft axis having the largest value at the surface of the shaft. The shearing stress f_s in a solid shaft is given by:

$$f_s = \frac{Tr}{J}$$

$$\therefore \qquad J = \frac{Tr}{J_s}$$

where,

T = Torque

r = Distance from the axis of shaft where the stress is determined.

One method to design shafts for a required torque is to select a maximum shearing stress which can be allowed for a given shaft material. Then, radius of shaft $r = r_o$.

Slow speed shaft diameter, $D_{\text{slow}} = 2r_o = 2^3\sqrt{\dfrac{2T}{\pi f_s}} = 2^3\sqrt{\dfrac{2 \times 794187}{3.14 \times 55 \times 10^6}} = 0.4190$ m

The high speed shaft diameter, $D_{\text{High}} = 2r_o = 2^3\sqrt{\dfrac{2T}{\pi f_s}} = 2^3\sqrt{\dfrac{2 \times 10163.97}{3.14 \times 55 \times 10^6}} = 0.098$ m

It is seen that the diameter of the low speed shaft is much bigger than that of the high speed shaft and the THM and also the cost of the WPP will go up if its length increases.

12.8.2 Geared WPP Nacelle Design

When the wind blows over the blades, the total aerodynamic force is the sum of the torque force (turning force) and thrust force (or bending loads). Nacelle design is crucial, as it has to transfer the torque force for conversion into electric power and remaining bending forces through tower safely to the foundation.

Over the years, manufacturers have tried and continue to try out several types of designs to reduce the THM and also to separate out the bending thrust force and useful torque force, as the wind power is harnessed by the geared WPPs.

The most common nacelle design down the years has been the conventional modular design [see Figure 12.8(a)]. The hub is directly supported by a casted frame on two bearings whereby the bending loads (or deflection loads) created by the wind on the rotor are transmitted directly to the tower (dashed arrows). Whereas, the gearbox is fully separated from the supporting structure leading to productive loads (torque) only being transmitted from the shaft to the gearbox and then, to the electric generator (dot-dashed line), resulting in a flexible drive train. Due to its intrinsic flexibility, such a design offers a comfortable environment for the gearbox, resulting in predictable loading and damping of transients.

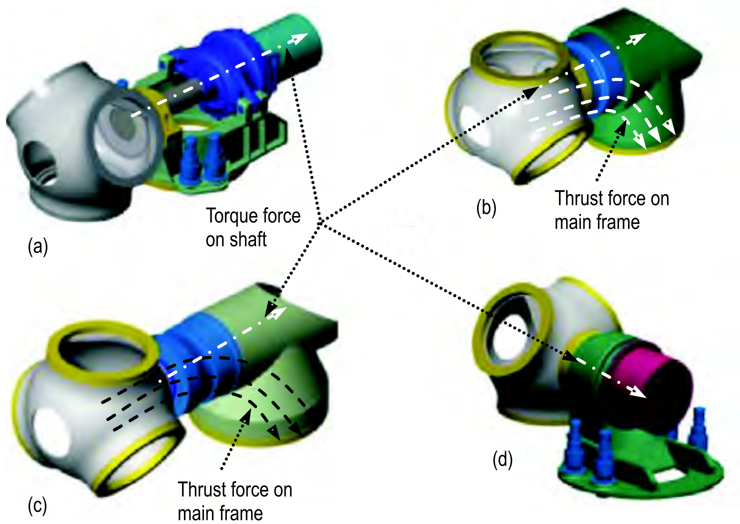


Figure 12.8 Nacelle Designs for Geared WPP: The aim of nacelle design is to reduce the THM and transmit the torque load to the generator with minimum losses.
Courtesy: Gear Consulting Services of Cincinnati; "This material has been reprinted with permission from National Renewable Energy Laboratory Subcontract Report NREL/SR-500-35524, entitled *Northern Power Systems WindPACT Drive Train Alternative Design Study Report; Period of Performance: April 12, 2001 to January 31, 2005*, by G. Bywaters, V. John, J. Lynch, P. Mattila, G. Norton, J. Stowell, M. Salata, O. Labath, A. Chertok, and D. Hablanian.

One of the main problems of a conventional drive train concepts is that the components are performing structural (thrust) and mechanical (torque) functions. This is especially true for critical components such as the gearbox and direct-drive

generators which are basically designed to withstand the torque moments. In the innovative nacelle designs [see Figure 12.8(b) and 12.8(c)], the thrusts and torque forces are bifurcated. The gearbox casing is located within the thrust force path and taken down to the ground through the tower. Whereas, the torque force goes straight into the main shaft connected to the gearbox. The 3 MW Alstom nacelle design and 3 MW Vestas V90 WPPs are the two examples that illustrate these innovative mainframe (bedplate) designs. The separation of torque moments and bending moments coming from the rotor increases the drive train reliability independently of the configuration, i.e., geared or direct-drive, greatly improving the drive train reliability.

The design shown in Figure 12.8(d) has a more optimised load path. This permits to separate out the bending and thrust loads from torque loads and transmit the latter to the low speed shaft only to be picked up by the generator.

12.8.3 Coupling Choice

The design of couplings is also crucial, as they also have to bear the useful torque forces. The first choice of coupling of shafts comes in when the hub with the blades is connected to the gearbox (for geared WPP) by the slow speed main shaft. It could be a flanged coupling or a shrink disc coupling. The latter is more preferred for large WPPs. In geared WPPs, the design is of the high speed shaft coupling between the gearbox and the generator. Different manufacturers have adapted different methods so that during extreme jerks caused by strong wind gusts from the gearbox side or due to electrical faults from the grid side, the relatively cheap replaceable high speed shaft coupling system is designed to break-off thereby saving the highly expensive gearbox and the electric generator.

12.8.4 Direct-Drive Nacelle Designs

The absence of the gearbox in the direct-drive WPPs renders the nacelle shorter than the geared WPPs. They also have the option of several designs (see Figure 12.9). The absence of the gearbox seems to have lesser weight, however in practice, it is something different. Due to the large diameter, multi-pole electric generator the top head mass (THM) increases, as the WPP is designed for higher capacities. For the same rating, practically, the THM of direct-drive works out to be more than that of a geared WPP, whether it is a wound rotor synchronous generator or a permanent magnet synchronous generator.

12.9 GEARBOX CHOICE

The main requirement for geared WPPs is to keep the THM as low as possible. A lighter and smaller gearbox is a better choice. It has a higher gear ratio in the minimum possible space, as the nacelle has to be compact.

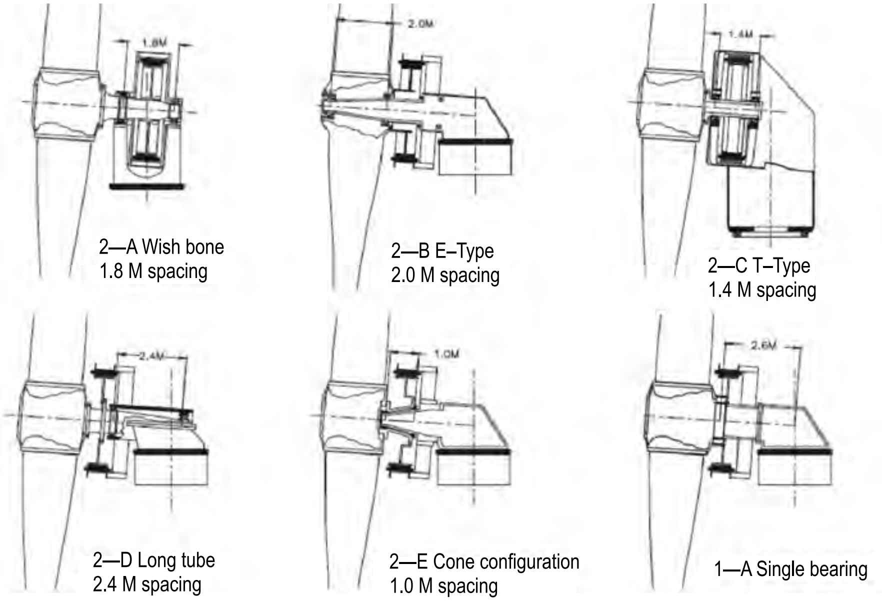


Figure 12.9 Nacelle Designs for Direct-drive WPPs.
Courtesy: Gear Consulting Services of Cincinnati; "This material has been reprinted with permission from National Renewable Energy Laboratory Subcontract Report NREL/SR-500-35524, entitled *Northern Power Systems WindPACT Drive Train Alternative Design Study Report; Period of Performance: April 12, 2001 to January 31, 2005*, by G. Bywaters, V. John, J. Lynch, P. Mattila, G. Norton, J. Stowell, M. Salata, O. Labath, A. Chertok, and D. Hablanian.

A modern WPP may have a gear ratio of 1:100 or more. Every time the blades make one revolution, the generator shaft spins 100 times. The blade tip speed, rotor diameter and also the generator design determine the gear ratio. The step-up ratio of the gearbox is equal to the generator shaft speed divided by the rotor shaft speed. The *transmission ratio* of the gearbox is the quotient of the angular speed of the first driving gear divided by the angular speed of the last driven gear of a gear train. If the rotation directions are the same, a plus sign is added to the transmission ratio and if the rotations are in the opposite direction a minus sign is denoted.

There are many gearbox design configurations (their applications have been discussed in the earlier chapters):

- Parallel shaft helical gearbox
- Planetary gearbox
- Combined planetary–parallel shaft gearbox
- Single gearbox with multiple generators
- Hydrodynamic gearbox
- Combination of planetary and hydrodynamic gearbox
- Hybrid (where the gearbox-generator is an integrated unit).

In the *parallel shaft helical gearboxes* (see Figure 12.10) two or more shafts with gears work in parallel. The slow speed shaft axis is offset from the high speed shaft axis. A two-stage gearbox has free shafts—an input shaft with gear, an output shaft with gear (e.g. the high speed shaft) and an intermediate shaft with gear. These gears constitute a gear train. However, this type of gearbox requires more space and stiffer structural support. In early years, this gearbox was used for smaller rated WPPs. However, such parallel shaft gearboxes weigh more than the modern planetary gearbox, but they are relatively quieter.

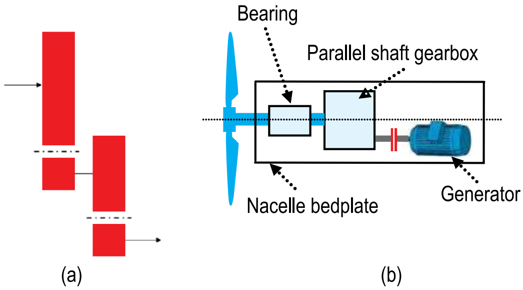


Figure 12.10 Parallel Helical Shaft Gearbox: (a) Helical gearbox concept, (b) Parallel shaft (plan view).

The *planetary gearbox* (see Figure 12.11) is more popular for medium and large scale WPPs. It consists of a ring of annulus planet gears mounted on a planet carrier and meshing with a sun gear from the inside (having external gears). The annulus is an internal gear as its teeth are present inside. The major strengths of the planetary type gearbox are as follows:

- It is highly compact and lightweight and requires little installation space.
- It has a high reliability due to proper distribution of stress among different load-bearing components.
- It has a very high transmission achieved with just one level.
- It can deliver high reduction ratios and transmit a higher torque.

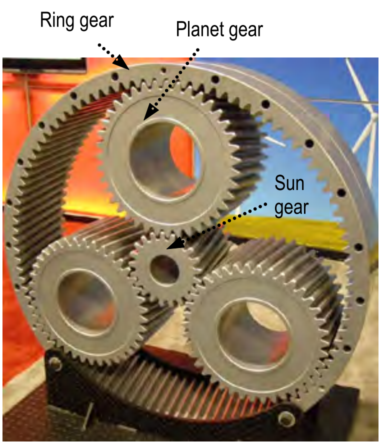


Figure 12.11 Planetary Gearbox Concept.
Picture by author.

To combine the strength of both the designs, most of the modern gearboxes typically use combined planetary–parallel shaft gearbox (two-stage planetary and one-stage parallel shaft with helical gears) which are connected to the generator of the WPP.

A patented special kind of single gearbox with multiple generators is used by some manufacturers such as the Clipperwind of USA (refer Figures 8.25 and 8.26). The advantage of this topology is that even if one generator is inoperative, the rest continue to generate power.

Some manufacturers use the hydrodynamic gearbox (refer Figure 8.17) or its different adaptations instead of a single conventional gearbox. Sometimes, a *combination of a planetary and hydrodynamic gearbox* (refer Figure 8.24) is also adapted. The major advantage of using hydrodynamic topology is that the WPP can be operated in a wide range of variable speeds and at the same time, achieving a constant speed output that can be directly coupled to a conventional four-pole synchronous generator providing a grid compatible electrical output without complicated PEC in the stator circuit.

In the *hybrid* (*semi-geared*) topology WPPs, the gearbox is not a separate unit (refer Figure 8.36) but integrated with the generator. The stator of the electric generator is directly connected into the gearbox cowling (as discussed in Chapter 8). The benefit of this design is that the intermediate high speed shaft is eliminated and at the same time a smaller medium speed electric generator of 15–200 RPM. can be adapted. However, the heat generated and the cooling arrangement of the gearbox also need to be considered.

Two other issues regarding gearboxes is the emission of noise and heat. To reduce the noise from going out into the environment, sound absorbant mats are to be fixed on the walls, floor and ceiling of the nacelle. Good cooling arrangement is also required to remove the heat.

EXAMPLE 12.6

A 1 MW WPP has three blades and a gearbox with a gear ratio of 1:100. The high speed shaft in the generator spins at 1500 r.p.m. Determine the rated RPM of the wind turbine rotor.

Solution:

Let the rated RPM of the wind turbine rotor be x.

Then,
$$\frac{1500}{x} = 100$$

$$x = \frac{1500}{100} = 15$$

Hence, the rated RPM of the wind turbine rotor should be 15.

12.10 DISC BRAKE SELECTION

Brakes for WPPs call for higher cycle rates, higher loads, greater reliability and often require to be in more compact packages as compared to the conventional factory equipment. Slowing and halting large diameter wind turbine rotor involves converting its enormous kinetic energy into heat. Low speed shaft braking is simpler as a big disc with a large friction lining area is easy to accommodate. However, the disadvantage is that the disc brake has to handle a high braking torque which generates considerable amount of heat and wears out the callipers quickly.

The most cost-effective position of the disc-brake is on the high speed shaft between the gearbox and the generator. The high gearbox ratio produces considerable amount of reduction in output torque of the high speed shaft and hence, a cheaper brake design with a fail-safe spring-loaded and hydraulically released one or more brake callipers.

The main criterion required for braking torque is:

$$\frac{T_b}{T_L} = 2 \quad \text{(factor of safety)} \tag{12.8}$$

where,

T_b = Brake torque

T_L = Load (aerodynamic) torque.

The other criteria that should be looked into is adequate friction brake pad area, acceptable rubbing speed, material compatibility with maximum disc temperature. The braking torque is generally designed with 20% overspeed; the rise in disc temperature and stopping time vary depending on the chosen service factors.

EXAMPLE 12.7

A WPP has a 1.2 MW rating and an aerodynamic torque of 120,000 Nm. Determine the braking torque.

Solution:

$$\frac{T_b}{T_L} = 2$$

Hence, the calculated braking torque $T_b = 2 \times 120{,}000 = 240{,}000$ Nm.

Electromechanical brake is a recent development for braking of large WPPs. In comparison to the hydraulic brakes, each electromechanical brake is driven by its own separate motor which is a safe advantage over hydraulic systems where all the brakes are supplied by one single hydraulic unit. Moreover, the electromechanical brakes continuously work for an unlimited period without requiring extra energy any further. This is of particular advantage to yaw brakes as well. The extreme temperatures is also not an issue as with hydraulic systems.

12.11 ELECTRIC GENERATOR CHOICE

The important criterion for increasing the capacity of a WPP is the swept area of the rotor. The larger the swept area, the more will be the energy that can be extracted from the wind. When the rotor size is set, a rating of the electric generator is chosen which also depends on the wind resources. The high inertia of the rotor and the drive train act as a flywheel and buffers the changes in RPM during wind gusts, making the power output more stable. The choice of the electric generator also decides the course of direction that the WPP design will take.

Every particular windy site has an annual average wind speed. The wind turbine rotor speed and electric generator speed need to be matched with the annual average wind speed at that location. If the generator (in terms of rated power output) is small, lesser wind speed is needed to turn it. A large diameter WPP rotor (capturing a large amount of wind energy) coupled with a small generator, therefore, produces electric power almost non-stop, as it works in even light winds. However, it does not produce much electric power as in strong winds if the power available from the rotor exceeds the rated maximum power output of the generator. Therefore, a larger generator will be efficient only at very high wind speeds but inactive at low wind speeds, as the force in the wind is insufficient to turn the rotor against the inertia caused by the generator.

The choice of electric generators is also based on the aerodynamic regulation for optimum TSR design (discussed in Chapters 4 and 5). The decision regarding the choice of the drive train to be chosen/designed along with the associated accessories is also influenced by the choice of the electric generator. With such a wide range of electric generator topologies available, the following questions regarding the choice of the electric generator are to be considered:

- Will the WPP be a constant speed or a variable speed one?
- Should an induction generator or synchronous generator be adapted?
  - If the choice is for an induction generator, then should it be a constant speed squirrel cage induction generator (SCIG), wound rotor induction generator (WRIG), doubly fed induction generator (DFIG), variable speed squirrel cage induction generator (SCIG)?
  - If synchronous generator is the choice, then should it be a wound rotor synchronous generator (WRSG) or permanent magnet synchronous generator (PMSG)?
    - If it is a WRSG, should it be a:
      - Direct-drive WPP with a multi-pole large diameter slow speed WRSG?
      - Geared WPP with a conventional smaller size high speed WRSG?
      - Geared WPP with hydrodynamic gearbox and high speed four-pole WRSG?
    - If it is a PMSG, should it be a:
      - Direct-drive WPP with a multi-pole large diameter slow speed PMSG?
      - Geared WPP with smaller size high speed PMSG?
      - Geared WPP with hydrodynamic gearbox and high speed four-pole PMSG?
      - Geared WPP with multiple high speed PMSGs?
      - Hybrid (semi-geared) WPP with medium speed PMSG?

The heat generated and the cooling arrangement of the electrical generator has also to be considered especially if it is a PMSG, as the permanent magnets are highly sensitive to high temperatures.

12.12 ELECTRONIC CONTROLLER CHOICE

The design/choice of the electronic controller at the nacelle top which is replicated at the tower bottom for redundancy depends on the type of generator, aerodynamic regulation, type of sensors, SCADA system and other parameters. For typical large megawatt scale WPP, there could be even upto 500 sensors which need to be monitored and controlled. For the sake of redundancy, some of the crucial sensors are duplicated. Three sixty-five/six days/24×7, the electronic controller has to monitor the condition of the WPP and take appropriate actions. In case of any malfunction (e.g. overheating of the gearbox or the generator and others), it has to automatically stop the WPP and call the turbine operator's computer via a telephone modem link. Therefore, a proven electronic controller having sufficient guarantee and warranty must be the choice.

12.13 HYDRAULIC AND LUBRICATIONS SYSTEMS

The design/choice of the hydraulic system in the nacelle required to operate the various hydraulic controlled devices, is another important decision to be taken. Some WPPs may be designed with a hydraulic yaw system as well. If more number of hydraulic operated devices are present, larger capacity hydraulic system may have to be considered. A backup supply for the hydraulic system must be considered.

The reliability of WPPs and their components can be enhanced by the proper choice and timely application of lubricants. The following properties may be considered:

- Good wear protection
- Good adhesion
- Good corrosion protection
- Long service life
- Low power consumption
- Long-term priming
- Pumpable via central lubrication systems.

12.14 TOWER DESIGN

Tower design is also crucial which should be based on strength, safety, cost, aesthetics or a combination of all these criteria. The tower design of large WPPs also differs, depending on whether it is a steel tubular tower, lattice tower, concrete tower, hybrid

tower, guyed tower or hydraulic tower for small wind turbines. Modern WPPs can even be mounted on lattice towers such as the Fuhrländer 2.5 MW 165 m height.

The tower structure and all components have to withstand significant loads originating from constant rotational torque force, wind thrust and gravitational loads. These loads could be static, quasi-static cyclic, dynamic cyclic or stochastic turbulence derived loads. The rate of change of thrust on a WPP is proportional to the square of the apparent wind speed. It is the cyclic and stochastic loads that cause most structural failures especially those due to fatigue. Additionally, the tower must be able to withstand environmental attack for the technical lifetime of the WPP which is generally 20 years.

As the tower is a cantilever beam, the tower and rotor blade vibrations should also be analysed during the design such as:

- Excessive torque loadings at the hub and drive train
- Tower shadow effects especially in downwind WPPs
- Start up and shutdown transients
- Rotor speed variations especially with variable speed WPPs.

Wind shear refers to the variation in wind speed with height. On sites with high wind shear, the wind speed increases significantly with height and hence, a taller but costlier tower produces more energy. But based on the windy site, a decision has to be taken if this additional expense is worth. However, taller towers are required to accommodate bigger diameter rotors. Presently, the largest diameter under series production is 154 m for the 6 MW Siemens WPP (i.e., the swept area is about 2½ times a football field).

The WPP rotor blades are made of material which is slightly flexible and hence they have a tendency to vibrate (say, once per second). The tower of any rotating WPP has an innate tendency to bend backwards and forwards at a particular frequency called the *Eigen frequency* (say about every three seconds). If this Eigen frequency, coincides with the vibration frequency of the rotor, it may affect the stability of the tower leading to enhanced vibration and ultimately collapse. Hence, it is essential to calculate the Eigen frequencies of each and every WPP component in the design of a tower.

The Eigen frequency is dictated by the height and diameter of the WPP tower, thickness of its tower walls, specific type and arrangement of steel members (in case of lattice towers) and the total weight of the nacelle and rotor blade assembly.

As the structural modulus decreases, the WPP structure become softer and that may lead to instability due to mechanical and aerodynamic loads. The damping properties of the tower structure decide how fast the system can restore itself to the equilibrium condition after the stress forces are removed. Finite element method (FEM) is a good tool for tower designs using IS-800.

12.14.1 Lattice Towers

Lattice towers (refer Figure 3.10) are free standing towers constructed of intersecting or criss-crossing steel angle bars bolted to each other. By spreading the lattice

tower's legs over a wider footprint than that of a conventional tubular tower, less excavation and less concrete are required for the footings. The struts of the lattice tower consist of stretch and compression-proof diagonals with supporting lattice-work.

Lattice towers, for the same stiffness of a tubular tower, require only about half of the material than that required for a tubular tower and hence, they are cheaper. Further, it has comparatively higher self-damping properties due to numerous joining points of the steel angle segments. The lay-down yard or staging area for assembly is also less and the assembly of the lattice tower does not involve much of technical expertise. By setting up lattice towers on site, it is also easier to reach inaccessible areas and less demanding transport requirements. In India, the lattice towers seem to be more popular as they are relatively cheaper than steel tubular towers, and convenient for transportation, assembly and installation as well. They also blend perfectly into open countryside, as their structure makes them transparent.

However, lattice towers do not provide protection against any environmental influences. The basic disadvantage of lattice towers is their visual appearance (although that issue is clearly debatable) as compared to tubular towers. Further, lattice towers require torquing of 400–500 bolts or even more, depending on the tower height. The inclination of the corner point of lattice tower differs in accordance with the height of the tower at three to four points, resulting in a hyperbolic form.

12.14.2 Steel Tubular Towers

Steel conical tubular towers (refer Figure 3.11) are preferred by many investors, as they provide better protection to the equipment and service personnel from the wind and also from the aesthetic point of view. From safety point of view, tubular towers are safer due the safe ladder access and a separate electrical control room can be avoided, as the enclosed tower base serves as the secure control room. The conical tower (diameter decreasing towards the top saves material and also increases the strength) is manufactured with steel plates of approximately 25 mm thickness and tubular segments of 20–30 m long. Depending on site conditions, different tower heights are to be designed that are suitable for inland, coast or offshore locations.

12.14.3 Concrete Towers

Concrete (ferro-concrete) towers, though cheaper, are much heavier than all the other types of towers. But they have better structural dampening characteristics than steel towers. One limitation is that it can never be re-used again. There can be two types of concrete towers which are given below:

(a) ***In-Situ:*** These are constructed on site (in-situ) thereby avoiding transportation and making fitting easier.

(b) ***Precast:*** In this type, individual tubular concrete sections are precast at a precasting plant to minimise the dimensional tolerances, ensuring a higher degree of fitting accuracy. These pre-cast sections are then transported to the site to be lifted and placed on the foundation one over the other. These sections are then fastened together to form an inseparable unit with steel stay cables running through jacket tubes in the concrete tower wall.

12.14.4 Hybrid Concrete Towers

Of late, concrete hybrid towers that use both concrete and conical steel tubular sections tower are being tried for large capacity WPPs. The lower part of the tower is of concrete section and over these, tubular steel segments are mounted one over the other to reach the hub height. These towers have proved to be successful. However, this seems to be economical only for large capacity WPPs.

12.14.5 Guyed Towers

Guyed towers or tilt-up towers usually built of narrow tubular pole towers such as 300 kW Carter WPPs, have guy (or stay) wires anchored to the ground on three or four sides of the tower to hold it perpendicular to the ground. Some of these guyed towers are erected by tilting them up by deflection rods and winches. However, the guy tension has to be checked regularly. It has the advantage of weight savings, material and thus, the cost too. Another advantage is that it can be tilted down for the maintenance work to the ground level and then tilted back upright. Although these towers cost less than freestanding towers, they require more land area to anchor the guy wires and hence make them less suitable in farm areas with all the guy wires strewn around.

12.15 SUBSTATION DESIGN

Next comes the choice and placement of the three-phase transformers, i.e., whether the transformers should be placed in the nacelle or at the tower bottom. If the transformer is in the nacelle, the size of drop down electric cables from the nacelle top to the tower bottom can be reduced greatly and so the losses accompanying it too. Then, additional cooling of the transformer has also to be taken care inside the nacelle. Another question based on its cooling, i.e., whether it should be air cooled or water cooler. With the transformer on the top, the THM also goes up. Another issue is the design and location of the electric/electronic control panel. Should the transformer be at the tower bottom or separately in a fenced switchyard with all other switchgear? So, a judicious design is to be done for the electric switchgear too. All of these have their merits and demerits. An optimum techno–economic choice needs to be taken for all these decisions.

12.16 FOUNDATION DESIGN

The foundation of a WPP has two basic functions. Firstly, it has to bear the dead load weight of the WPP and tower and keep it permanently upright without sinking. Secondly, due to the wind thrust and other forces, it has to prevent the WPP from tipping over. The foundation must resist this tipping; it should be stiff enough to prevent the tower from rocking when acted upon by wind or earthquake. The design of the foundations may affect the speed (and cost) with which they can be constructed.

Normally, the design load condition for the foundations has to be extreme for once in 50 years wind speed of that area/region may lie anywhere between 45 m/s to 70 m/s wind speed.

Since earth conditions are quite varied, foundation design is critical to the success of a WPP project. It is important to investigate geological hazards such as sinkholes, swelling soils, collapsing soils, underground mining, surface mining, surface spoils from mining, landslides, volcanic activity, earthquake issues, etc., as these can have a significant effect on the foundation of the WPP.

The performance of the foundation depends on the strength and compressibility of the soil or rock that may be present under the footing which affects the size and depth of the footing. For knowing this, the bearing capacity of the ground at the site has to be determined for which earth samples are taken by drilling holes into the ground and collecting samples by either driving (or pressing) a tube into the soil or using a diamond coring tool if is a rock.

The shape of the foundation could be circular, square, octagonal or cross shaped depending on the soil conditions. Circular foundations are favoured firstly, because:

- Forces are equal in all wind directions.
- It reduces the size of the form-work area, thereby reducing the amount of reinforcement and concrete requirement.

For the lattice tower foundation, the four legs are set well apart in reinforced concrete base to support the entire load. After sufficiently curing the foundation, backfilling is done and the lattice tower is mounted on it with the help of cranes. The four corner foundations support the corner legs to ensure the anchoring of the entire system by bolts in anchor bars.

For tubular foundations, to cater to the two basic functions, depending on the soil condition, the foundations could be a plate (shallow) foundation also called the *inverted-T* (see Figure 12.12) for tubular towers. The plate (spread footings) foundation is the most commonly used type of foundation for WPPs. A large reinforced concrete plate under the earth forms the footing of the WPP tower. After sufficiently curing the concrete, the tubular tower sections are then mounted one over the other on this concrete plate foundation and backfilling of the soil from the excavated pit is done.

Spread footings rely on soil bearing and the weight of the foundation itself. The soil backfill on top of the foundation to resist tilting under wind loads. A typical reinforced concrete foundation could be 13 m to 15 m across a hexagonal form and might be 2 m to 3 m deep.

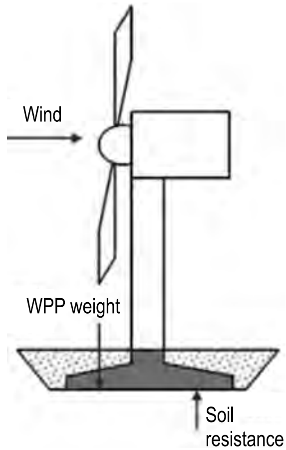


Figure 12.12 **Inverted 'T' Soil weight and concrete balances the foundation to prevent tipping over.** *Courtesy:* www.altenergymag.com

In soft subsoils, deep foundations are to be adapted to transfer the load to the deeper load bearing soil strata. Deep foundations function differently than the spread footings. Deep foundations such as driven piles or drilled piling may be necessary. Pile foundations are preferred where the foundation plates are fixed using piles. Such foundation can be a concrete or the steel cylinder pile, depending on the cost and installation factors.

Generally, the WPP supplier provides a complete specification of the foundation loads as part of a tender package. Deep foundations may include single piers (caissons), groups of driven piles or groups of drilled piles (see Figure 12.13). Single piers use the bending strength of the pier to resist tilting. For groups of piles, the tilting resistance comes from tension in the piles on one side of the foundation while piles on the other are loaded in compression.

Anchored foundation is another option which consists of a spread footing that has anchors extending through it into bedrock. This foundation eliminates the need for soil cover and takes advantage of high strength rock at the surface.

12.17 KEY EQUATIONS FOR WPP DESIGN ANALYSIS

In wind power statistics, different key equations can be found that are used to estimate the efficiency of WPPs with respect to the annual energy production. The overall efficiency of a WPP is the product of the turbine rotor's power coefficient C_p and the gearbox efficiency η_g or power electronic converter in the case of variable speed WPP and electrical generator efficiency η_e.

$$\therefore \quad P_{\text{actual}} = C_p \ 1/2\, \rho A v^3 \eta_g \eta_e \eta_r \tag{12.9}$$

Sometimes, C_p is set to 0.593 and η_{rotor} or η_r is used to show how large share of the theoretically available power the rotor can utilise. If the power coefficient C_p = 0.49, the rotor efficiency will be η_r = 0.49/0.593 = 0.83.

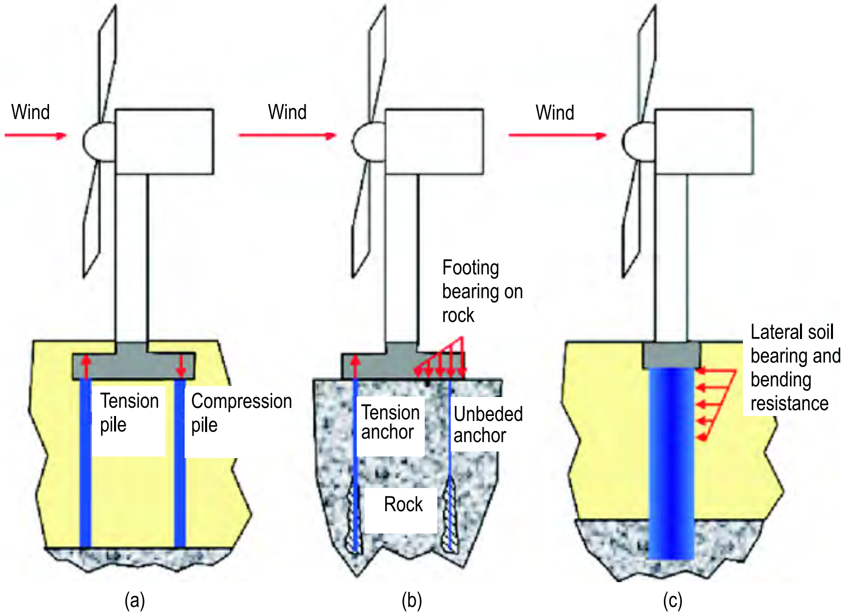


Figure 12.13 **Three Deep Foundation Systems:** (a) Pile group, (b) Anchored footing, (c) Single pipe. *Courtesy:* www.altenergymag.com

Another statistic full load hours kWh/kW.

$$\text{Full load hours} = \frac{\text{Production per year}}{\text{Nominal power}} \text{ kWh/kW} \tag{12.10}$$

Still another statistic is power production/swept area, kWh/m^2:

$$\text{Energy per swept area} = \frac{\text{Production per year}}{\text{Rotor swept area}} \text{ kWh/m}^2 \tag{12.11}$$

In both the above cases, annual averages are used. None of these key figures on its own give a good estimate of the efficiency of a WPP. A WPP that has a large rotor in relation to the nominal power of the generator produces much energy in relation to the nominal power and gets a high score in kilowatt hour per kilowatt. A WPP with a small rotor and a large generator produces much energy in relation to the swept area and gets a high score in kilowatt hour per square metre. It is, thus, possible to get a very high score for one of these key figures by choosing a bad relation between rotor diameter and generator size. In fact, an efficient WPP should have good scores for both of the above statistics.

Plant load factor (PLF) is the third key equation. It is the average power of a WPP during a year as compared to its nominal power:

$$\text{Plant load factor} = \frac{\text{Production per year}}{\text{Nominal power} \times 8760} \times 100 \tag{12.12}$$

PLF may theoretically vary from 0% to 100%, but in practice for WPPs they generally range between 25%–30%. For older WPPs, it was around 20% but for modern ones, it is around 35% in high wind areas.

Full load hours can also be expressed by multiplying the PLF with the annual hours. For example, if PLF is 0.35, then the full load hours is 0.35 × 8760 hours = 3066 full load hours.

EXAMPLE 12.8

If a 1 MW WPP produces 2500000 kWh in a year, find its PLF and its full load hours.

Solution:

$$\text{Plant load factor (PLF)} = \frac{\text{Production per year}}{\text{Nominal power} \times 8760} \times 100$$

$$\therefore \quad \text{PLF} = \frac{2500000}{1000 \times 8760} \times 100 = 28.53\%$$

$$\text{Full load hours} = \frac{\text{Production per year}}{\text{Nominal power}}$$

$$\therefore \quad \text{Full load hours} = \frac{2500000}{1000} = 2500 \text{ hours}$$

Availability of a WPP is also a key statistic. Availability describes the amount of time a WPP is ready to produce energy. It is defined as the ratio of the number of hours the WPP operates to the number of windy hours over the same time period. A high availability describes a WPP that produces power whenever the wind blows. This figure is given as a percentage. If a WPP is out of operation six days in a year due to service and maintenance problems, the availability of the WPP is 98%. In modern WPPs, availabilities over 95% are expected. For small wind turbines, availability over 99% is quite common.

$$\text{Availability} = \frac{8760 - \text{Stop hours}}{8760} \times 100 \tag{12.13}$$

Not only is the technical efficiency that is decisive, but the cost efficiency also has a say in the choice of WPP. This is one of the best tool to compare different WPP models, sizes and configurations at a specific site (or some comparable site). It gives a measure of the economic efficiency:

$$\text{Cost efficiency} = \frac{\text{Investment cost}}{\text{Production per year}} \tag{12.14}$$

However, costs for operations and maintenance are not included in this key statistic, so it does not give a final answer. On an average, the splitting of the investment for a WPP is 70% for the nacelle, rotor and tower and the rest 30% for the remaining part (foundations, installation, electrical substructures and others.

12.18 SPECIFIC RATING OF WPP

There are several ways to compare WPP designs despite differing sizes, specifications and configurations. For the same rating, if a WPP is mounted with different types of electrical generators, the percentage variation of the power produced will be different, especially at lower values of wind speeds. No best relationship between rotor diameter and generator rating exists. One of the indices to compare WPPs is called *specific rating* (or specific power) that can be defined as the ratio of a WPP's rotor swept area to the rated power of the electric generator. It is expressed in kilowatt per square metre.

$$\text{Spacific rating of WPP} = \frac{\text{Rated power in kilowatt}}{\text{Swept area of wind turbine rotor in square metre}} \quad (12.15)$$

The value of the specific rating varies from 0.2 kW/m^2 for small rotors to 0.6 kW/m^2 for large ones, as this range presents the best compromise among the energy capture, component loading and the costs.

WPPs at sites with lower wind speeds (such as 5.0 m/s to 6.5 m/s annual average at hub height) tend to have larger rotors and lower specific ratings to improve energy capture. Whereas, WPPs at high wind speed sites exceeding 8.5 m/s tend to have smaller rotors and higher specific ratings. The smaller rotor helps in reducing loads on components and thus, improves reliability at windy sites.

EXAMPLE 12.9

Determine the specific rating of a 6 MW wind power plant having a diameter of 154 metres.

Solution:

$$\text{Specific rating of WPP} = \frac{\text{Rated power}}{\text{Swept area of wind turbine rotor}}$$

$$\therefore \quad \text{Specific rating} = \frac{6000}{3.14 \times (77)^2} \text{ kW/m}^2$$

$$= 0.32 \text{ kW/m}^2 \text{ (since swept area of wind turbine rotor} = \pi R^2)$$

This is a fairly acceptable value.

EXAMPLE 12.10

The requirement of a village/community is 20,00,000 kWh. If the choice is for a three-bladed, upwind, horizontal axis, geared, onshore, tubular type WPP, determine the rating of the WPP to meet this energy requirement, as well as the estimated costs. Given that the power coefficient is 0.4, wind speed at 90 m hub height is 8 m/s, air density is 1.225 kg/m^3, PLF is 0.3, number of hours in a year is 8760 and cost per megawatt of a WPP is ₹ 60000000 (₹ 6 crores).

Solution:

Power density of air $P_{total} = 1/2\,\rho v^3$

$$= 1/2 \times 1.225 \times (8)^3$$
$$= 313.6 \text{ W/m}^2$$

If the gearbox efficiency is assumed 90%, generator efficiency 95% and $C_p = 0.4$, then,

Overall loss factor = 0.9 × 0.95 × 0.4 = 0.342

Actual power density = 313.6 × 0.342 = 107.251 W/m^2

Annual energy density = Power density × Hours in a year

$$= 107.251 \times 8760$$
$$= 939520.51 \text{ W/m}^2$$
$$= 939.52 \text{ kWh/m}^2$$

$$\text{Swept area of the rotor} = \frac{\text{Total annual energy required}}{\text{Useful energy density}}$$

$$= \frac{2000000}{939.52} \text{ m}^2$$
$$= 2128.75 \text{ m}^2$$

i.e., $2128.75 = \pi R^2$

$$\therefore \quad \text{Radius, } R = \sqrt{\frac{2128.75}{3.14}} = 26.04 \text{ m}$$

WPP power rating = Actual power density × Area of rotor

$$= \frac{107.251 \times 2128.75}{1000} = 228.31 \text{ kW}$$

This value is on the assumption that the wind will blow for all the 8760 hours of the year which actually does not happen. Hence, the PLF (capacity factor) has to be applied.

$$\therefore \quad \text{Actual WPP rated power} = \frac{228.31}{0.4} \quad \text{(since capacity factor = 0.4)}$$

$$= 570.77 \text{ kW}$$

= 600 kW (rounded off to the nearest available WPP rating)

Therefore, a 600kW WPP will be sufficient to annual energy requirement of the industry/community.

By rule of thumb, the cost of a WPP per megawatt is around ₹ 60000000

∴ Cost of the WPP = 60000000 × 0.6

= ₹ 36000000, i.e., ₹ 3.6 crores.

EXAMPLE 12.11

A multi-blade windmill has to pump water at the rate of 5 m^3 per hour for a lift of 9 m. If the average wind speed is 7 m/s, design its rotor of suitable diameter and also determine its angular velocity. Given that the power coefficient is 0.28, water density is 1000 kg/m^3, g is 9.8 m/s, water pump efficiency is 55%, efficiency of rotor to pump is 75%, air density is 1.225 kg/m^3.

Solution:

Power required to pump the water $= \dfrac{5 \times 1000}{3600} \times 9.8 \times 9 = 122.5$ W

Power required at rotor $= \dfrac{122.5}{0.55 \times 0.75} = 296.97$ W

It was proved earlier that $P_{max} = C_p \times P_{total}$

i.e.,
$$296.97 = 0.28 \times \left(\frac{1}{2} \times 1.225 \times \pi R^2 \times (7)^3\right)$$

(where, R is the radius of the rotor)

$$= 0.28 \times 659.67\ R^2$$

$$\therefore \quad R = \left(\frac{296.67}{0.28 \times 659.67}\right)^{1/2} = 1.27 \text{ m}$$

∴ Diameter $D = 2.54$ m

For a multiblade water pumping machine, TSR, $\lambda = 1$

It was proved earlier that $\lambda = \dfrac{\omega R}{v}$

∴ Angular velocity, $\omega = \dfrac{\lambda v}{R} = \dfrac{1 \times 7}{1.27} = 5.51$ rad/s

∴ RPM of the designed rotor is $= \dfrac{\omega \times 60}{2\pi} = \dfrac{5.51 \times 60}{2\pi} = 52.64 = 53$ (say)

SUMMARY

In this chapter, it is endeavoured to make the reader aware of the various design considerations that has to be of concern when undertaking the design of a WPP and its various components. This is because of its complex mechatronic nature. The main design drivers for current wind power technology are low wind and high wind sites, grid compatibility, acoustic performance, aerodynamic performance, visual impact and offshore projects. Generally, the WPP design is undertaken for its various components by different computer software (which is usually practised by different large WPP manufacturers) and then integrated together into a WPP.

EXERCISES

12.1 Name the IEC codes to be followed in WPP design for the following:
- (i) Full scale structural testing of rotor blades
- (ii) Wind turbine power performance testing
- (iii) Measurement and assessment of power quality characteristics of grid connected wind turbines
- (iv) Electrical simulation models for wind power generation

12.2 Analyse the first four major questions to be considered in the design of a WPP.

12.3 Compare different types of transient loads that a typical WPP has to withstand.

12.4 Describe the WPP design steps.

12.5 Compare the main features of five different types of hubs.

12.6 For optimum blade design, state the typical ranges of TSR, solidity, chord and twist.

12.7 Compare at least four blade design theories.

12.8 Describe the main feature of each of the four wind turbine blade design theories.

12.9 Design a slow speed shaft for a geared horizontal axis WPP which has to transmit 500 kW of mechanical power at a rotational speed of 30 RPM using solid steel. Assume the maximum stress to be 55 MPa.

12.10 A steel shaft 1.9 m in length is used to deliver 600 kW of mechanical power to a generator running at 1500 RPM. The shaft diameter is 0.09 m and the shear modulus G is 0.9 GPa. Determine the total twist, angle θ and total energy stored in the shaft?

12.11 Design the rotor blade for a WPP to develop 3 MW at a wind speed of 12 m/s. NACA 4412 aerofoil may be used. The assumptions are as follows:

Power coefficient = 0.4
Efficiency of drive train = 0.90
Efficiency of electrical generator = 0.98
Efficiency of auxiliary services = 0.97
Efficiency of power electronic converter = 0.98
Air density = 1.225 kg/m^3

12.12 Compare at least five requirements of the materials used for blade manufacture.

12.13 Give reasons for the increased use of CFRP in the manufacture of modern WPP blades.

12.14 Compare the features of at least four blade manufacturing technologies.

12.15 Describe the filament and tape winding process of manufacturing WPP blades in about 300 words.

12.16 Compare the four main shaft support topologies in geared WPPs.

12.17 Give reasons for the planetary gearbox to be more popular in WPP applications.

12.18 A 1.5 MW WPP has three blades that spin at 15 RPM. The high speed shaft in the generator spins at 1500 RPM. Find the gear ratio of this WPP.

12.19 A WPP has a rated capacity of 3.0 MW. To produce this amount of energy, the generator needs to be spinning at 1500 RPM. If this WPP has a gear ratio of 120:1, how fast do the blades need to be spinning to reach the rated capacity?

12.20 The gearbox of a WPP is made up of three gears. The largest gear has 1260 teeth and is meshed to the second gear which has 70 teeth. The 70-tooth gear is then meshed to the last gear which has 14 teeth. What is the gear ratio of this WPP? If the blades are spinning at 12 RPM how fast is the generator shaft spinning?

12.21 Compare the main features of different types of towers used for large WPPs.

12.22 At a particular site, the wind speed is 6.1 m/s at 60 m above the ground level and at 80 m height wind speed is 6.5 m/s. Determine the power law index and extrapolate the wind speed at 100 m height at that particular site.

12.23 Analyse the various requirements for the choice of electric generators in the design of large WPPs.

12.24 An island requires 20000000 kWh. If the choice is for a three-bladed, upwind, horizontal axis, geared, onshore, tubular type WPP, determine the rating of the WPP to meet this energy requirement as well as the estimated costs. Given that the power coefficient is 0.45, wind speed at 80 m hub height is 7 m/s, air density is 1.225 kg/m^3, capacity factor is 0.2, number of hours in a year is 8760 and cost per megawatt for WPP is ₹ 60000000 (₹ 6 crores).

12.25 Justify the type of foundation that would be suitable for a large onshore WPP which has a weak subsoil.

12.26 Explain the importance of the specific rating of a WPP.

12.27 A multiblade wind mill has to pump water at the rate of 7 m^3/h for a lift of 11 m. If the average wind speed is 6.5 m/s, design its rotor of suitable diameter and also determine its angular velocity. Given that the power coefficient is 0.28, water density is 1000 kg/m^3, g is 9.8 m/s, water pump efficiency is 55%, efficiency of rotor to pump is 75%, and air density is 1.225 kg/m^3.

12.28 Determine the specific rating of a 7580 MW wind power plant having a diameter of 127 metres.

12.29 If a 1.5 MW WPP produces 4000000 kWh in a year, find its PLF and its full load hours.

13

Small Wind Turbines

For thus says the LORD, you shall not see wind or rain.
—II Kings 3:17

Learning Outcome

On studying this chapter, you will able to choose/build the most appropriate small wind turbine for domestic/small power applications.

CHAPTER HIGHLIGHTS

13.1 INTRODUCTION

Micro-generation which includes technologies like small wind turbines (SWT) can act as a catalyst for the cultural changes in the consumer attitude and facilitate the availability of some power especially to the rural poor in the Indian context. SWTs (also called aerogenerators) are one of the most adaptable, flexible and easy to use technologies for generating sustainable and cheap electricity especially for the domestic consumption in windy urban and suburban areas as well. SWTs (see Figure 13.1) are commonly used today to power residential and farm houses, remote telecommunication stations for both military and commercial uses.

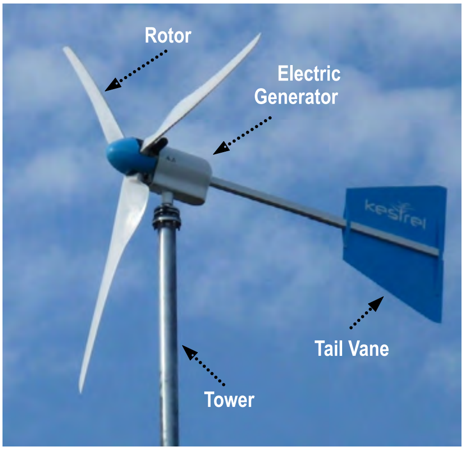


Figure 13.1 **Small HAWT:** Consists of the rotor, electric generator, tower and tail vane. *Courtesy:* www.teroc.se

Small wind is booming. WWEA's Small Wind World Report 2015 states that China alone produced 6,25,000 SWTs in the beginning of 2014, followed by USA with 1,57,700. The installed capacity in the world is about 755 MW and it is expected that this will grow to 2 GW by 2020. It is interesting to note that very few large wind turbine (LWT) companies manufacture SWTs while the SWT manufacturers produce only the small ones and standing apart as two different entities. All those interested in knowing more about SWTs and how they are different from LWTs will find this chapter interesting as the basics of varied SWT technologies is briefly discussed here.

Figure 13.2 depicts the combinations of various topologies that are adapted by different SWT manufacturers.

13.2 NEED OF SWT

At the sight of it, a SWT looks like miniature versions of the LWT. But, on a closer look, it can be observed that they differ on several fronts and are, therefore, treated as a different class of wind turbines. Even many of technologies adapted by

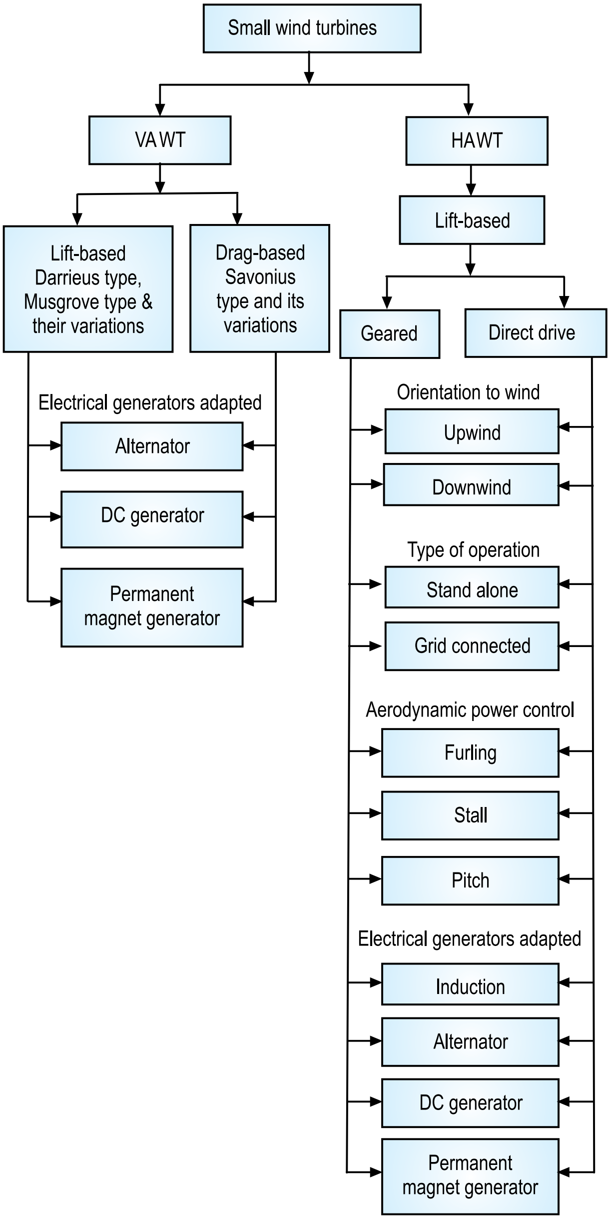


Figure 13.2 Small Wind Turbine Topologies.

the SWTs are drastically different from the LWT technologies. Some of the other features are as follows:

- SWT can be used even in semi-urban and urban areas.
- For SWTs of less than 10 m hub height, no building permits are required.

- They are very much suitable for telecommunication towers in windy regions.
- SWTs are convenient and affordable in remote homes.
- Their capacities can be progressively added as needed.
- Towers are much cheaper and installations relatively easier than LWTs, as no cranes or heavy equipment are required.
- SWTs are extremely durable in storms.
- They can be placed closer to property lines as they require lesser area than the LWTs which are generally of 50 m hub height and 50 m radial fall zone.
- SWTs are used for a wide variety of applications, not just for grid-connection (for mechanical water pumping, which may not even have an electrical generator).
- Mini-wind farms blend in with scenery and have a high acceptance rate from neighbours and community.

13.3 SWT CLASSIFICATION

There are different ways of classifying SWTs. There are different definitions of small wind turbines as well. Many countries have other size limits when it comes to providing subsidy for wind power programmes and projects. IEC 61400–2 Ed. 2 applies to wind turbines with less than < 300 m^2 swept area (generating at a voltage below 1000 V AC or 1500 V DC) and applies to SWTs which is not only on the basis of rated power, but also on the basis of the swept area (see Table 13.1). But for the sake of discussion and general understanding, wind turbines below 100 kW are considered as small wind turbine in this book.

Table 13.1 SWT Classifications (IEC 61400–2)

S.No.	Rated Power	Rotor Swept Area	Category
1	P_{rated} < 1 kW	A < 4.9 m^2	Pico wind
2	1 kW < P_{rated} < 7 kW	A < 40 m^2	Micro wind
3	7 kW < P_{rated} < 50 kW	A < 200 m^2	Mini wind
4	50 kW < P_{rated} < 100 kW	A < 300 m^2	Small wind

Source: CIEMAT

Based on different criteria, other classifications of SWTs are as follows:

(i) VAWT and HAWT
(ii) Drag and lift-based VAWTs
(iii) Upwind and downwind SWTs
(iv) Geared and direct-drive SWTs
(v) Stall and pitch controlled SWTs
(vi) Off-grid, on-grid and hybrid SWTs.

13.4 VAWT AND HAWT

These are two broad categories into which most of SWTs fit into. These are:

- Vertical axis wind turbines (VAWTs)
- Horizontal axis wind turbines (HAWTs).

13.4.1 VAWT

The axis of the VAWT drive shaft is perpendicular to the ground. The small VAWT is an omnidirectional SWT, i.e., it will rotate from whatever direction the wind blows (refer Figure 4.1). Hence, no yaw mechanism is required. It does not require a constant adjustment or streamline velocity wind. VAWTs are mainly beneficial in areas with turbulent wind flow such as rooftops, coastlines, cityscapes and other places. Unlike large VAWTs, small VAWTs and their variations are competing in the market alongside the small HAWTs.

Unlike the large VAWTs that have not attracted much investment; there are a considerable number of VAWT manufacturers and users due to the considerable amount of low power applications. Small stand-alone VAWTs can be very conveniently used in telecommunication towers, remote houses and small homes. In this category, both drag and lift type VAWTs are also popular.

Other than its omnidirectional feature, another merit of a small VAWT is that it has a lower startup wind speeds than the HAWT. It has also an advantage that it may be built at locations where tall structures are prohibited. Moreover, it has comparatively a lower noise signature than HAWTs and massive tower structures are less frequently used.

13.4.2 HAWT

Almost all small HAWTs (refer Figures 13.1) have a rotor, a nacelle (or electric generator) and a tail vane. They are available in many sizes ranging from a few hundred watts up to hundred kilowatts. These are generally used under streamline wind conditions where a constant stream and direction of wind is available in order to capture the most wind energy. They are inefficient where the wind is turbulent and are, therefore, located in areas such as fields with a constant directional airflow. Due to the size and orientation of HAWTs, they must be placed with an adequate spacing between each SWT to avoid the turbulence created by one another's spinning blades.

13.5 DRAG AND LIFT-BASED VAWTS

Based on the principle of working, small VAWTs are classified as drag-based and lift-based. It is interesting to note that in small wind category world over VAWTs of both lift type and drag type SWT continue to be produced and used for small

power applications. Although the drag type is not very significant among LWTs, they are considerably popular among SWT manufacturers.

13.5.1 Drag-based VAWT

Among the drag-based VAWT, the Savonius design (see Figure 13.3) is by far the simplest of these various mechanisms. This machine designed on the drag principle was invented by the Finnish engineer *Sigurd Savonius* in 1924 and was patented in 1929. Its rotor consists of two half cylinder-shaped scoops that are open in different directions. Centrally, these blades are arranged to overlap allowing air flow into the opposite blade. Since the drag coefficient of the concave surface is more than that of the convex surface, the greater drag force on the concave side forces the rotor to rotate. The TSR is less than 0.8 and the power coefficient is about 35%, i.e., it experiences a 35% power stroke. Nearly all of the other SWT designs involve advanced aerofoil shapes and other complicated structures.

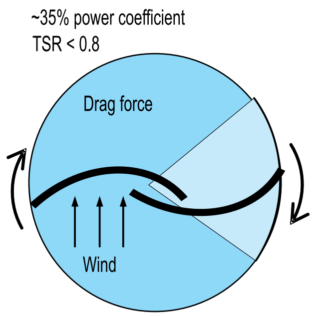


Figure 13.3 Drag Type VAWT—Two-bladed Savionius Rotor Top View: Darker shade depicts the dominant drag force area.

Savonius rotor has a rather low maximum efficiency of about 14%. This efficiency does not drop off rapidly as in most of the other SWT designs (only the HAWT has a wider range of wind speeds for high efficiency). No aerofoil shape is involved which is part of the explanation for the very low efficiency. In addition, it has a high solidity rotor and hence, has a tremendous starting torque too. Whereas, most other designs have very little torque at low rotational velocity. This design is technically called a *low tip speed* (or slow speed) *cross wind axis SWT*.

The main characteristics of the Savonius SWT are as follows:

- It is suitable for small power applications only.
- It is a slow SWT (based on the peripheral tangential speed at the extremities of the blades).
- Since it is having less efficiency, adequate speed control is required to keep the efficiency within acceptable values.
- As blades are fixed, aerodynamic surface cannot be reduced in case of speeds exceeding the rated value.
- A mechanical brake required for stopping the SWT.

- Noise level is relatively low.
- It is having a robust structure required to withstand extreme winds due to high exposed surface of the blades.

13.5.2 Lift-based VAWT

The blades of the Darrieus wind turbine (refer Figure 13.4) are also having aerofoil cross-sections, i.e., streamlined lifting surfaces like the wings of an aircraft. They are also quite efficient, since they depend purely on the lift forces produced as the wind (they travel at 3 to 5 times the wind speed) moves over the blade surface.

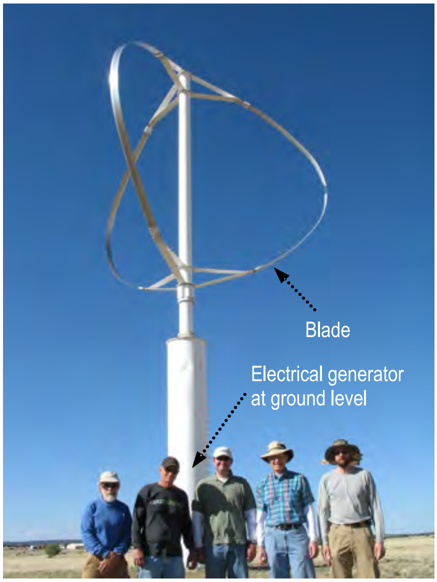


Figure 13.4 Darrieus Type VAWT: 60 kW three-bladed VAWT, Albuquerque, USA. *Courtesy:* VAWT Power Management, Inc.

In a two-bladed Darrieus type VAWT, each blade pulls 50% (see Figure 13.5) of the time. Each of the blades generate a maximum torque at two points on its rotation cycle (back and front), thereby creating torque pulsations as well. It can be seen that the back blade operates in the wind shadow of the front one. They do spin faster than the wind speed but not as much as HAWTs. This design is technically called a *high tip speed cross wind axis turbine*. It can be seen here that the TSR which is less than 2.5 is better than that of drag type rotor blades. However, it is much less than HAWTs. The aerofoils allow this style to have efficiencies as high as about 32% over a fairly wide range of wind speeds.

The main characteristics of the Darrieus SWT can be summarised as follows:

- It is omni-directional and adaptable to variations in the direction of the wind.
- Operates under turbulent wind conditions also.

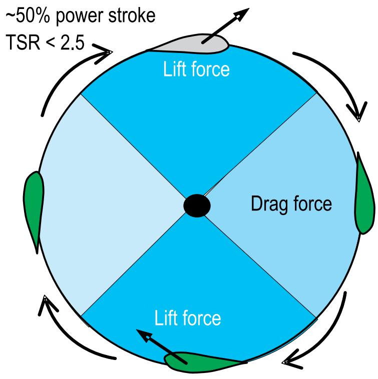


Figure 13.5 Top View of two-bladed rotor Lift Type VAWT: Square shaded area depicts dominant lift force area, while shaded area is drag force.

- It is having fast turbine which is good for electricity generation.
- This is effective for winds with an important vertical component of speed–sites on slopes or installation on the roof of the buildings 'corner effect'.
- It is adaptable for low values of wind speed and for a limited range.
- Its gearbox and electric generator may be positioned at ground level.
- It produces low noise and the vibrations are limited to foundations, thus, it is suitable to be installed on buildings.
- Its structure is not extremely robust to withstand extreme winds (a smaller surface of the blades is exposed to the wind in comparison to Savonius turbines).
- It is having a reduced efficiency in comparison to HAWTs, as great part of the blade surface rotates very close to the axis at a low speed.
- As blades are fixed, aerodynamic surface cannot be reduced in case of speed exceeding the rated value.
- It necessitates an adequate speed control to keep the efficiency within the acceptable values.
- It is mounted with mechanical brake required to stop it.
- It is not self-starting.

The three-bladed H-rotor type (see Figure 13.6) or multibladed H-type rotor of a VAWT (or their variants) also works on the lift principle (discussed in Chapter 4) and rotates on the vertical axis to turn a generator to produce electrical power. They are also lift type, since the blade section has a streamlined aerofoil and the surface presented to the wind causes a lift force on the blade to generate a distribution of the pressure on the blade, creating a torque that causes the blades to rotate.

The H-rotor although popular due to the ease of assembly and mass production, has the disadvantage of pulsations in the power output. This issue is resolved to a great extent in small VAWTs by using a twist of the blades (see Figure 13.7) wherein each of the vertical aerofoil blades is given a helical twist of 120°. This is a variation of Darrieus type VAWT in order to evenly spread out the torque over the entire revolution space. An added advantage of the helical twist is that the blades generate a torque even from an upward slanting airflow. The wind pushes each blade around both the windward and leeward sides of the turbine.

Figure 13.6 **Three-bladed Lift-based H-Rotor.** *Courtesy:* www.cleanfieldenergy.com

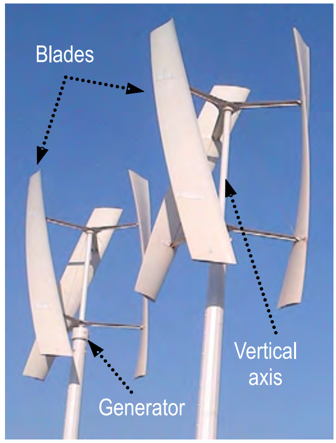


Figure 13.7 **Innovation of H-Rotor Lift-based VAWT.** *Picture by author.*

13.5.3 Musgrove Lift-based VAWT

Prof. Musgrove (Reading University, UK) developed this small VAWT which also works on the lift principle rotating the blades connected to a spindle around a vertical axis (see Figure 13.8). It is also an H-rotor with aerofoil shaped blades working on the lift principle. At high winds beyond the designed limit, the blades feather out due to the centrifugal force at the hinges, thereby eliminating higher aerodynamic forces on the blades and the total structure.

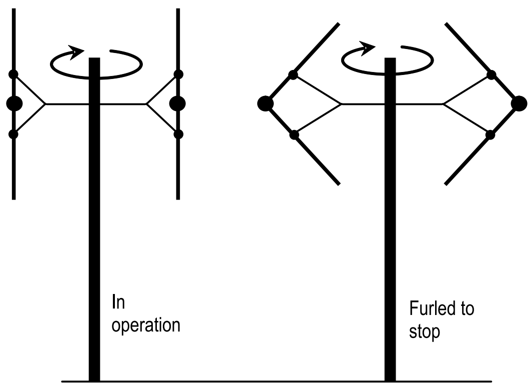


Figure 13.8 **Musgrove Lift-based VAWT.**

13.5.4 Drag Plus Lift Hybrid Blade Design

This is an innovation applicable in small VAWTs (see Figure 13.9). The major difference of this VAWT is the J-blade. The conventional VAWT blade is a closed pouch-like structure like that of an aeroplane wing. Whereas, the J-blade features a cut section towards the rear of the blade, giving the overall blade cross section a J-shape.

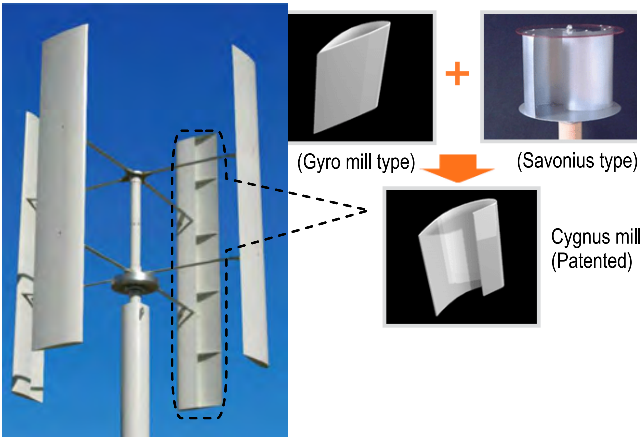


Figure 13.9 Hybrid Drag Plus Lift Blade Design.
Courtesy: http://cygnus-power.com

This J-shaped bag structure blade design incorporates both the lift and drag principles of wind turbine working. In addition to the aerodynamic lift caused by the laminar flow over the smooth surface of the blade, this design also allows the wind to be caught in the notch at the back of smooth aerofoil of the blade. As a result the J-blade operates due to both simultaneous lift and drag forces.

It is seen that one side of the blade has an aerofoil profile like conventional wind turbine blades, giving minimum resistance, whereas, the opposite side of the blade has a notch (see Figure 13.10). When the wind blows from the left, the rotation of the upper blade is powered by the lift action. The blade side with aerofoil profile facing the incoming wind acts as a normal aerofoil getting a lift force at the cut-in speed and starts to rotate. Simultaneously, the drag force due to the notch in the J-blade further assists the rotation of the blades. In other words, it uses the same wind more than once creating more torque, thereby improving its rotational efficiency and allowing it to begin operating even in a gentle breeze.

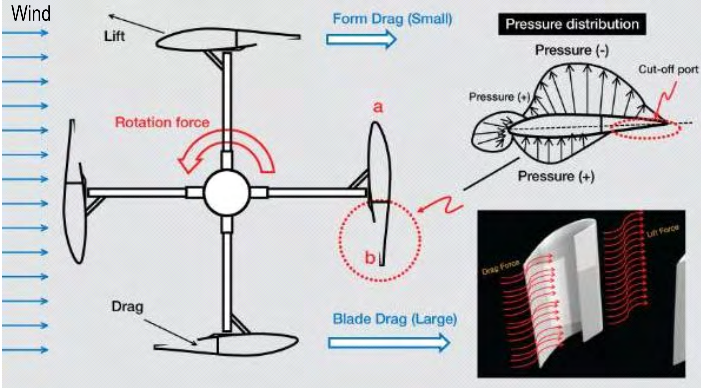


Figure 13.10 Performance of Drag Plus Lift Blade Design.
Courtesy: http://cygnus-power.com.

This phenomenon leads to more energy gains while the conventional blades with smoother surface design on both sides. This J-blade claims to be about 20% more efficient than conventional pouch-like structure lift type VAWT blades. If the SWT works for 8760 hours a year, even a small difference in efficiency will make substantial savings in the energy costs being saved.

13.5.5 Integrated Savonius and Darrieus Rotor Design

Generally, a Darrieus VAWT is not a self-starting machine, so some mechanism for starting needs to be done. This strategy where the wind turbine rotor is constructed using a combination of both the drag and lift principles tries to overcome this problem. The advantage of this design is that it has a better starting torque due to the Savonius drag blades and at the same time, more efficient, as the Darrieus lift blades increases the overall efficiency of the VAWT after the self-starting by the drag force.

13.6 HAWT FEATURES

The axis of the drive shaft in this small HAWT is parallel to the ground. This SWT working on the lift principle is quite commonly used to produce electrical power for household and small business purposes. Two-bladed and three-bladed SWTs working on the lift principle (discussed in Chapter 4) are quite popular.

Three-bladed HAWTs (see Figure 13.11) have purely lift type aerofoils, although they suffer the disadvantage of reduced speed near the hub. All three blades experience the same apparent wind speed with respect to actual wind speed and experience large lift forces, pulling all the blades in the same direction all the time over a 100% power stroke. For most SWTs, the optimum TSR value is around 5 to 7 which means that the tip speed of the blade has a linear velocity around 6

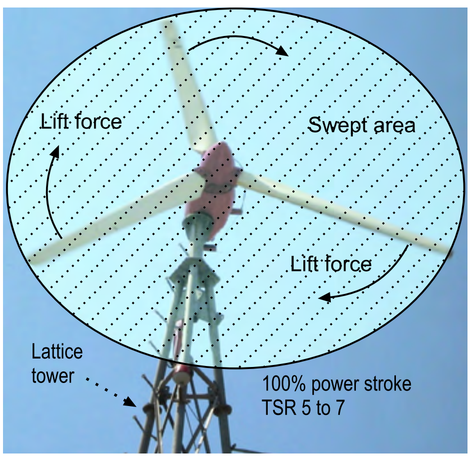


Figure 13.11 Lift based three-bladed SWT: The arrows depict dominant lift force area. *Picture by author.*

times the wind speed. The main advantage of SWT is that the tall tower of 10 m to 15 m allows access to stronger and relatively lesser disturbed winds at higher levels of the atmosphere and hence, a smoother electrical power output is obtained.

Currently, an innovative 2 kW one-bladed SWT, Thinair 102 (see Figure 13.12), is being manufactured by Powerhouse Wind, New Zealand. This single 1.8 m long blade with two small counterweights, teetering hub, downwind, stall regulated design, automatically adjusts the blade's angle to accommodate changes in the wind speed and is quieter in operation. It has a modern three-phase axial flux variable speed PMSG operating in the range of 60 RPM to 400 RPM at the rated wind speed of 10 m/s. Multi-bladed small HAWTs which are tilted to catch the wind correctly are inefficient in high winds and vulnerable to turbulence.

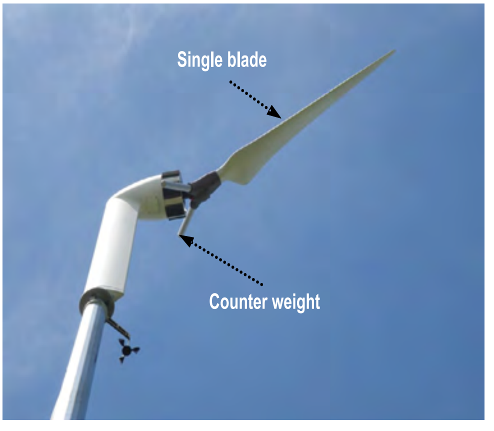


Figure 13.12 **One-bladed Downwind SWT:** This one-bladed 2 kW downwind SWT is mounted with an axial-flux direct-drive permanent magnet synchronous generator.
Courtesy: www.powerhousewind.co.nz

13.7 UPWIND AND DOWNWIND SWTs

The upwind SWTs (refer Figure 13.1) are distinctive by their tail vane which acts as passive yaw system (sometimes called a free yaw system) and keeps the rotor blades facing the wind all the time to keep it rotating. Almost every upwind SWT has a tail vane. Although, most of the SWTs self-align with the wind due to the tail vane, there are some upwind SWTs which use forced yaw system to keep the rotor blades facing the wind. They have a higher efficiency in comparison to the downwind machines, since there is no aerodynamic interference with the tower.

However, due to the constantly changing wind direction and turbulence, the output power from the upwind SWTs with tail vane largely fluctuates, as the tail vane continuously swings back and forth at the slightest change in wind direction and the phenomenon of hunting occurs till it becomes steady. In case of forced yaw system, such fluctuations caused due to minute changes in wind direction are reduced to a great extent and hence, the power produced is more or less constant.

In downwind two-bladed SWT (see Figure 13.13) which do not a have tail vane, the blades are on the leeside of the tower, i.e., the wind reaches the blades after passing the tower. Hence, they are affected by the negative aspects of the tower-rotor interaction. But, they are intrinsically self-aligning and have the possibility to use a flexible rotor to withstand strong winds. However, downwind topology leads to earlier fatigue and structural failure because of the wind turbulence (due to mast wake), as the blade passes through the tower's wind shadow all the time.

Figure 13.13 **Downwind HAWT:** Two-bladed guy wired with tilt up tubular tower Vergnet SWT. *Courtesy:* www.thewindpower.net

13.8 SWT COMPONENTS

Irrespective of their rating, almost all SWTs consist of the following major parts:

- Rotor
- Electric generator/alternator
- Tail vane or yaw system
- Tower
- Control and protection systems
- Gearbox (in some SWTs).

13.8.1 Rotor

The rotor of a SWT could be two-bladed, three-bladed or multi-bladed turbine (see Figure 13.14). According to IEC 61400–2–Design Requirements for Small Wind Turbines, they are to be designed to rotate in a clockwise direction to harness the energy from the wind. The blades are generally fixed to the hub at an appropriate

angle of attack for the lift force to act upon and make them rotate. The blades are usually built of glass fibre reinforced plastic (GFRP) which are relatively lighter and durable than wood or metal.

Figure 13.14 **Five bladed SWT.**
Picture by author.

13.8.2 Generator/Alternator

A number of types of electric generators are used in SWTs. The performance, reliability and cost are the main considerations for their choice. A generator which produces alternating current (AC) power is called an *alternator*.

(a) DC Generator

Many SWTs upto the capacity of 1 kW, direct-drive (refer Figure 13.1) use direct current (DC) generators which produce direct current (DC) power because the high rotor speed for small diameters is suitable for direct-drive and good for battery charging and small power applications. The limitation with such generators is the high maintenance of slip rings and brushes.

(b) PMSG

Generally, for the SWTs above 1 kW capacity, multi-pole permanent magnet synchronous generators (PMSG) are increasingly preferred because of its low cost, reduced power losses, simple construction and no external magnetisation requirement. Their starting torque is quite low because there is no gearbox (thereby reducing undesirable frictional losses), and also they do not have any laminations which may generate magnetic drag. Such SWTs can therefore, start even at very low wind speeds to produce useful power. A PMSG also allows the rotor to be stopped and locked

in light to moderate winds to enable servicing. The power losses in a PMSG are quite small in low wind speeds which are also the best time for battery charging.

(c) SCIG

Where a high speed squirrel cage induction generator (SCIG) is used (see Figure 13.15) in a SWT, it has to be connected through a gearbox to convert relatively lower RPM of the turbine blades to match its higher RPM. Some SWTs above 20 kW capacities adapt SCIGs. They are also popular, as they are cheaper and relatively more durable and maintenance free The main advantage is that the SCIG produces electricity that can be transferred directly to the power grid (without the use of complex and expensive PEC) leading to increased production and lower equipment and maintenance costs.

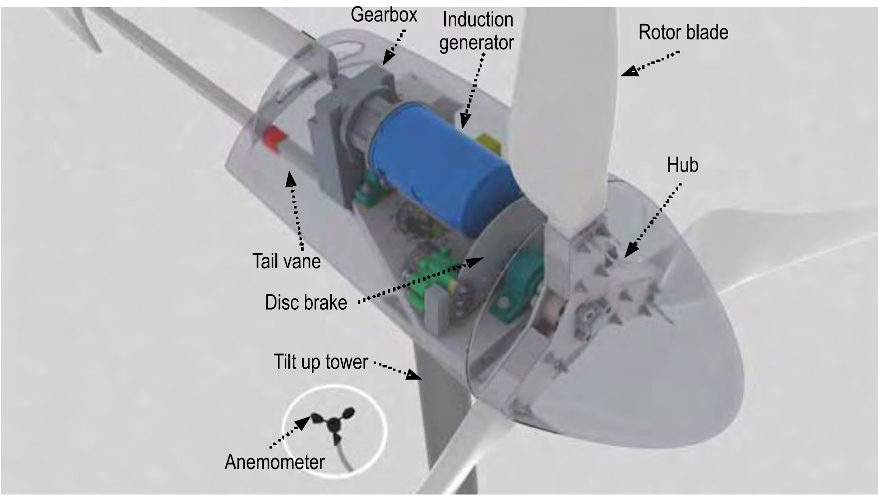


Figure 13.15 Upwind Geared SWT: This 5 kW stall regulated SWT rotor is connected to an induction generator through a gearbox.
Courtesy: Endurance Wind Power Inc.

The SCIG starts as an induction motor taking the excitation current (reactive power) from the utility grid to start and spin the turbine blades even at lower wind speeds without relying solely on the wind to start it. If grid power becomes unavailable, the SCIG will not produce power. These eliminate the possibility of the SWT backfeeding power into the grid during a power outage and potentially injure someone working on the electric lines. It should be noted that standard SCIG has some losses also when operating at low wind speeds other than the rated wind speeds, e.g. a 10 kW induction generator may have losses of even upto 800 W to 1000 W.

13.8.3 Gearbox

Some SWTs use a gearbox (see Figure 13.15) to convert relatively slow rotation of the rotor to match the high RPM of the electric generator. The gearbox placed between

the rotor and the generator usually consists of two stages of helical/spur gears filled with lubrication oil. Once in every 2–3 years or as specified by the manufacturer, the gearbox oil should be tested for contamination and moisture content and changed, if required. Only light oil should be used. For example, Hypoid SAE oil is too thick and must be diluted 50% with light engine oil if lighter gear oil cannot be found.

13.8.4 Control and Protection System

The control panel with the protection system is usually situated in the control room at the tower bottom. The output from the generator/alternator is variable (as the wind speed varies), requiring a control system to produce a stabilised constant output power. The control systems for this purpose vary from simple switches, fuses and battery charge regulators to computerised systems for control of brakes, connection and disconnection switches and others. The sophistication of the control and protection system varies, depending on the application of the SWT and the energy system it supports.

(a) Rectifier/Inverter

As the voltage and frequency of the electric power generated by these SWTs vary with wind speed, it is incompatible with the utility grid. The majority of the SWTs are of variable speed, invariably employing the inverter to produce grid acceptable electric power. If the output of the SWT is DC power, the inverter conditions it so that it can be fed to the electric grid or used to operate normal household appliances.

Light duty inverters (100 W to 1000 W) are typically 12 V DC and suitable for lamps and small appliances such as televisions, computers and small hand tools. Heavy duty inverters (1000 W to 10000 W) can be 12 V, 24 V or 48 V DC and can be used to run just about anything found in a home or small business. A gust in high winds can cause an inverter to shut down to prevent damage and typically, the inverter remains off for a programmed period of time (~ five minutes). A gust at low winds may also cause an inverter to turn-on, when the low wind speed can not produce power.

It is noted that inverter-based systems also suffer losses from the conversion of power from AC to DC then back to grid compatible AC. Inverters consume approximately 10% of the generated electricity (treated as a loss) when converting from DC to AC. However, a typical inverter generally works at an efficiency of around 85%. 15% of the cost of a typical SWT is due to the inverter. Some inverters can act as battery chargers.

(b) Transformer

Generally, the treated output from the control system is required to be stepped up to match the utility voltage and hence, a transformer is also required. A three-phase transformer steps up the output from the inverter to operate the home appliances. A load is required to be connected to the output of the transformer when the SWT operates, or else the voltage rises to the damaging levels. The transformer must be in a dry, clean, ventilated area, as it becomes quite warm when running at full power.

(c) Wind System Batteries

Batteries are required to store the generated electric energy if the SWT is not connected to the electric grid. If the output of the SWT is AC and entire power output is to be used for only battery charging, then the relatively cheaper rectifier will suffice to be connected directly to the battery bank.

Standard monitoring equipment for a wind battery charger usually includes a voltmeter for measuring battery voltage and depth of discharge and an ammeter to monitor energy production or use. Deep discharge batteries are better, as they can safely discharge a significant amount (50% to 80% of the battery storage) daily and can be charged back by the next day. More sophisticated monitoring equipment includes alarms for system problems such as low or high voltage conditions. For a typical home, properly-sized batteries can last 3 to 5 years.

13.8.5 Tail Vane (Yaw System)

Most micro and mini SWTs upto a capacity of about 10 kW use a simple tail vane (refer Figure 13.1) at the back of the horizontal axis SWT nacelle so that the turbine rotor keeps facing the wind. In the absence of the tail vane, forced yaw system keeps the rotor facing the wind.

13.8.6 SWT Tower

The SWT tower could be tubular type (refer Figure 13.1) or lattice type (see Figure 13.11). Several different types of towers are available, depending upon the design and manufacturer. They could be free standing or guy wired. Each type has its merits. Standard tower lengths are 20 m and 30 m. It must be designed to withstand extreme winds and hail. A rule of thumb for proper and efficient operation of a SWT is that the tower hub height should be at least 10 m above anything around 100 m of the tower.

Higher above the ground, the wind speed increases and the flow is more laminar. Electric power generation increases exponentially with the wind speed. Hence, relatively small additional investments in increased tower height can yield very high rates of return in electric power generation. For instance, installing a 10 kW SWT on a 30 m tower rather than an 18 m tower involves only a 10% increase in overall cost of the system, but it can result in ~30% more power and annually, this amount is substantial.

(a) Guyed Tilt-up Towers

Guyed towers (refer Figure 13.13) are economical, very strong when properly installed and are usually tilt-up and tilt-down type. The guy wires require space around the base of the tower so that they can be properly anchored. But then, the space does not become available for agriculture.

(b) Non-tilt-up Towers

Non-tilt-up self-supporting towers (refer Figure 13.14) are usually lattice type or tubular and are generally used for SWTs above 10 kW rating. These towers are usually erected by a winch or heavy vehicle and are usually not supported by guy wires. They are very strong but more expensive. This strategy leaves more space for agriculture.

(c) Hydraulic Tilt-up and Tilt-down Towers

Instead of guyed wire towers, with the advancements of hydraulics, hydraulically operated tilt-up free standing towers (see Figure 13.16) can also be designed, as this does away with the messy guy wires that get strewn all around the place, freeing the area for more agricultural farming. Moreover, with this type of tower, a single person can operate the hydraulic system to tilt up or tilt down the tower for the routine or breakdown maintenance of the WPP. When the total load of the SWT is known, a suitable hydraulic jack can be chosen.

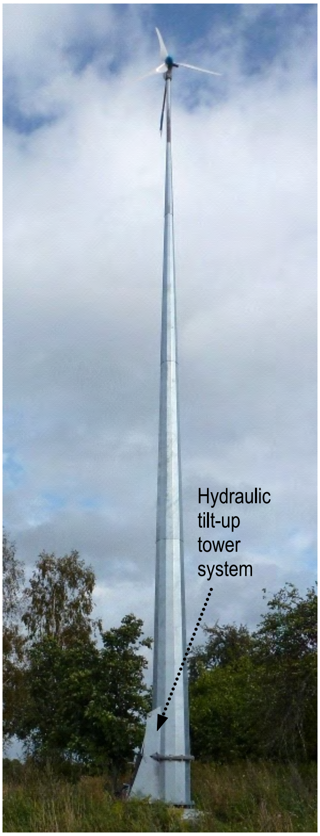


Figure 13.16 Hydraulic Tilt-up and Tilt-down System.
Courtesy: www.teroc.se

13.9 GEARED AND DIRECT-DRIVE HAWTs

Another way of classifying SWTs are as direct-drive and geared. In a direct-drive SWT (see Figure 13.17), the rotor is directly connected to an electric generator without a gearbox. The generator could be a DC generator or alternator or a multi-pole PMSG. The state-of-the-art transverse flux permanent magnet (TFPM) generators used by some manufacturers (such as Eocycle, Canada) help to reduce the mass and space for equivalent power and torque requirements as compared to the axial flux permanent magnet (AFPM) generators using or radial flux permanent magnet (RFPM) generators. The TFPM allows the creation of higher magnetic forces per unit volume, thus creating relatively higher electric power and higher permissible torque values at lower rotational speeds. But the aerodynamic control adapted here is stall control.

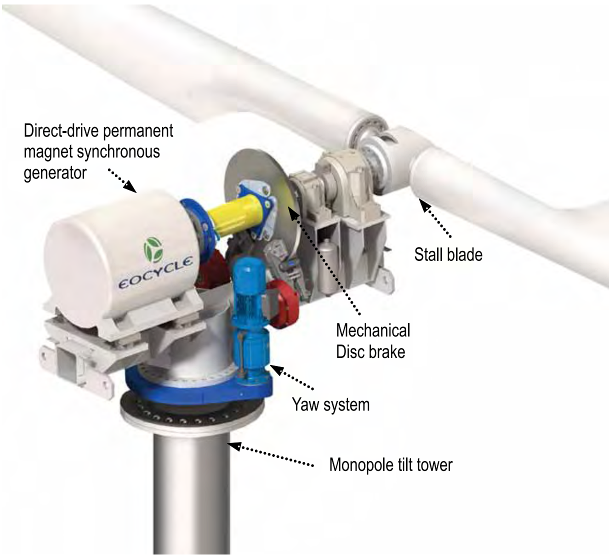


Figure 13.17 Upwind Direct-Drive SWT: This 25 kW stall regulated SWT is mounted with mechanical disc brake.
Courtesy: Eocycle Technologies Inc. (eocycle.com)

Geared SWTs (refer Figure 13.15) employ a gearbox between the turbine rotor and the electric generator to obtain a high speed to match the RPM of the generator which is generally a 4-pole or 6-pole squirrel cage induction generator. In some SWTs, a mechanical disc brake (refer Figure 13.17) is also incorporated to bring it to a stop completely as and when required.

13.10 SPEED REGULATION OF SWTs

There are different ways of regulating the speed of SWTs. It is based on what design the manufacturers adapt depending on the type of aerodynamic control and

electric generators chosen by them as well as other economic factors. Some of the SWT aerodynamic methods for speed regulation are discussed below:

(i) Twisting of blades
(ii) Furling
(iii) Stall regulation
(iv) Pitch regulation
(v) Mechanical braking (or disc braking)
(vi) Electrical braking
(vii) Combination of any of the above.

13.10.1 Twisting of Blades

Twisting of blades for speed regulation adapted by some very small SWTs can be considered as almost there is no control of the SWT. A few small SWTs use flexible plastic blades that are highly resistant to fatigue. When the wind speed goes beyond the rated speed of the SWT, these blades bend, twist and flutter, thereby spoiling the lift action and the SWT comes to a stop. Although this technique is effective, it is comparatively noisier, as the excess power in the wind is turned into noise and the fluttering noise is quite distinctive.

13.10.2 Furling

Furling (also called passive furling) is the most common method of high wind regulation method adopted in micro and mini SWTs for control, as it is a cost-effective method. *Cut-out speed* defines the speed at which the SWT is designed to be shut down to prevent damage to it. The wind speed is usually monitored by the SWT control system. At cut-out wind speed, SWTs do not have braking mechanisms, instead, as the wind speed increases, the furling mechanism operates.

When the wind speed goes high, the process of furling forces the SWT nacelle out of the wind direction to spoil the lift action and stop the rotor, reducing the SWT strain and power output. Furling works by decreasing the angle of attack in order to increase the induced drag to stop the rotor. In the stopped condition, a fully furled turbine rotor has either the leading or trailing edge of the blades facing towards the wind.

Furling is, however, not very reliable as the wind direction can suddenly change, hitting the rotor straight during high winds and decreasing the power production in high winds. One major problem in designing SWTs to stop the rotation in high winds is getting the blades to stall or furl quickly enough, should a gust of wind cause sudden acceleration.

SWTs with furling mechanisms generate power upto the survival wind speed which is around 50 m/s, while non-furling SWTs do not operate at wind speeds higher than the cut-out wind speed of 25 m/s.

All modern SWTs are generally equipped with autofurl mechanisms in high winds. *Autofurl* is an effective protection mechanism that has successfully worked in water pumping windmills for decades. There can be two types of auto-furling:

- Sideways horizontal autofurl
- Upward and backward vertical autofurl.

(a) Sideways Horizontal Autofurl

In the sideways horizontal furling SWT (see Figure 13.18), the rotor power speed is regulated by turning the SWT nacelle sideways. The strategy is to make the tail boom break away when enough turning force is present on the unit because of high winds. The SWT frame is designed with a built-in offset, and the tail vane is hinged both sideways and inwards.

Figure 13.18 Sideways Autofurl of SWT: Tail in break away position has made the SWT to stop. *Picture by author.*

When wind speed begins to go beyond the rated speed of the SWT which is near about 25 m/s, the strategy is so designed that the tail boom breaks away or folds up (refer Figure 13.18 and see Figure 13.19), yawing the machine at an angle to the wind. This also reduces the effective swept area and hence, the efficiency too. When wind speed drops below the rated speed due to gravity, the tail vane returns back into the normal position and tracks the wind straight head on and once again the turbine rotor starts spinning.

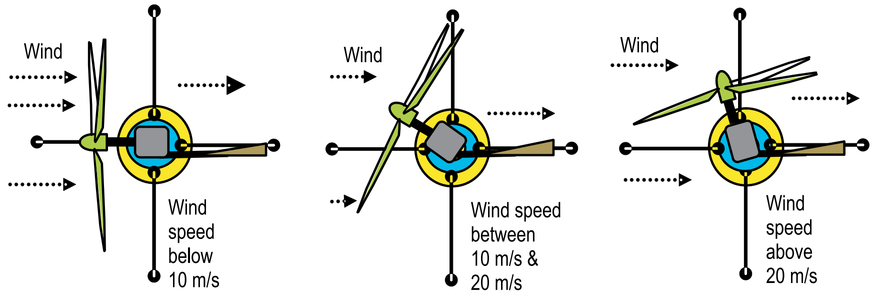


Figure 13.19 **Sideways Autofurl SWT (looking from top).**

(b) Upward and Backward Autofurl

In the upward and backward furling SWT (see Figure 13.20), the nacelle along with the generator rotor starts to turn upwards and backwards on a hinge as the wind speed increases. When the wind speed goes beyond 20 m/s, the nacelle and the rotor are almost perpendicular to the ground and the rotation is stopped (see Figure 13.21).

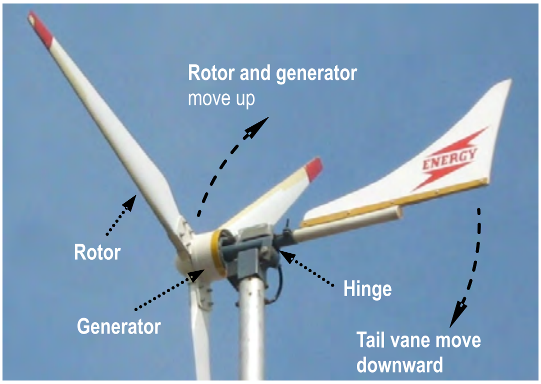


Figure 13.20 **Upward Furling SWT:** When the wind speed increases beyond the prescribed limits, this SWT turns upwards about the hinge.
Picture by author.

In the manual braking arrangement for these autofurling types of SWTs, a lever or winch at the base of the tower can be used to manually furl the turbine. This pulls the tail vane around 90° so that the edges of the rotor blades face the wind. Manual furling enables the output to be reduced, if necessary and also slows down the blades to enable the rotor to be stopped for servicing.

Some small SWTs of slightly higher ratings use hydraulic systems to control the furling. Generally, such SWTs are also additionally spring loaded so that if hydraulic power fails, the blades automatically furl out to stop the SWT.

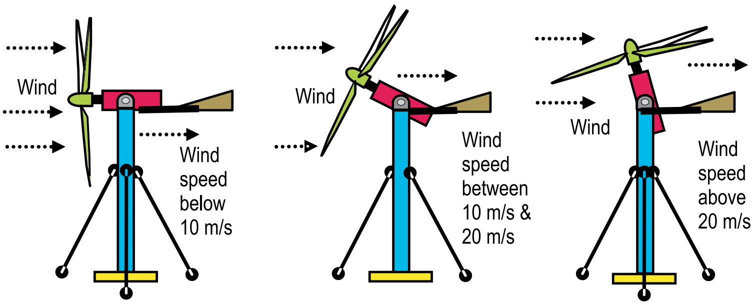


Figure 13.21 **Upward and Backward Autofurl of SWT (looking from the side).**

13.10.3 Passive Stall Regulation

Another method used to control excess power from SWTs during high winds is called *passive stall* (discussed in Chapter 5). Passive stall or simply called stall is a simple aerodynamic method of spoiling the lift force to stop the rotor and it does not have any additional requirements.

Such SWTs have the blades pitched at a fixed angle and work by increasing the angle of attack at which the relative wind strikes the blades and it reduces the induced drag (drag associated with lift). The passive stall keeps the rotor from overloading or overspeeding. This technique successfully used in large HAWTs is adapted (see Figure 13.22) in some SWTs as well.

Figure 13.22 **Stall Regulated SWT.**
Courtesy: www.aircon-international.com.

13.10.4 Passive Pitch Regulation

Changing the blade pitch is better to take the best advantage of varying wind speeds (discussed in Chapter 5). In a passive pitch regulated SWT each blade is turned automatically along its longitudinal axis by an appropriate angle depending on the wind speed as directed by the passive pitch control system. The SWT adapting the mechanical centrifugal pitch mechanism keeps track of the RPM and automatically keeps adjusting the blade pitch following wind rotor RPM to keep SWT at rated rotating speed to ensure steady voltage output and safe working. SWTs (below 50 kW) with variable pitching generally use systems operated by centrifugal force.

Some SWT manufacturers use the mechanical centrifugal pitch mechanism (see Figure 13.23). This is operated by centrifugal force by flyweights. Pitch angles and preloads of the SWTs are set in the factory. Final adjustments are reset in the field if the wind conditions dictate the need for individual site adjustment.

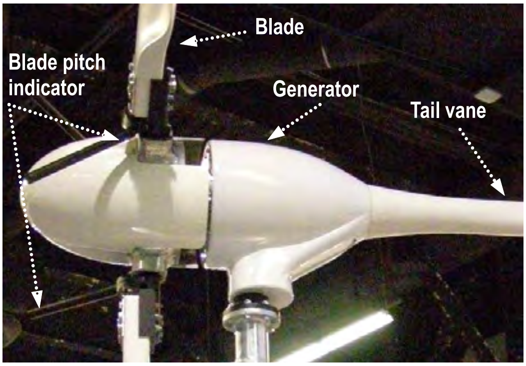


Figure 13.23 Passive Pitch Regulated SWT.
Picture by author.

These simple pitch regulation systems are not very popular, as there are fewer buyers of such machines due to the higher cost and the payback at small scales is not sufficiently enough due to relatively higher complexity and cost.

13.10.5 Electrical Braking

Electrical braking is generally employed only in very small capacity SWTs. This method of braking is achieved by shorting the alternator electrical phases. When the wind speed crosses the SWT rated wind speed or the generator's output power exceeds 125% of the rated power, electric braking is initiated by dumping excess energy from the electric generator into a resistor bank and converting the kinetic energy of the rotor rotation into heat.

This method is useful if the kinetic load on the generator is suddenly reduced or becomes too small to keep the SWT speed within the permissible limit. Cyclic braking causes the blades to slow down which increases the stalling effect and reduces the efficiency of the blades. The same braking system also serves as a parking brake.

13.10.6 Mechanical Braking

Mechanical braking or disc braking is quite common in large wind turbines after the aerodynamic braking has been operated. Some manufacturers of SWT (generally of more than 10 kW rating) have also adapted this strategy (refer Figure 13.17) in some of their models to brake the SWTs when required. But then, to increase the longevity of the brake pads, such brakes are usually applied only after the RPM has come down substantially by blade furling or electromagnetic braking in order to lower the torque force. Mechanical braking is of greater use for service personnel.

Table 13.2 provides a comparison of the features of HAWT and VAWT.

Table 13.2 HAWT versus VAWT Comparison

Sl.No.	Parameters	HAWT	VAWT
1	Orientation	Uni-directional	Omni-directional
2	Cut-in speed	2.5 m/s to 5 m/s	1.5 m/s to 3 m/s
3	Cable twist	Yes	No
4	Rotating speed (RPM)	High	Low
5	Noise level	5 dBA to 60 dBA	0 dBA to 10 dBA
6	Wind endurance	Weak	Good endures typhoon
7	Blade rotation space	Large	Small
8	Failure rate	High	Low
9	Gearbox	Yes, preferred above 10 kW	No
10	Power generation efficiency	50% to 60%	Above 70%
11	Electromagnetic interference	Yes	No
12	Effect on birds	More	Less

If all the SWTs are considered, the following could be a rough estimate of the aerodynamic power regulation methods used by different wind turbine manufacturers in the world:

- Twisting of blades or no control or (~14%)
- Sideways (or horizontal axis) furling (~10%)
- Tilt-up (or vertical axis) furling (~33%)
- Stall control (~8%)
- Passive centrifugal pitch control (~35%).

13.11 OFF-GRID AND ON-GRID SWTs

Another classification of small wind systems based on the application is given below:

- Off-grid (also called as stand-alone) SWTs
- On-grid (also called as grid connected, grid tied) SWTs. They are used in cottages, homes, farms or in businesses.

13.11.1 Off-grid SWT

Off-grid refers to a SWT operating without connection to the public electrical grid network. Stand-alone SWTs which operate without being connected to the national grid are also called *isolated grid systems*. Stand alone power systems (SAPS) are off-grid electricity generation systems which may include wind power, solar photovoltaics, microhydro turbines, battery bank and sometimes, a backup diesel generator. They are also commonly used at mountain tops, islands, single residential (see Figure 13.24), multi-residential, on boats or remote stations. SWTs can help in reducing the use of diesel generators, thereby saving fuel costs and reduce pollution.

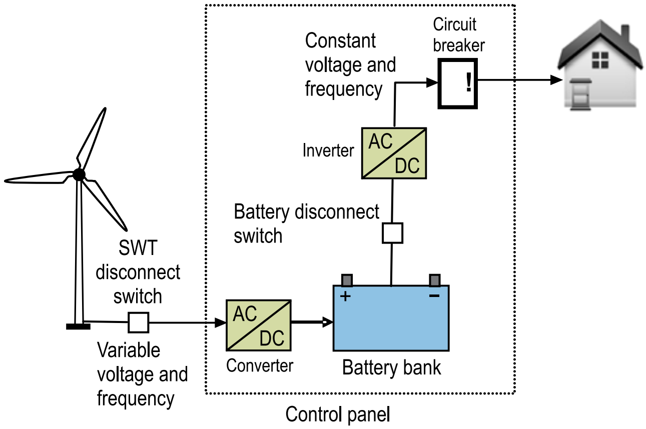


Figure 13.24 Off-grid Home SWT.

Since wind is usually a varying energy resource, off-grid systems are typically installed with some form of energy storage device (usually, a battery bank) that stores excess wind-generated electricity and supplies it to the load (e.g. homes) when there is insufficient wind.

If the SWT has a DC generator, it is used directly for battery charging. Alternatively, an inverter can convert DC power into AC power of the same quality as grid power. A battery bank can supply reserve power during calm spells. The advantage of such systems is that it is easy to set up. But the disadvantage is that the batteries are expensive and require regular maintenance.

13.11.2 On-grid SWT

For an on-grid (or grid tied) system (see Figure 13.25), the SWT can help in supplementing grid electric power and reducing dependency on the local electrical utility. SWTs above 30 kW commonly use SCIG that produce grid compatible AC electric power that can be connected to the grid directly without inverters. Such SWTs usually need to be connected to the grid in order to operate, since the SCIG

relies on the grid for field excitation and frequency synchronisation, as discussed in Chapter 7. However, grid connection requires careful planning to obtain approval for interconnection from the utility company.

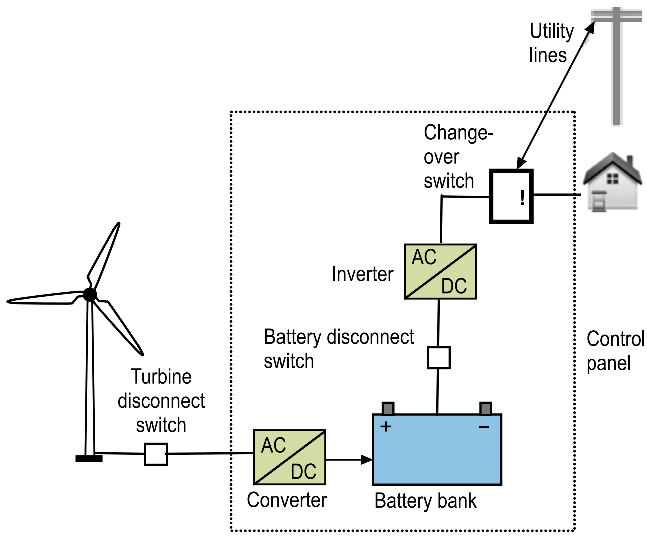


Figure 13.25 **On-grid Home SWT.**

13.12 HYBRID WIND ENERGY SYSTEMS

For remote locations, a hybrid system with both solar and wind power systems together, rather than a single energy source is advisable to avoid dry spells and outages. Households normally use microwind turbines that are smaller than 5 kW. Small communities or groups of houses might use up to 20 kW in size. Micro-generation is one form of distributed generation which refers to local electricity generation connected to local distribution networks rather than the national grid.

Hybrid systems can be stand-alone pole mounted (see Figure 13.26) or grid connected systems. This may be a hybrid system consisting of microwind turbines, solar panels, microhydro generation systems, diesel systems connected with (or without) a battery bank. The benefits of a hybrid system are manifold. During the summer months, when there is not much wind, there should be ample sunlight to be used and during the monsoon and winter months, it is usually windy and hence, wind power can be used. The required generating capacity of the basic solar and wind energy conversion units can also be reduced, since the total load is shared. Because of the supply diversity, the capacity of the battery can also most likely be reduced.

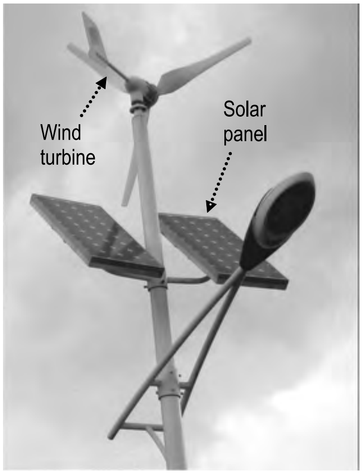


Figure 13.26 **SWT Hybrid System.**
Picture by author.

A small standby diesel (bioenergy) generating set to supply critical loads in case of an emergency is advisable. These systems are complementary. Table 13.3 depicts the typical specifications for a hybrid system.

Table 13.3 Typical SWT Hybrid System Specifications

S.No.	Item Name	Specifications
	WIND TURBINE	
1	Orientation	Upwind HAWT
2	Rated power at 11 m/s	900 W
3	Rotor diameter	3 m
4	Rotor swept area	7.07 m^2
5	Number of blades	3
6	Direction of rotation (looking downwind)	Clockwise
7	Blade material	Fibre glass
8	Overspeed protection	Passive pitch control
9	Generator type	Permanent magnet (direct-drive)
10	Cut-in wind speed	2.5 m/s
11	Cut-out wind speed	N/A
12	Yaw control	Passive by tail vane
13	SWT class (according to IEC 61400–2)	II
14	Tower top mass	75 kg
15	Protection index	IP55
16	Operating temperature range	–40°C to +45°C
17	Tower/mast	Different types available

S.No.	Item Name	Specifications
WIND TURBINE INVERTER		
18	Type	Grid following
19	Output power form	230 V AC, 50 Hz nominal
20	Power factor	1
21	Max efficiency	92%
22	European standard efficiency	90.4%
23	Self consumption	< 4 W in operation, 0.1 W in standby
24	Harmonic distortion of output current	< 4%
25	Protection index	IP65
26	Operating temperature range	–25°C to +60°C
27	Relative humidity range	0% to 100%
28	Maximum operating altitude above sea level	2000 m
29	Islanding detection	Yes
30	Country-specific parameter settings	Sweden
INDOOR SYSTEM MODULE—EXTERNAL CONNECTIONS		
31	AC input	CEE 216–6 inlet or terminals for incoming grid or genset power
32	Wind turbine input	Terminals
33	Solar PV input	MC4-connectors for PV array
34	AC output	CEE 216–6 outlet and Schuko sockets
35	Grounding	Mandatory (by grounding rod)
36	Ethernet	10/100 BaseT, 8P8C (RJ45) connector
INDOOR SYSTEM MODULE—GENERAL		
37	Battery bank type	VRLA deep cycle (1200 cycles according to IEC 896–2)
38	Battery bank voltage	24 V nominal
39	Battery bank capacity	400 Ah nominal (C_{100})
40	AC input voltage range	190 to 265* V AC
41	AC input frequency	45 to 65 Hz
42	AC input current maximum (transfer relay)/ Output current maximum	50 A/56 A
43	Protection index	IP10
44	Operating temperature range	–20°C to +55°C
45	Operating relative humidity range	10% to 90%
46	Battery under voltage protection	Automatic stop of inverter with automatic restart
INDOOR SYSTEM MODULE—INVERTER AC OUTPUT		
47	Type	Grid forming
48	Output voltage	Pure sine wave 230 Vac (+/–2%)*

(*Contd.*)

S.No.	Item Name	Specifications
49	Output frequency	50 Hz or 60 Hz nominal*
50	Maximum apparent power, continuous at 25°C	2000 VA
51	Maximum apparent power, 30 min at 25°C	2400 VA
52	Maximum apparent power, 5 s at 25°C	6 kVA
53	Maximum load	Up to short-circuit
54	Load detection (stand-by limit)	2 W to 25* W
55	Power factor	0.1 to 1
56	Maximum efficiency	94%
57	Self-consumption off/Standby on	1.4 W/1.6 W/9 W
58	Harmonic distortion	< 2 %
59	Overload and short-circuit protection	Automatic disconnection with automatic three-time restart attempt
60	Overheat protection	Warning before shut-down with automatic restart
INDOOR SYSTEM MODULE—PV INPUT		
61	Solar input voltage range	28 to 120 V
62	Maximum solar input current	60 A (restricted to 48 A by NEC, where applicable)
63	Maximum solar input power	1600 W
64	Charge regulator self consumption	1.3 W to 2.7 W

* = adjustable
Courtesy: www.teroc.se

Modern hybrids and SWTs come with electronic modems and real time datalogging systems which are useful for the owners, as they can comfortably monitor how their SWT and solar PV are working from their homes on their computers/cell phones. They can also measure the amount of energy they use, e.g. at the home. For example, in the screendump (see Figure 13.27), it can be observed how the hybrid system has worked. It can be observed that the temperature was very low and almost there was no wind for some days. However, it was sunny and the solar PV array charged the battery which raised the voltage in the middle of the later three days.

13.13 HYBRID WIND DIESEL SYSTEMS

Hybrid wind-diesel systems reduce reliance on diesel fuel. The successful integration of wind energy with diesel generating sets relies on complex controls to ensure correct sharing of varying wind energy and controllable diesel generation to meet the demand of the usually variable load especially on islands and remote locations with no power grid.

A wind-diesel hybrid power system (see Figure 13.28) consists of diesel generators and SWTs and may be some ancillary equipment such as PECs and batteries. They

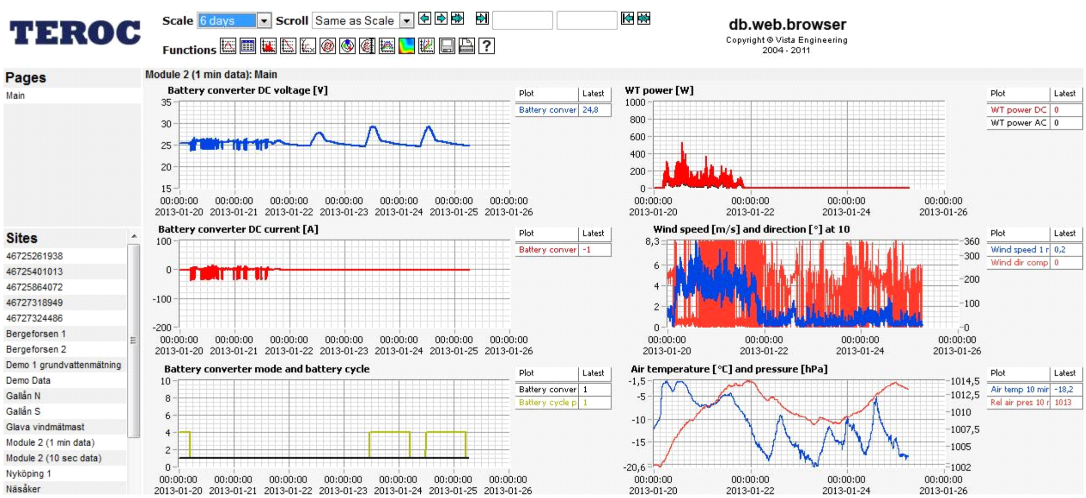


Figure 13.27 **Hybrid Energy:** The real time energy production of hybrid energy systems can also be monitored from the home computer systems as this screendump.
Courtesy: www.teroc.se

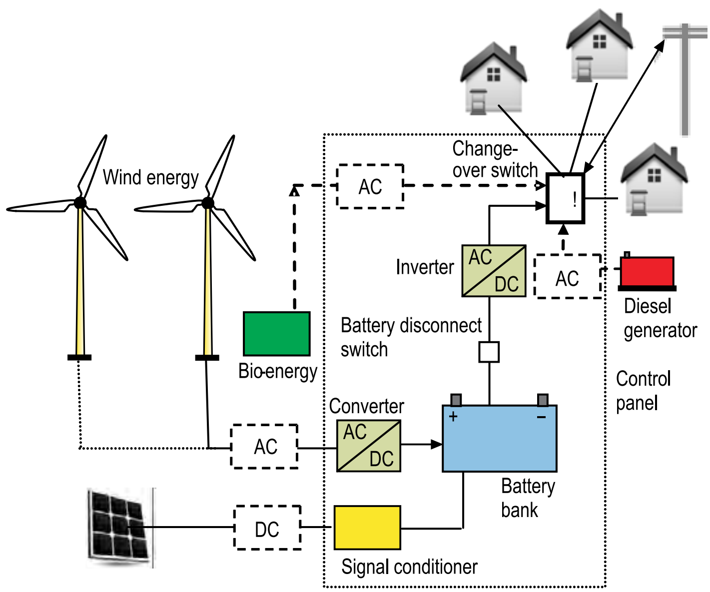


Figure 13.28 **Hybrid Wind Diesel System.**

are designed to increase the capacity of the power produced and reduce the cost as well as the environmental impact of electrical generation in remote communities and facilities that are not linked to an electric grid.

Wind penetration levels also decide the manner in which a hybrid system is to be integrated onto the grid system. A grid network is considered to be of *high penetration*

with small hybrid system when the amount of wind produced at any one time versus the total amount of energy produced is over 100%. The grid is called *low penetration* when the energy being produced from wind is less than 50% peak instantaneous penetration and it is called *medium penetration* when it is between 50% to 100%. Low and medium penetration systems are considered as mature for connecting wind diesel systems. High penetration systems, however, still have many problems especially when installed with the capacity to operate in a diesel-off mode.

13.14 CONSUMER LABELLING

With such a large variety of SWTs available in the market, to take an informed decision about the choice of the most suitable SWT becomes difficult for the common man. In a such a situation, it is advisable to buy a consumer labelled (third party certified) SWT which helps in getting bank loans and insurance. Smaller is the SWT, the higher will be the cost/generated kilowatt hours. Nevertheless, SWTs can have a shorter payback time than large grid connected large wind turbines when SWTs are used to reduce consumption of fuel (e.g. in hybrid power systems).

In recent years, there has been a movement to improve the reliability of SWTs. On a national level, American Wind Energy Association (AWEA) and British Wind Energy Association (BWEA) have produced safety and performance standards for SWTs. USA and UK have also established frameworks for certification of SWTs through the Small Wind Certification Council (SWCC) and Micro-generation Certification Scheme (MCS) respectively.

To help the consumers in selecting the relevant SWT, a method for *consumer labelling* has been developed under the wings of International Energy Agency (IEA) and International Electrotechnical Commission (IEC). This labelling method is a benefit to professional buyers of SWTs and should spur the industry to develop better products.

13.15 CHOICE OF SWT

The quality of each SWT topology varies. From among the various SWT topologies, the right choice of SWT is crucial to get the maximum energy at a particular wind site. They may not perform as per the specifications. The quality of SWTs varies very much. Some types of SWTs lack the formal documentation which is often necessary but are sold illegally, e.g. in China and Europe. Therefore, going for certified SWTs is always advisable. Such a decision also helps in securing bank loans and insurances.

The first step in setting up a SWT is to identify the most appropriate location where sufficient wind is available.

The next step is the choice of the SWT technology to be adapted. Although the SWT rating is a useful guide, at the actual site, the power produced is lesser, as the SWT is not exposed to the envisaged ideal conditions at all times. Generally, on an average, it produces 10% to 40% of their rated capacity every hour over the year.

A SWT produces the rated power only at the rated wind speed (usually somewhere between 10 m/s to 13 m/s) as stated in the manufacturer's specifications. Therefore, the rated wind speed and the output power are relative values that only give an indication of the wind speeds required for the SWT to produce large amounts of power. Further, the efficiency (power coefficient) in converting the wind into useful energy is usually lower than large wind turbine.

If the SWT has a rated wind speed which is much higher than the typical wind speed for the site, it is probably not a good choice of the SWT, as there is a little time when the SWT produces full rated power. Hence, the SWT has to be chosen so that its rated speed should match with the annual average wind speed at that location. This ensures that the generator more or less produces the rated power most of the times.

To work out how much electricity a SWT will generate on an average day, the rated capacity is multiplied by 24 hours and then it is again multiplied by the capacity factor ranging from 10% to 40%. For example, a 2 kW wind turbine might generate between 4.8 kWh and 19.2 kWh a day (i.e., 2 × 24 h × 10% = 4.8 kWh/day or 2 × 24 h × 40% = 19.2 kWh/day) on an average. The average household may use 8 kWh of electricity in a day per person. Based on this, an average family of four would need about 13 kW worth of installed wind capacity.

EXAMPLE 13.1

For a SWT with a rotor diameter of 1.75 m at a wind speed of 10 m/s, power coefficient of 0.35 and a generator efficiency of 95%, determine its output.

Solution:

$$\text{Output} = 0.5\ \rho A v^3\ C_p\, \eta_{el}$$

$$\text{Output} = 0.5 \times 1.225[3.14 \times (2.4/2)^2] \times 10^3 \times 0.35 \times 0.95 = 921\ \text{W}$$

Annual output = Output at average wind speed × 1.9 (Wind speed variation function) × 8766 (Hours in the year)

$$\text{Annual Output} = 921 \times 1.9 \times 8766 = 15339623\ \text{Wh}$$

$$= 15339.623\ \text{kWh per annum (as claimed by manufacturer)}$$

But actually, at a site, the average wind speed is around 5 m/s in which the same SWT will give

$$\text{Output} = 0.5 \times 1.225[3.14 \times (2.4/2)^2] \times 5^3 \times 0.35 \times 0.95 = 115\ \text{Wh}$$

$$\text{Annual output} = 115 \times 1.9 \times 8766 = 1915371\ \text{Wh} = 1915.371\ \text{kWh}$$

This is one way in which the manufacturer's claim can be judged and the economics of investing in the SWT worked out.

EXAMPLE 13.2

If a manufacturer of 2.4 m diameter SWT claims a rating of 1.5 kW for a wind speed of 12 m/s, determine the assumed efficiency.

Solution:

The assumed efficiency is

$$C_p = \frac{\text{Output}}{0.5 \times \rho A v^3 \eta}$$

$$= \frac{1500}{0.5 \times 1.225 \times 3.14 \times (1.2)^2 (12)^3 \times 0.95}$$

$$C_p = 32.99\%$$

One needs to rightly interpret the specifications for selecting an optimal SWT. When sizing a SWT, swept area of the rotor is the most important parameter to be considered first, as it is the swept area (refer Figure 13.11) that determines the energy capture of the SWT. Power is directly proportional to the swept area of the rotor in which the rotor blades spin. Theoretically, if the diameter of the rotor is doubled, swept area quadruples and so does the power produced too. Increasing swept area means the height and strength of the tower must be built to sustain higher wind loads for the longer swing of the blades.

Maximum practical efficiency of a SWT is around 35%. Most SWTs work at efficiencies between 22% and 31% at 10 m/s and between 17% and 26% at a speed of 12 m/s.

The SWT's power performance characteristics are determined by the measured power curve (see Figure 13.29) and the estimated annual energy production (AEP) which is generally given by the manufacturer. A power curve is not universally valid. It depends on turbulence, atmospheric pressure and ambient temperature at the measuring location. A power curve is usually corrected to sea level and 20°C ambient temperature. The SWT power curves can be calculated either based on the design of the turbine or measured from actual turbine operation. For small permanent magnet generators, it is especially important to get a measured power curve from the manufacturer, since this curve can be different from the calculated version.

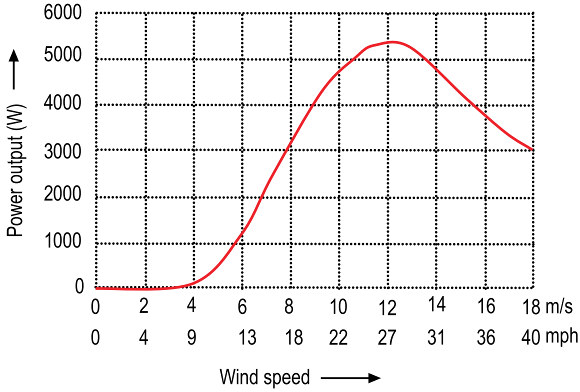


Figure 13.29 Power Curve of a Typical SWT.

Some manufacturers also provide the annual production curve (see Figure 13.30) which helps very much in arriving at the payback period of the SWT project. One way to check the manufacturer's claim is to insert the manufacturer's output rating for a given wind speed into the output equation and calculate the assumed efficiency. Some other factors such as rotor mass, type of bearings, blade aerodynamics and the electrical generator efficiency may also affect the power output when scaling up a design.

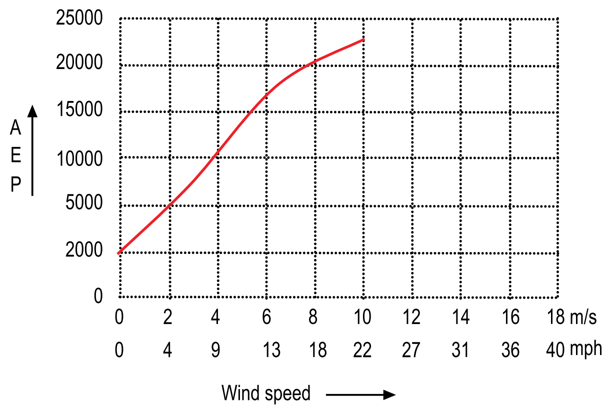


Figure 13.30 Annual Energy Production (AEP) Curve of a Typical 5 kW SWT.

When selecting a SWT, the following safety functions should also be checked for their availability:

(i) Emergency shutdown operation (as SWT shuts down at normal and high wind speeds)
(ii) Speed and power control (as SWT has the capability to control the RPM and power output)
(iii) Overspeed protection
(iv) Start-up and shutdown functions at the rated speed
(v) Excessive vibration protection mechanism
(vi) Battery overvoltage and undervoltage protection mechanism (in case of battery bank)
(vii) Cable twist safety mechanism provided due to yawing
(viii) Anti-islanding protective measures provided for grid tied systems.

EXAMPLE 13.3

Suppose an average power of 1500 kWh per month is consumed and cost per kilowatt hour is ₹ 5. Wind maps, backed-up with actual measurements show that the average 24 × 7 wind speed is 8 m/s. With tax credits, a 5 kW small wind turbine when fully installed will cost ₹ 500000. Determine the expected savings and the number of years that will be taken to recover the investment.

Solution:
The first step is to locate the power curve for the SWT given in the technical specifications. It can be seen in the power curve (see Figure 13.31) that the maximum rated output occurs when the wind blows at 12 m/s. To find the expected output, follow the horizontal axis of the graph back to the measured 8 m/s and note the corresponding output on the dashed line which happens to be 3200 W. Over a period of time, the SWT can be expected that to produce 3200 W/h or about 12.5 kWh/day, since the wind speed is based upon a 24 × 7 average.

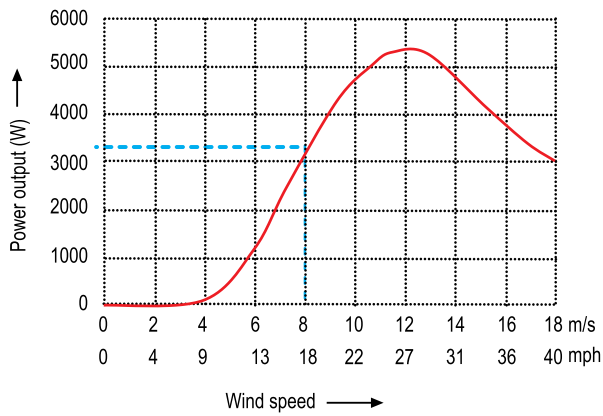


Figure 13.31 Power Curve of a 5 kW SWT.

Looking at a typical electric bill averaged 1500 kWh/month or 50 kWh/day, a 25% reduction can be expected in cost if wind generation delivers 12.5 kWh per day. Using 12% per kilowatt rate for this example, monthly savings would amount to ₹ 5400. Dividing the net project cost of ₹ 5,00,000 by the monthly savings shows that it will take 9.26 years to recover the investment.

Although it takes a little longer time to recover the investment, this example evaluates the project from an economic standpoint. Since an independent source of emergency backup power is available or lowering carbon emissions are also considered important, it will help to take a final decision on the viability of this small wind power project.

13.15.1 Choice of SWT Tower

The least expensive tower for a SWT is the guyed monopole tower. Guyed lattice tower is the next cheapest one, such that are used by cell phone towers. Self-supporting towers, either lattice or tubular in construction, take up lesser space and are more attractive but they are also relatively more expensive. Towers, particularly guyed towers, can be hinged at their base and suitably equipped to allow them to be tilted up or down using a winch, vehicle or hydraulic mechanism. This allows all maintenance and service work of the nacelle to be done at ground level. Towers

are usually offered by SWT manufacturers and purchasing one from them is the best way to ensure proper compatibility and safety. Aluminum towers should be avoided because they are prone to developing cracks.

13.15.2 Choice of the Hybrid Wind System Battery

Since the wind power comes in gusts and spurts, having an appropriately rated battery will help to make more effective use of the wind's varying nature. The choice of the wind system battery depends on whether it is grid tied or it is in the micro-generation mode and following simple rules can be followed:

- Buy the right kind of battery
- Buy enough of the right kind of battery
- Treat the batteries safely and wisely.

Individual batteries are usually rated only between 2 V and 12 V and need to be arranged in an array to give the required voltage and current. If the battery bank is too small, it may be discharged at a low level too often which shortens its life. Typically, battery banks for wind-solar hybrid systems are to be sized for several days storage depending on the total electricity requirement and generating capacity of the system. If the battery bank is too large, it costs more and it may not be fully charged regularly which can also shorten the battery life.

The size of the battery is determined by the longest period of windless weather. Since this may be very difficult to determine in advance, a deep cycle battery (discussed in Chapter 1) bank would be better choice. The backup may vary from 7 to 14 days or more and is relatively maintenance free.

A deep cycle battery is designed to discharge between 50% and 80% depending on the construction and operational manual. Although these batteries can be cycled down to 20% charge, the best lifespan versus cost method is to keep the average cycle at about 50% discharge, as there is a direct correlation between the depth of the discharge and the number of charge and discharge cycles the battery can perform.

Batteries are normally rated at a temperature of 20°C. Ambient temperature can have a drastic effect on the battery life. Although valve regulated lead acid (VRLA) batteries are not of the deep cycle type, being cost-effective, they are still commonly used. They are of the gel type specified to be capable of 1200 cycles according to IEC 896–2 (where discharge conditions are equivalent to a depth of discharge of 60% of C_{10}, (which is the 10-hour capacity of the battery).

13.16 SWT SITING

A small increase in wind speed leads to a large increase in energy output, as the energy available in the wind is proportional to the cube of the wind speed. Therefore, site selection is quite important even for SWTs. If wind maps or local data are not available, then one of the best ways is to look around and observe the deformation

of vegetation and trees. The Griggs–Puttnam index (see Figure 13.32) looks at wind deformed vegetation to get a first level information of the wind resource potential at a particular wind site.

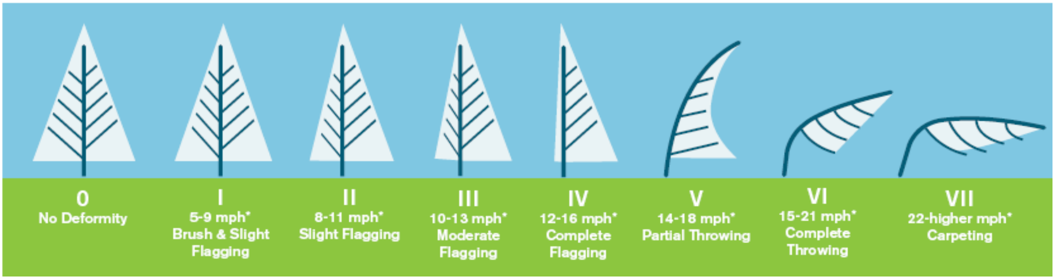


Figure 13.32 The Griggs–Puttnam Index: The Griggs–Puttnam Index is a scale to assess wind speeds at 10 m above the ground level from deformation of vegetation (10 mph = 4.5 m/s, 20 mph = 9 m/s).

The trees' shape (especially conifers or evergreens) is often influenced by winds. Strong winds can permanently deform the trees. This deformity in trees is known as *flagging*. Flagging is usually more pronounced for single, isolated trees with some height. Although, this is not a very reliable method, but it gives an indication of good wind power sites. A site can however also have very good wind resources without any deformed vegetation.

Turbulence reduces performance and the SWT has to work harder than in case of smooth air. Obstacles cause turbulence to the laminar flow of the wind and reduce efficiency of a SWT. Turbulence is highest close to the ground and reduces with greater heights. Hence, the height of the obstacle and the distance between the obstacle and the SWT is quite important to avoid the *shelter effect*. If the distance of the SWT increases from the obstacle, the shelter effect decreases similar to the smoke plume getting diluted when it moves away from a smokestack. If the SWT is closer to the obstacle than 5 times the obstacle height, the results are more uncertain because then it depends on the exact geometry of the obstacle.

The roughness of the terrain has also an important influence on how much the shelter effect is felt. In terrains with very low roughness (e.g. water surfaces), the effect of obstacles (e.g. tall buildings) may be measurable upto 20 km away from the obstacle. SWTs typically go on shorter towers than larger WPPs. It is not recommended to mount SWTs on small buildings where people live because of the inherent problems of turbulence, noise and vibration.

Wind speed increases with height above the ground. By rule of thumb it can be said that the wind power increases 12% each time when the height is doubled. Therefore, mounting a SWT on hills, tall buildings and towers increases the amount of wind energy available (see Figure 13.33). The rule of thumb for siting is that the SWT must be located at least 10 m above any obstacle within 100 m, or a SWT must be installed on a tower such that it is at least about 6 m above any obstacle

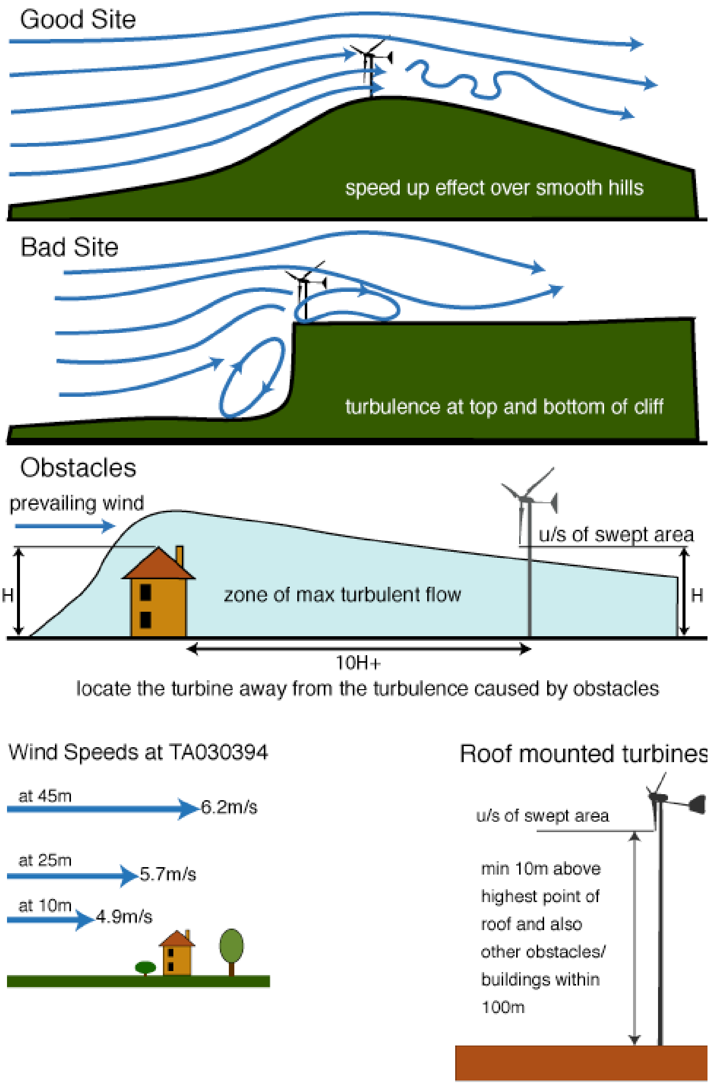


Figure 13.33 Siting of Small Wind Turbines.
Courtesy: www.greenspec.co.uk/small-wind-turbines.php

within 75 m. But if the hill is steep or has an uneven surface, turbulence in the wind may negate the advantage of higher wind speeds.

The power available from a typical SWT at 30 m can be upto 100% higher than the power available at 10 m. Therefore, rather than going for two SWTs on two 10 m towers, one large SWT producing as much power as two SWTs on a 30 m tower is preferred. For example, a 1 kW SWT is often, installed on a 10 m to 15 m tower, while a 10 kW turbine usually needs a tower of 20 m to 30 m.

13.17 MAINTENANCE ISSUES

Like other machines, maintenance is also required for SWTs. Preventive maintenance is usually done once in every 3 to 4 months and a comprehensive maintenance is required once in a year. Generally, 10 years after a SWT is installed, the blades or bearings may have to be replaced. But with proper installation and maintenance, the SWT lasts upto their technical lifetime of 20 years or longer. Typical annual maintenance includes checking of:

- Tightening of bolts and electrical connections
- Replacing corroded components
- Replacing of worn out edge tape on the leading edges of the blades, if required
- Tightening of guy (stay) wires for proper tension, if necessary
- Battery bank connections
- Inverter connections.

13.18 HEALTH OBJECTIONS TO SWT

Some view SWTs as a great way to produce clean energy but some view that wind turbines affect the health considerably. SWTs do make some noise, but not enough to be found objectionable by most people. A typical residential wind system makes less noise than the average washing machine. The noise level is audible if one is out of doors and listening for it, but not noisier than the average refrigerator. Most of the sound that emanates from SWT is the aerodynamic noise caused by the blades passing through the air. Most SWTs are direct-drive machines with fewer moving parts. Unlike large wind turbines, they do not have high speed transmission drive trains.

Infrasound from SWT is another such sound generally inaudible to the human ear. WHO states that there is no reliable evidence that sounds below the hearing threshold to produce physiological or psychological effects. There is no published scientific evidence to support such adverse effects of SWTs which results in anxiety, hearing loss and interference with sleep, speech and learning, as well as other health related issues.

Shadow flicker is the flicking on and off of the shadow of the rotating blades. This is not much of an issue in the tropical regions. Even if it is there for SWTs, it is almost negligible and that too only for a brief period which is not considered as irritating.

Blade glint happens when sunlight reflected from the surface of the SWT blades reaches the eye. Since all major SWT manufacturers coat their blades with a low reflectivity material, this reflection is almost absent.

It has been found that SWTs do not create electromagnetic interference (EMI). In fact, most SWTs use blades made of fibre glass or composite materials that do not cause TV reception problems and similar problems.

13.19 SWT INDUSTRY CHALLENGES

Presently, there are 33 countries in which SWTs of less than 30 kW are being manufactured. But more countries can join the bandwagon. SWT industry has not grown at the pace of LWTs. Following are some of the barriers which stand in the way for the growth of the SWT industry:

- Lack of effective standards and designs (Currently, NIWE Chennai has also started the labelling and certification of SWTs).
- Lack of awareness of the potential of SWT and its applications. (MNRE provides some incentives for SWTs as well).
- Lack of substantial and convenient financial assistance from banks for SWTs.

The main drivers for the growth of the SWT sector are as follows:

- Individual homes to own SWTs, especially in windy regions.
- Initiate policies so that there will be shorter payback periods.
- Seminars and workshops at state and regional levels to educate the community for the use of wind power.

SUMMARY

It has been seen that the small wind turbines have some features distinctive of their own as compared to large wind turbines. There are also considerable technological differences among the different types of SWTs. It has also been seen that VAWTs and HAWTs are equally performing well in the SWT sector as they find special applications in the industry, urban, semi-urban areas as well as in the villages and islands.

EXERCISES

13.1 Justify the need of small wind turbines.

13.2 Compare the three main classifications of SWTs based on the swept area.

13.3 Compare the main features of small HAWTS and VAWTS.

13.4 Distinguish between drag and lift-based SWTs.

13.5 Compare the construction and performance of Darrieus rotor and H-rotor VAWTs.

13.6 Explain the working of the drag and lift combined blade design VAWT.

13.7 Describe the features of integrated Savonius and Darrieus rotor design.

13.8 Analyse the features of direct-drive HAWTs.

13.9 Explain the reason for the use of permanent magnet generators in HAWTs.

13.10 Describe the role of gearbox in SWTs.

13.11 Compare the features of different types of towers used for SWTs.

13.12 Compare the five types of speed regulation methods for SWTs.

13.13 Explain why blade twist is not preferred as a control mechanism in larger rating SWTs.

13.14 Compare the features of the two types of autofurling in SWTs.

13.15 Stall regulation is the simplest of all the speed regulations methods. Comment in about 500 words.

13.16 Pitch regulation in not very popular in SWTs. Comment in about 300 words.

13.17 Describe the features of mechanical and electrical braking of SWTs.

13.18 With an appropriate sketch, explain the working of (i) an off-grid SWT and (ii) a grid-tied SWT.

13.19 For a SWT with a rotor diameter 3 m at a wind speed of 9 m/s with a power coefficient of 0.33 and a generator efficiency of 95%, determine the output.

13.20 Describe the criteria to locate the best site for a SWT in an urban or semi-urban area.

13.21 Justify the need for consumer labelling of SWTs.

13.22 Develop the broad specifications for a SWT.

13.23 Some people say that SWTs affect the health. Comment in about 400 words.

13.24 For a SWT with a rotor diameter of 12.5 m at a wind speed of 9 m/s, power coefficient of 0.36 and a generator efficiency of 95%, determine its output.

13.25 Comment on the three main drivers for the growth of the SWT sector.

14

Wind Project Life Cycle

After this, I saw four angels standing at the four corners of the earth, holding back the four winds of the earth.
—Revelation 7:1

Learning Outcome

On studying this chapter, you will able to describe the salient aspects with respect to a typical wind project cycle.

CHAPTER HIGHLIGHTS

14.1 INTRODUCTION

With increased emphasis of renewable energy projects around the world to tide over the fossil fuel crises, newer and larger capacity grid compatible WPPs are being designed and produced. Added to this, larger capacity onshore and offshore wind farm projects are being launched and operated and hence project life cycle is being looked with more seriousness. Further, specialisation into wind project cycle is gaining momentum because of the increased investment, safety standards, reliability and other factors. Wind project life cycle which is applicable to both large and small wind power projects is gaining more importance with more awareness of its benefits and also because of greater wind power penetration as regards grid connected large WPPs in various regions around the world. Issues related to wind project life cycle such as technical lifetime and repowering are also discussed briefly in this chapter. However, for more details, the reader may refer to the author's earlier book on *Wind Power Plants and Project Development* by the same publisher.

14.2 WIND PROJECT LIFE CYCLE

To better understand the potential effects of a wind farm, it is important to understand the components of the day-to-day work and general stages in the life of a utility scale wind power project. A wind farm has a lifespan of 20–30 years that starts with development and goes through construction, operation and ends with decommissioning or occasionally repowering, i.e., replacing old WPPs with newer ones. The wind project life cycle consists of several key phases (see Figure 14.1) that are discussed in the following sections:

- Site feasibility study
- Permissions and procurement
- Installation and commissioning
- WPP operation.

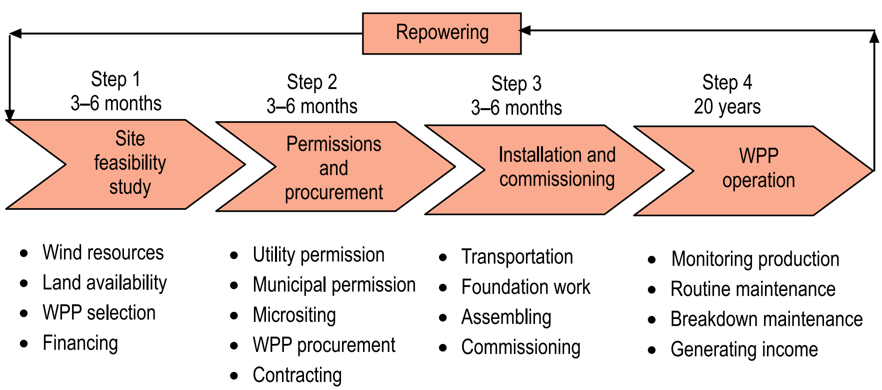


Figure 14.1 Wind Project Life Cycle.

Irrespective of the land size, geographic location or proximity to electricity demand, wind farms are constrained on the wind that blows through the proposed wind farm. Therefore, the wind project cycle is a dynamic process guided by the collection and modelling of the wind data on site. This essentially requires an interdisciplinary team comprising of technical experts from the following fields for the wind project:

- Civil engineering
- Mechanical engineering
- Transportation engineering
- Electrical engineering
- Meteorological modellers and wind assessment technicians
- Biologists
- Permitting specialists
- Wetland scientists
- Geologists
- Archaeologists
- GIS technicians
- Financial analysts
- Attorneys
- Environmental planners
- Telecommunication and radar technicians
- Surveyors.

14.2.1 Site Feasibility Study

During the feasibility study, a wind project developer has to critically examine the wind resources for the site under consideration. It includes examining the wind rose, frequency distribution and other matters required for project development (discussed in Chapter 2 in the earlier book). If the output of this scrutiny turns out to be uneconomical, it is better to end the project at an early stage and find a better site. Access to the project site is crucial to install and operate WPP, so an agreement with the land owner(s) should be made at an early stage.

Before acquiring the windy site, the local zoning laws for the WPP project are to be examined. Investigating zoning laws early in the development of the wind project can help in avoiding unnecessary delays. If the zoning in the area does not allow high towers, it should be checked whether the special permits are possible or not. If this is clear, the land can be leased out or bought.

Selecting a WPP is a crucial decision which decides the success of a wind power project. This is an informed decision to arrive at the most appropriate WPP and is to be taken in consultation with experts based on the wind assessment data.

WPPs have a high investment cost but very low operational cost, since the wind used as fuel is free. In the project development process, the various purchases have to be financed. For different financing options, determination of the income from probable production, calculation of the cost of energy (COE) and the analysis of the economics should be done.

The income depends on the annual energy output and a number of different factors affect it. These are given below:

- Wind farm layout and associated losses
- Site dependent factors, such as annual average wind speed
- Conceptual design features, i.e., whether the design is pitch or stall regulated
- Geometric characteristics, such as the rotor diameter or hub height.

$$\text{Cost of energy} = \frac{(\text{Initial capital cost} \times \text{Fixed charge rate}) + \text{Soft costs}}{\text{Gross annual energy production}}$$

Although the wind farm layout and the collection system can impact the energy yield at the point of grid connection, it generally does not impact the yield of an individual turbine measured prior to the transformer. Tower height is an important parameter in efficient use of the wind resource. The cost effectiveness of a tower is influenced by many factors including top head mass (THM) and the loads from the rotor during both operation and survival conditions.

14.2.2 Permissions and Procurement

Utility permission is one other key factor to be considered in taking up wind power projects. In early years of wind power development, connecting the WPP to the grid was not a big issue, because the wind power penetration was low, the grid was sufficiently strong to accept the first generation relatively small capacity WPPs. But with greater capacity WPPs and larger wind power projects, the scenario has changed. With higher wind power penetration levels, the grid operators want WPPs that will more or less behave like the conventional power plants having sufficient FRT capabilities to maintain the power system stability in order to avoid brownouts and blackouts in the region.

There are several other factors to be considered, i.e., the amount of power that can be connected to the grid, specification about minimum annual production, maximum investment costs and demands on economic return from the investors/owners. Power purchase agreement (PPA) must also be negotiated.

The wind power project should not only give the best possible returns on the investment made, but also has to be compatible with the legitimate regulations of government authorities so that necessary municipal related permissions are obtained. The impact on neighbours and environment has to be checked. In fact, the developer has to choose the best option.

Micrositing is to find the best available site. The exact spots where the WPPs will be installed have to be identified in the feasibility study. Wind resource assessment must be undertaken for at least about a year and half to arrive at various finer decisions. WPPs of different sizes (height and rotor diameter) and nominal power should be analysed (theoretically) at different sites within the area, even using computer simulations (discussed in Chapter 11).

When all necessary permissions are obtained WPP procurement is to be taken up. A review of technical specifications of WPPs should be undertaken to determine the most appropriate technology and model that would be most suitable in terms

of capacity, size, price and availability. A tender enquiry document (TED) should include basic information about the project time plan, planning status, financial, technical and operational information, contractual issues, scope of supply, technical specifications, maintenance and repair conditions as well as agreements for warranty and insurance. Then, tenders should be called from several different suppliers. The different tenders have to be evaluated to find the one that is most favourable. The supplier's record, ability to offer good service and maintenance and other factors should also be considered. It is not always the supplier that offers the lowest price.

Contracts have also to be signed with landowners, grid operator and a power company, utility or a third party that will buy the power. Contracts for credits from banks and other financial institutions should be signed as well. Contracts for other equipment such as transformers, electrical switchgear have to be signed. Local entrepreneurs to create local employment can be encouraged to build access roads, cable ditches, foundations and other tasks which realise the project successfully. Since all of these works have to be coordinated, a detailed timeline has to be worked out for all these contracts.

The time from placing an order for the WPP and to its delivery to the site can vary from three months to a year. In the meantime, the access roads, foundations and substation as well as the electrical infrastructure can be built. Existing roads will be used to the fullest extent possible so as to avoid unnecessary impacts. Each WPP will need a road built upto the base of the WPP. Initial roads will be widened to accommodate the crane used for construction.

Further, the installation is weather sensitive. To install the WPPs during the rainy season is not a good idea nor it should be done in the windy season. Delays due to bad weather conditions increase the cost, but can be avoided by good planning.

14.2.3 Installation and Commissioning

WPPs are large and heavy, so suitable site access for transport is required. The transport vehicles are also quite long and may have problems with bends on the road and up and down hills. The supplier usually checks out the transport route to make it work. Some trees may have to be felled in sharp curves, telephone and power lines raised or temporarily removed. The turning radius of the roads is evaluated to accommodate the long trailers that transport WPP blades, towers and nacelles. Some earth removal, straightening and widening of roads may be necessary to allow trucks and trailers for safe turning room. Additionally, an area for placing the crane is cleared around the WPP tower base typically 50 m × 50 m and is compacted and covered with gravel. There are cases that in some places, the blades can even be transported and air-dropped by helicopters at the site, if that option is more viable.

WPP foundations of reinforced concrete have to harden for a month. The construction phase for a large WPP lasts about 2 to 3 months. The WPPs are usually mounted and installed by the supplier.

On-site storage and assembly work require an open space at the base of each tower of approximately 50 × 70 m. Heavy cranes are required on site; a 2 MW turbine requires a crane with capacity to lift 600 tons for hoisting the tower sections,

nacelle and rotor into position. To install the transformer (if it is not integrated in the WPP) and a power line to the grid is the task of the developer.

When the WPP components finally arrive, it does not take more than one day to mount it on site, if everything is well prepared and the weather allows. Once the WPPs are installed, about two weeks are needed to complete the installation work, commission the system and connect the wind power plant to the grid.

The procedure for commissioning is formulated in mutual cooperation with the agreement of all the stakeholders. The records of the civil engineering construction are also seen. Inspections of mechanical engineering components are also undertaken. Often some defects are discovered during the inspections and these defects are listed. Commissioning tests will include electrical tests for electrical components and WPP. The WPP is then transferred to the client, the owner/operator.

14.2.4 WPP Operation

From the date of handover by the contractor, the owner is responsible for the daily operation of the WPP. The owner/operator can either handover the operations and maintenance of the WPPs to a third party. If they are willing, a new contract can even be given to the contractor who has commissioned the wind power project.

Third party WPP operations are well established in major countries. Due to the power purchase agreement (PPA) with the utilities, regular dialogue is a common phenomenon between the operator and the utility company. The hourly production of modern WPPs can be monitored by the owners of the WPP via phone and internet due to the electronic modems installed in the WPPs. Many wind farms are subjected to project finance and hence, regular reporting to the lenders has to be done.

The warranty and 'maintenance' contracts become valid from the date of handover. The terms of warranties can vary for different suppliers. Normally, the manufacturer provides a warranty of two years. But in some cases, they can be valid even upto twenty years from the date of handover which include repairs and modifications. Some warranties also cover technical availability of individual WPPs and 95% of the certified power curve.

During the first year of operation, some teething problems are usually there, especially if it is a new model WPP. But the manufacturers are prepared to take corrective measures to resolve them. It usually takes about 3 to 4 months for the WPP to reach full mature and commercial operation.

Maintenance

After the WPPs have been installed, connected and started to feed electrical power to the grid, they operate unattended. Modern WPPs require regular maintenance service twice a year. The WPP manufacturer can do this service. This is often included in the warranty for two years or longer. After that, a contract for regular service should be negotiated with the manufacturer or an independent service company.

The typical preventive maintenance of a WPP is about 40 hours every year. A typical WPP maintenance crew consists of 2 to 3 persons for every 20 to 30 WPPs in a wind farm. The owner or the one who is in charge of the operation can keep

them under surveillance from his desk in the office, since the WPP's SCADA system is connected to the operator's personal computer. Simple operational disturbances can be attended from a distance and the WPP can be re-started from the personal computer.

For a WPP in the MW class, planned preventive maintenance takes two to three working days for two engineers. Oil samples are taken from the gearbox at regular intervals and analysed; filters are replaced and gears are inspected for damage. They inspect and test the control and safety devices, repair small defects and replace or replenish gearbox lubrication oil depending on the requirements.

It is recommended for the owner/operator to create a contingency fund to set aside money for major repairs that may have to be done after the warranty has expired. When more serious disturbances occur, the operator has to go to the WPP to attend the fault before the WPP can be re-started. When a fault occurs, the operator gets an alarm on his/her cell phone or personal computer. The number of repairs a WPP requires varies widely for different WPPs, but the likely average is three to four mechanical or electrical faults per year that require a visit by a service engineer. The downtime for each WPP failure can last for two to four days.

After 10–12 years of operation, it is common practice to undertake a major overhaul of a WPP which includes cleaning of the rotor blades, refurbishment of the drive train and if necessary, replacement of bearings and gearbox parts.

The amount of power the WPPs produce is registered on a meter of which the grid operator takes the readings. Settlements are usually made once a month when the owner gets paid for the power that has been delivered to the grid in the preceding month. Rules for how this is done should be included in the power purchase agreement (PPA).

14.3 TECHNICAL LIFETIME

The technical availability, in other words called the technical lifetime of series produced WPPs are quite high which is estimated to be around 20 years. The economic lifetime can be shorter if the maintenance costs increase too much when the WPP gets old. A WPP at a good site can pay back the energy that has been used to manufacture the WPP even much earlier than envisaged. When a WPP has served its time, it can be dismantled and most of the components can be recycled. The quality of the components in WPPs can vary widely. Some components have Rolls-Royce quality, virtually indestructible while others may not have that high quality. Many manufacturers have a mix of high and low quality components.

14.4 REPOWERING WIND POWER PROJECTS

After the envisaged 20 years of operation by which time it can be said that the WPP has seen its days, it is the time for the WPP to be dismantled or replaced for a new wind project cycle to begin (refer Figure 14.1). This replacement process of WPP

in the same area is termed as *repowering*. The main aim of the repowering is to use the existing renewable energy resources on site more efficiently in a technically adapted or improved manner. This term also includes all measures which improve the efficiency and capacity by means of retrofit to the latest technology. This also paves the way for a large second hand market.

Repowering is a process by which with half the infrastructure, the capacity of WPPs is doubled and the energy output is tripled in same area of the available land. Repowering also leads to reduction in the number of WPPs due to the significant growth of hub heights and a reduction in the rotational speed, thereby providing greater beauty to the landscape. As many as 20 old WPPs can be replaced by a single WPP built with the advanced WPP technologies. This was one of the reasons why repowering began quite early in California, USA in early 1990s when many wind farms scrapped the first and second generation WPPs for fewer, newer and efficient ones and at the same time, restored the landscape near tourist routes.

Germany and Denmark were the other pioneers of repowering. The actual repowering of larger capacities and entire wind farms in Germany started since the amendment of the renewable energy law in 2004 which also has provisions for financial incentives for repowering projects. Since Germany runs short on productive sites onshore, the government and the wind energy industry have placed their hopes on repowering onshore before the offshore market is tapped.

Wherever the land available is exhausted, repowering could be the next alternative apart from offshore wind farms. As on today, 16% of Spain's electricity demand is met by the wind. Denmark has 26% of its electricity demand supplied by the wind. Danish government aims to get 50% of its electricity from wind by 2025.

It is reported that in India 1380 MW of wind power capacity was installed before 2002. This capacity sits on the best wind sites but working sub-optimally. Therefore, repowering is one of the best solutions for all stakeholders which eventually leads to the next wind power project cycle. In response to this challenge, repowering of wind power projects are gradually picking up in India since the year 2011.

In dismantling old WPPs, most of the parts can be recycled as scrap metal. The only components that can not be recycled today are the rotor blades but efforts are being made to find methods for that as well. The scrap value of a WPP is about the same as the cost to dismount it. The foundation of reinforced concrete, built below ground level is left behind if it does not affect ground conditions in a negative way. Otherwise, it can be removed and reused as filling material for roads or buildings.

Wind project life cycle can help in ensuring the availability, safety and reliability of wind power plant and auxiliary equipment. Figure 14.2 (not drawn to scale) depicts the different stages of a wind project life cycle in a different perspective and final envisaged outcomes. At the end of technical lifetime, either the WPP can be decommissioned or repowered. The technical lifetime is considered as 20 years. The cost assumed for 1 MW wind power project from 'cradle to commissioning' is taken as ₹ 6 crore only (i.e. 60000000).

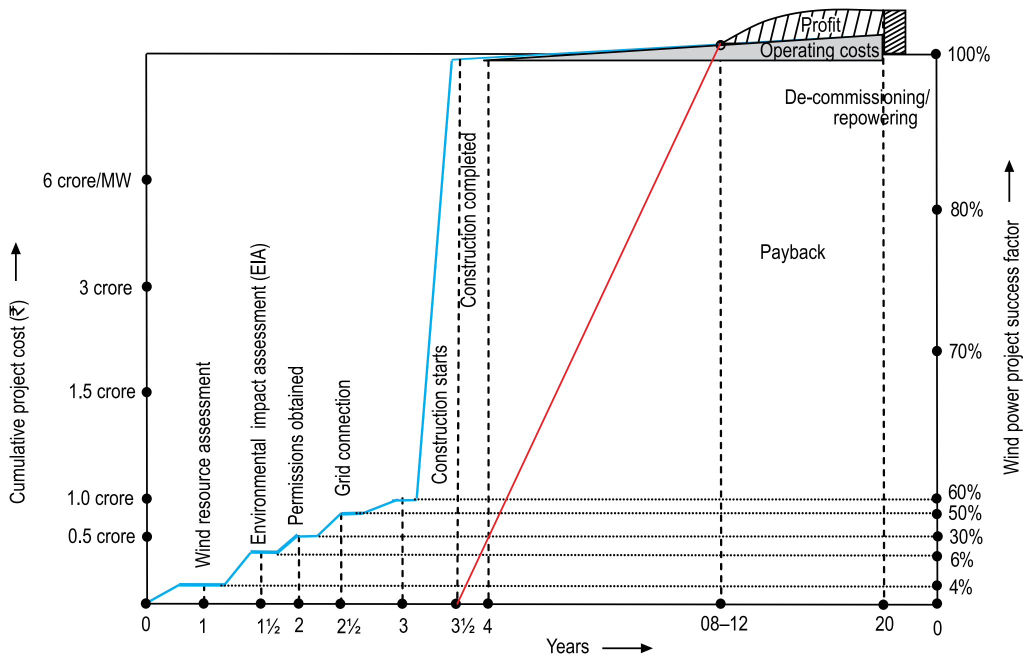


Figure 14.2 Wind Power Project Life Cycles Stages.

SUMMARY

For the success of a wind power project, it was seen in this chapter that for the various components of the wind project cycle, if a detailed and meticulous planning is considered, the chances of failure can be greatly minimised. It has also been seen that after the technical lifetime of 20 years of a WPP, to include the higher capacity and more efficient WPPs and greater income, the next wind project cycle begins if repowering is considered, as the scarce windy sites will be utilised more efficiently.

EXERCISES

14.1 Describe the wind project life cycle, using a block diagram.

14.2 Describe the various components of site feasibility study phase of a typical wind project cycle.

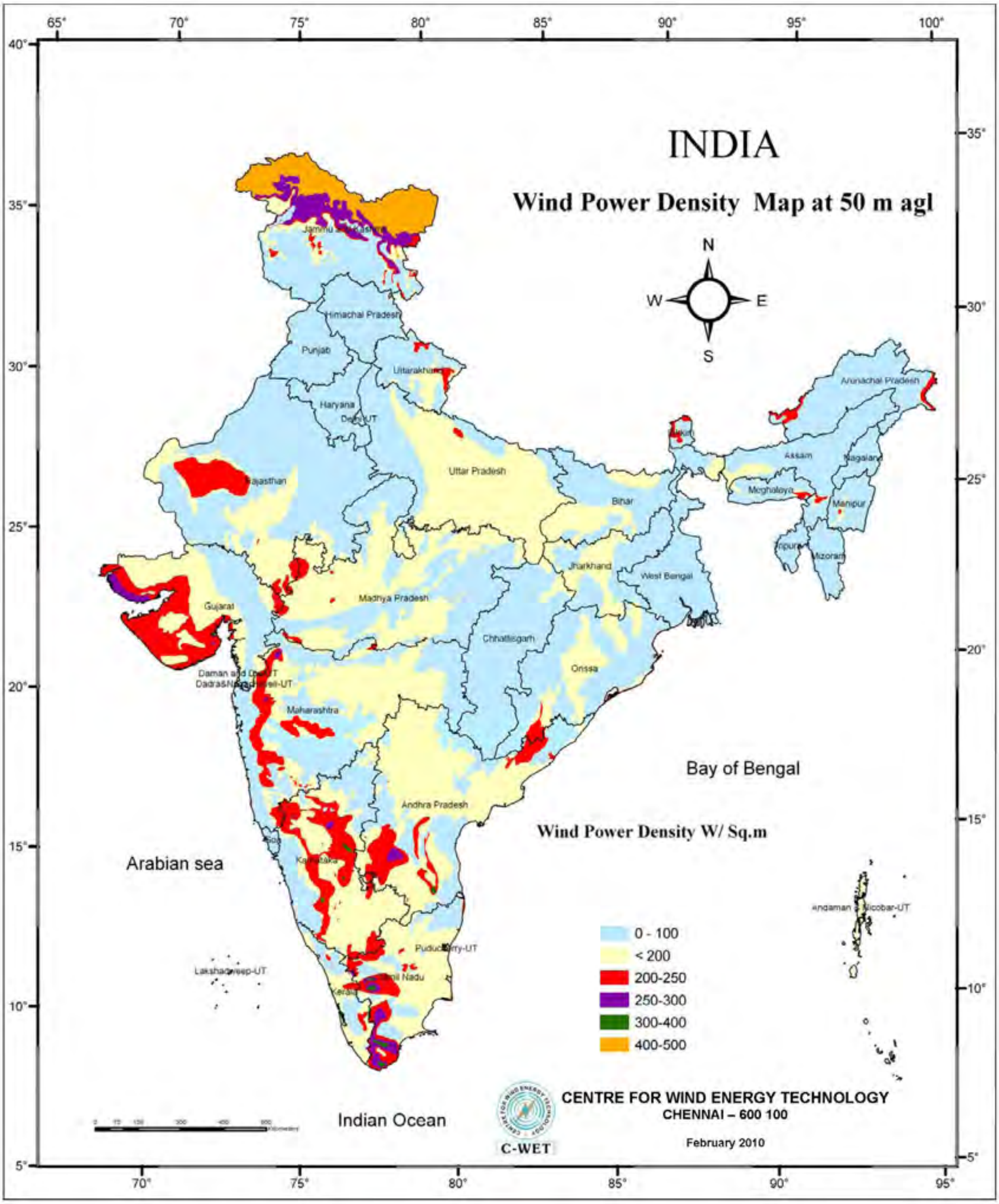
14.3 Explain the various components of permissions and procurement phase of a typical wind project cycle.

14.4 Describe the various components of installation and commissioning phase of a typical wind project cycle.

14.5 Describe the various components of WPP operation phase of a typical wind project cycle.

14.6 Explain the term cost of energy with its justification.

14.7 Explain the circumstances under which repowering needs to be undertaken.


INDIA
Wind Power Density Map at 50 m agl
N
W
E
S
Wind Power Density W/ Sq.m
0 - 100
< 200
200-250
250-300
300-400
400-500
Arabian sea
Bay of Bengal
Indian Ocean
Rajasthan
Gujarat
Punjab
Haryana
Himachal Pradesh
Uttarakhand
Uttar Pradesh
Madhya Pradesh
Maharashtra
Chhattisgarh
Jharkhand
Bihar
West Bengal
Orissa
Andhra Pradesh
Karnataka
Tamil Nadu
Kerala
Assam
Meghalaya
Manipur
Mizoram
Nagaland
Arunachal Pradesh
Lakshadweep-UT
CENTRE FOR WIND ENERGY TECHNOLOGY
CHENNAI – 600 100
February 2010
C-WET

15

Electronics in Renewable Energy Systems

Lightning and hail, snow and clouds, stormy
winds that do HIS bidding
—Psalms 148:8

Learning Outcome

After studying this chapter, the interested persons will be encouraged to address the concerned electronics related problems to improve the effectiveness and efficiency of the renewable energy systems.

CHAPTER HIGHLIGHTS

15.1 INTRODUCTION

The buzzword today being energy security, renewable energy has gained considerable importance and India is one of the few countries who are taking the lead. Historically, renewable energy has not been attractive, because of its intermittent nature. The resurgence of interest in the use of renewable energy is due to the urgency to reduce the high environmental impact of fossil-based energy systems. Further, the advancements in different branches of engineering, especially in electronics, digital electronics, power electronics and material technologies have made the renewable energies more reliable and dependable. Changing dynamics, non-linearities and uncertainties exhibited by renewable energies are challenges that require advanced control strategies to increase the performance and the number of operational hours.

The success of the modern renewable energy plants has been the efficient design of electronics and digital electronics applications with power electronics to control and protect the equipment and the power system which continue to be researched all over the world. The uses of advanced digital technologies such as microprocessor-based measurement and control, communications, computing, and information systems are continuously improving the systems in terms of reliability, security, inter-operability and efficiency of the electrical grid.

As regards to the electronics related problems of renewable energy systems, the major role of the postgraduate electronics engineers is to find solutions to those problems, while that of the graduate electronics engineers is to do testing and commissioning. The technologists (the graduates of the polytechnic system in India) need to maintain these electronics for effective and efficient functioning of the renewable energy power flow, whereas the work of the technicians is to undertake the routine troubleshooting of the subcomponents of the electronics systems. This chapter is written to inform about the location and use of the electronics and power electronics that have become part and parcel of the various modern electronically controlled renewable energy power plants and thereby to encourage all the above mentioned 'players' to address the problems related to electronics for their efficient functioning.

15.2 ELECTRONICS AND POWER ELECTRONICS

To make it simple to understand the role of electronics, the block diagram of a renewable energy power system is explained using Figure 15.1. Whatever be the type of renewable energy source (maybe from solar, wind, micro-hydro, biomass, ocean energy or geothermal), the output power emerging from block-1, generally is not of constant voltage and constant frequency which is an essential criterion for feeding the power to the electric grid. Hence, the variable voltage and variable frequency power has to be conditioned in block-2, which is the digital electronics block to produce constant value sinusoidal lower power. This output from block-2 is then fed to power electronics block-3, to produce grid friendly electric power that will then be fed to the electric grid.

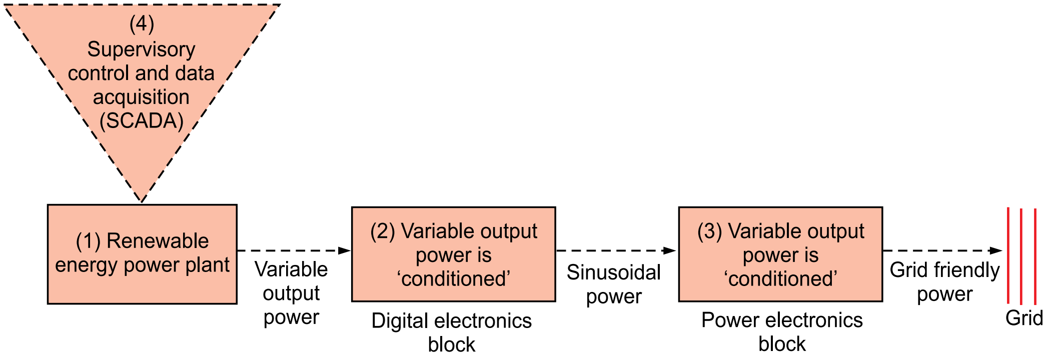


Figure 15.1 Electronics in Renewable Energy Technologies.

It can be noted that the most of the modern state-of-the-art renewable energy grid connected technologies are generally supervisory control and data acquisition (SCADA) as represented by Figure 15.1 (triangular block-4) and in Figure 11.3 as well. It is interesting to note that currently, almost 80–90% of the renewable energy technology-based power plants in India are owned by private investors who would like to know on an hourly basis, not only about the amount of electric power being produced by their renewable energy power plants, but also about their 'health' (see Figure 3.12) while sitting in their homes in remote locations. This is indeed happening now, because most of the modern renewable technologies are SCADA enabled (see Figure 11.3) and controlled. Therefore, electronic communication technologies, both analog and digital, as well as computer communication play a substantial role in all grid-connected renewable energy power plants to monitor the power generation and/or transmission and/or control or even all the three functions for sustained electric power production.

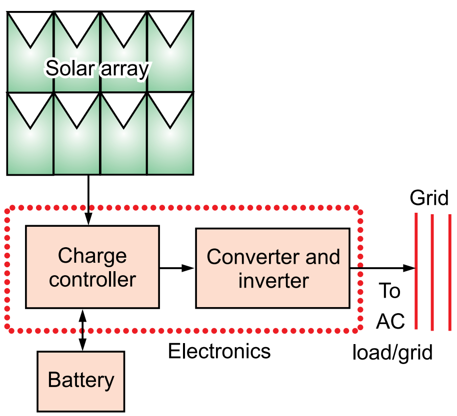


Figure 15.2 Electronics in PV Systems.

15.3 ELECTRONICS IN SOLAR POWER PLANTS

Electricity from solar power can be generated either directly using photovoltaic (PV) cells or indirectly by collecting and concentrating solar power (CSP) to produce steam, which is then used to drive a turbine to provide the electric power. CSP systems use optical devices and sun-tracking systems to concentrate a large area of sunlight onto a smaller receiving area for which a wide range of concentrating technologies exists such as solar dishes, parabolic troughs and others discussed in Section 1.5.1 of this book. For a conventional thermal power plant, this concentrated solar power becomes a heat source. However, the control of CSP generally involves some form of electronic control to render the system fully automated and digitally controlled. Every manufacturer develops their own control system for their CSP system.

In the case of solar PV systems (Figure 15.2), it is in microvolts that the solar cells produce power and by series and parallel connections, resulting power is fed to the charge controller. It converts higher voltage DC output from the solar panels down to the lower voltages needed for charging the batteries. The power produced by the solar PV arrays is in proportion to the intensity of sunlight striking the array surface, which varies throughout a day, as well as day-to-day, and hence the actual solar power output varies substantially. To extract maximum power during a day, 'panel tracking', i.e., the solar panels are on a mount that gets tilted as it follows the sun and is also electronically controlled.

The output from the solar arrays varies more than the rated voltage (for example, a solar panel rated 12 V can produce up to 20 V) depending on the solar intensity. Hence, to regulate the varying voltage emanating from the PV array and also to protect the battery from excess voltage, a 'charge controller' is necessary. This charge controller is an electronic device, which comes in various forms and designs depending on the application and manufacturer.

The DC power that comes out from the charge controller and inverter (Figure 15.3) is then fed to an input amplifier (Figure 15.4). The input amplifier is adapted to boost up the PV voltage which brings it within an acceptable range of the PV converter specifications and then fed to the 'signal conditioner' (shown by dotted line), which are electronic circuits. This signal conditioner consists of analog-to-digital converter (ADC) and digital-to-analog converter (DAC) to convert analog signal to digital signal and digital signal to analog signal respectively. The signal conditioner ensures the sine-wave form of the voltage and current, with a low amount of harmonics. The output from the signal conditioner is then amplified to be fed to the load/electric grid.

A high-frequency (HF) transformer is the essential device in the conventional grid-connected solar PV power systems. It limits the ground current flowing into the grid and ensures that no direct current (which could saturate the distribution transformer) is injected into the grid. However, using a transformer increases the weight, size, and cost of the PV system, which in turn reduces its efficiency. With the increasing high solar PV ratings and efficiencies, the PV converters are mostly transformer-less now-a-days.

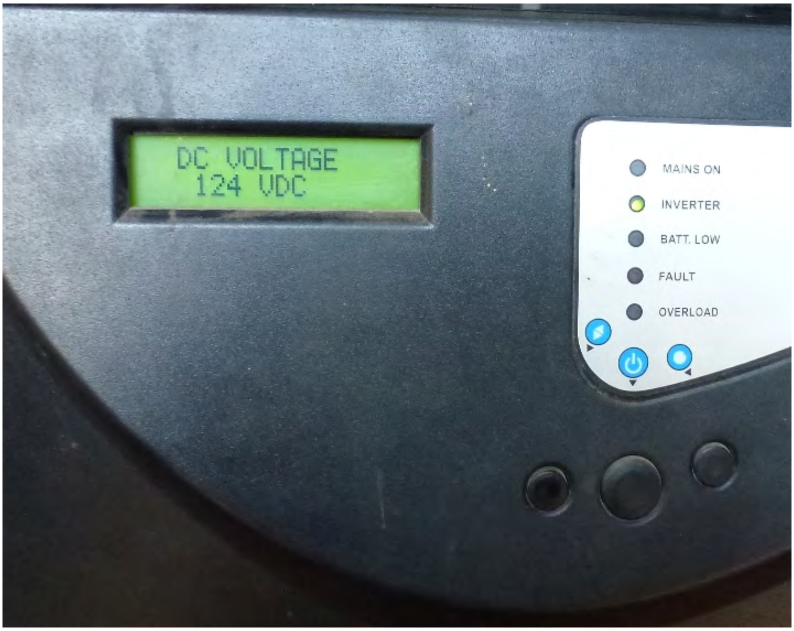


Figure 15.3 **Solar PV Inverter.**

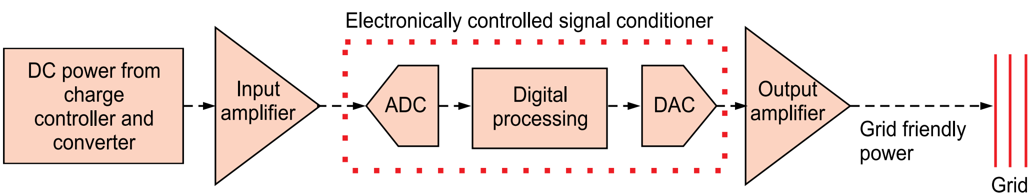


Figure 15.4 **Solar PV Signal Conditioner Technologies.**

15.3.1 Maximum Power Point Tracker (MPPT)

The first priority in any renewable energy system is to extract as much energy as possible during the normal operation is called *maximum power point tracker* (MPPT). The MPPT is one of the key functions in any typical solar PV system, because it ensures that the maximum available electrical power is produced by the solar PV array (PV panels) at any irradiance and temperature values. The older non-digital MPPTs (i.e., analog) are much easier and cheaper to build than the digital ones and their overall efficiencies vary considerably.

The modern MPPT (Figure 15.5) is a microprocessor controlled high-frequency electronic device that optimises the match between the solar array and the battery bank or utility grid. Figure 15.6 illustrates a typical MPPT technique implemented for a solar PV system. The switching converters and MPPT blocks consist of electronic circuits and devices. They take the DC input from the solar PV array, change it

Figure 15.5 Solar PV Charge Controller.

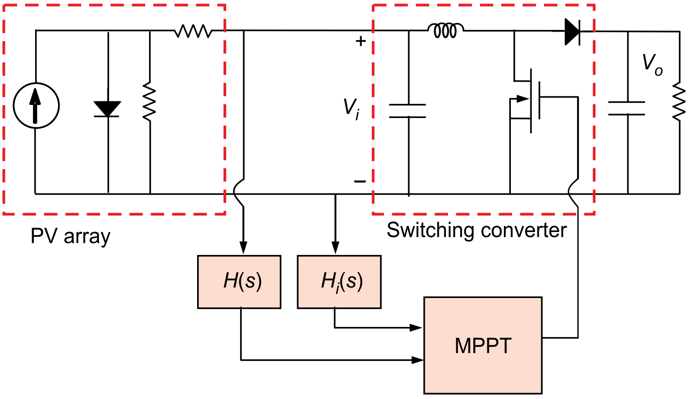


Figure 15.6 Typical MPPT Technique for Solar PV System.

to high-frequency AC, and convert it back, down to a different DC voltage and current to exactly match the solar panels to the batteries. The two most frequently used MPPT algorithms are *perturb and observe* (P&O) *and incremental conductance* (IC). Both of them are based on a repeated adjustment of the PV voltage to detect the fulfilment of a proper condition involving the actual values of the PV current, voltage, and power.

The MPPTs operate at very high audio frequencies, usually in 20–80 kHz range. The advantage of high-frequency circuits is that they can be designed with very high-efficiency transformers and smaller components. The typical gain because of the MPPT is 20–45% power gain in winter and 10–15% in summer. There is considerable scope of research for electronic engineers in this area due to the increased interest in novel architectures based on the adoption of switching converters employing a PV module-dedicated decentralised MPPT (DMPPT) function is giving rise to new challenging problems.

15.4 ELECTRONICS IN WIND POWER PLANTS

In every wind power plant, there exists an electronics control cubicle and the power electronics control panel. Without electronics and digital control, the working of power

electronic circuits would not have been possible and the phenomenal success of the wind power technology would not have been there in India and around the world.

The electronics control cubicle (Figure 15.7) in the wind turbine nacelle is the brain of the wind power plant. It comprises of the microprocessor, microcontroller and the associated analog and digital electronic circuits in the electronic control cubicle. Based on the various input signals received from the different types of sensors in the wind power plant, the electronics in this cubicle take the relevant decisions all round the year for the continuous healthy and successful operation of the wind power plant.

Figure 15.7 Electronic Control Cubicle in Wind Turbine Nacelle.

For redundancy and operational security, a similar electronic control panel is duplicated at the wind-turbine tower bottom, as well. Therefore, instead of climbing upto the top of the tower, the wind power plant operator can even control the wind power plant operation from the bottom of the tower. In the state-of-the-art wind power plants, monitoring and control is even possible remotely through the internet and SCADA, but still there is much scope to improve the reliability and efficiency of the electronic control systems.

Section 6.6 of this book also discusses about the back-to-back power electronic controller (widely used in wind power plants) in which *electronics and digital control* plays an inseparable role. Energy security is the key and hence to make this renewable energy source more robust and reliable, continual research is going on in both micro and power electronics for controlling the power electronic circuits and devices for the various wind power plant technologies already discussed in the earlier chapters of this book.

15.5 ELECTRONICS IN OCEAN ENERGY POWER PLANTS

Oceans cover approximately 75% of our planet's surface and is a very good source of renewable energy. The tapping of electric power from the ocean is based on four different sources and their respective technologies, i.e., wave power, tidal power, marine current and ocean thermal energy conversion (OTEC), discussed in Section 1.7 of this book. Out of these four, the first three are highly intermittent, wherein the use of digital electronics are substantial (Figure 15.8), which have to work in tandem with power electronic converters such as the back-to-back converter and the emerging multilevel converters.

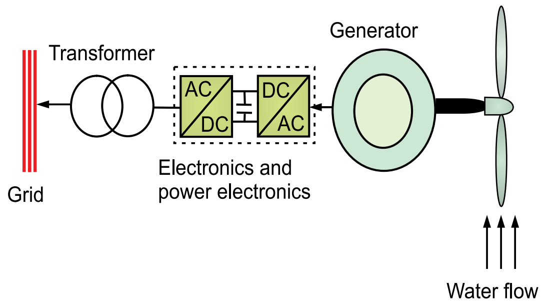


Figure 15.8 Electronics and Power Electronics in Ocean Energy Power Plants.

The reliability and robustness of ocean energies are essential and so continual research in this area is being undertaken due to the need of connecting several distributed power sources, whose power is continuously growing and assuring good power quality levels. Multilevel converters can be used as rectifiers, where the electricity is generated by AC generators. Three basic multilevel converter topologies are being continually being researched: *neutral point clamped* (NPC), *flying capacitor*, and *cascaded H-bridge* (CHB) converters. In the first two topologies, the connected renewable energy source technologies cannot be independent. However, in the case of CHB, the renewable energy sources can be independent.

15.6 ELECTRONICS IN SMALL HYDEL POWER PLANTS

Figure 15.8 holds good as the role of *digital electronics* are substantial, after scaling down the electronics depending on the rating of the hydel power plants. Even if the operation of many of the small hydel power plants (discussed in Section 1.3 of this book) are seasonal (as the water flow is not always constant as in large hydro power plants), still they are economically viable alternatives in remote areas. The mechanical and electrical details are already discussed in Chapter 1 of this book. Therefore, there is ample scope for maintaining, simulating and designing the related electronics and power electronics for the low, medium and high head micro-hydel power plants.

15.7 ELECTRONICS IN BIOMASS POWER PLANTS

As discussed in Section 1.6 of this book, a biomass-fired power plant produces electricity and heat by burning biomass in a boiler. The most common types of boiler are steam boilers in which crop residues and other types of biomass are used as fuel, in the same way as coal, and gas. Although, burning biomass releases carbon emissions, it is classified as a renewable energy source in the EU and UN legal frameworks, because plant stocks can be replaced with new growth. It can be observed in Section 1.6 that there are different types of biomass technologies depending on the type of biomass being used as fuel. However, it is worth noting that ultimately the biomass energy source works out to be a heat source to produce steam to run steam turbines attached to conventional electric generators, which generally produce grid friendly electric power. Therefore, the role of electronics and power electronics is relatively minimal as compared to the rest of the renewable energy technologies.

15.8 ELECTRONIC COMMUNICATION SYSTEMS FOR GRID INTEGRATION OF RENEWABLE ENERGY RESOURCES

The specific demands of any renewable energy plant connected to the electric grid are:

- Secure power supply
- High efficiency, low cost, small volume effective protection
- Active and reactive power control
- Dynamic grid support
- Electronic communication for monitoring of various parameters for reliable electric power flow.

Therefore, electronic communication systems are crucial technologies and fundamental infrastructure required to transmit measured information for grid integration of renewable energy resources. Two-way communication is essential for accommodation of the distributed energy generation to assist in the re-configuration of network topology, if needed.

A typical electric grid communication system consists of a high-bandwidth backbone (generally consisting of combination of fibre optic systems and microwave radio) and lower-bandwidth access networks [comprising of wired lines—power line communications (PLC), and wireless systems] connecting individual facilities to the backbone. The main benefit of the PLC is that it allows communication signals to travel on the same wires that carry electricity. But the limitations are the inherent electromagnetic interference (EMI) in the communication and also relatively expensive when compared to wireless networks. Hence, now-a-days, wireless networks (which are completely electronics) with respect to IEEE 802.11 and IEEE 802.16 are more popular which have to be maintained by technologists and tested and re-designed by electronic engineers for improving the efficiency and effectiveness.

SUMMARY

It was seen in this chapter that electronics and power electronics that have become part and parcel of the various modern electronically controlled renewable energy power plants, i.e., solar power plants, wind power plants, small hydel power plant, etc. Therefore, it is necessary that technologists and engineers are made aware of them so that they would be trained to maintain them for the efficient functioning of such plants.

EXERCISES

15.1 Describe the need for SCADA in renewable energy power plants.

15.2 Explain with sketches the role of digital and power electronics in solar power plants.

15.3 Explain with sketches the role of MPPT technology in solar power plants.

15.4 Explain with sketches the role of digital and power electronics involved in wind power plants.

15.5 Explain with sketches the role of digital and power electronics involved in ocean energy power plants.

15.6 Explain with sketches the role of digital and power electronics involved in small hydel energy power plants.

15.7 Explain with sketches the role of digital and power electronics involved in biomass-based power plants.

Bibliography

ABB S.P.A., *Technical Application Paper No. 13*—Wind Power Plants, ABB SACE, Italy, 2011.

Ackermann, Thomas, *Wind Power in Power Systems*, John Wiley & Sons, 2nd ed., Chichester, England, 2012.

Akhmatov, V., Variable-Speed WPPs with Doubly-Fed Induction Generators—Part I: Modelling in Dynamic Simulation Tools—*Wind Engineering,* Vol. 26, No. 2, 2002.

Akwarandu, John, Wind Mills and Transmission System Interaction, Thesis, Department of Electric Power Engineering, Chalmers University of Technology, Goteborg, Sweden, 2006.

Amirat, Y., et al., Generators for Wind Energy Conversion Systems: State of the Art and Coming Attractions, Survey paper *Journal of Electrical Systems,* 3–1, pp. 28–38, 2007.

Andreas, Basteck, Hydrodynamic Gearbox for Variable Speed Wind Turbines without Power Electronics, *Proceedings of European Wind Energy Conference*, Athens, Greece, February–March 2006.

Bagnall, Trevor, et al., Operational Experience of STATCOMs for Wind Parks, *Proceedings of European Wind Energy Conference*, Brussels, April 2008.

Baywater, G., et al., Northern Power NW 1500 Direct-Drive Generator, Subcontract Report; NREL/SR-500-40177, NREL USA, October 2007.

Behnke, Michael R. and William L. Erdman, Impact of Past, Present and Future Wind Turbine Technologies on Transmission System Operation and Performance—Report: CEC-500-2006-050 California Energy Commission Public Interest Energy Research (PIER) Program Intermittency Analysis Project (IAP), March 2006.

Behnke, M., et al., Development and Validation of WECC Variable Speed Wind Turbine Dynamic Models for Grid Integration Studies, *Proceedings of Windpower Conference*, Los Angeles, California, 4–7 June, 2007.

Bhadra, S.N., et al., *Wind Electric Systems*, Oxford University Press, New Delhi, 2005.

Blaabjerg, Fred and Chen Zhe, *Power Electronics for Modern Wind Turbines*, Morgan & Claypool, San Francisco, USA, 2006.

Böhmeke, G., Development and Operational Experience of the Wind Energy Converter WWD-1, *Proceedings of European Wind Energy Conference*, Madrid Spain, June 2003.

Bolik, S.M., Grid Requirements Challenges for WPPs, *Proceedings of Fourth International Workshop on Large-scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms*, Billund, Denmark, 2003.

Bollen, M.H.J. G. Olguin, and M. Martins, Voltage Dips at the Terminals of Wind Power Installations, *Proceedings Nordic Wind Power Conference*, 1–2 March, 2004.

Braun, M., Reactive Power Supplied by Wind Energy Converters—Cost-Benefit-Analysis, *Proceedings of European Wind Energy Conference*, Brussels, April 2008.

Burton, Tony, et al., *Wind Energy Handbook*, John Wiley & Sons, Chichester, England, 2002.

Carlin, P.W., et al., The History and Art of Variable Speed Wind Turbine Technology, Technical Report, NREL/TP-500-28607, USA, 2001.

Carlson, Ola, et al., Power System Voltage Stability Related to Wind Power Generation, *Proceedings of European Wind Energy Conference*, Athens, Greece February-March, 2006.

Causebrook, A., Fault Ride-Through: Shifting The Balance of Power from Blade Pitch to Electrical Resistance, *Proceedings of European Wind Energy Conference*, Athens, Greece, February-March 2006.

Chen, Z. and Blaabjerg, Frede, *Power Electronics for Modern Wind Turbines*, Synthesis Lectures on Power Electronics#1 Morgan and Claypool Publishers, Denmark, 2006.

Chilakapati, N., et al., An Improved Doubly Fed Twin Stator Induction Motor Drive Using Optimisation of Decoupled Control Flux, *Proceedings of IEEE-PES/IEE/CSEE International Conference on Power System Technology* (*POWERCON?2000*), Perth, Western Australia, 4–7 December, 2000.

CIGRE Technical Brochure Working Group 08 of Study Committee C06, Grid Integration of Wind Energy, *Proceedings of International Conference on Large High Voltage Electric Systems*, July 2009.

Dubois, M., Optimized Permanent Magnet Generator Topologies for Direct Drive Wind Turbines, Ph.D. Dissertation, Delft University of Technology, Delft, The Netherlands, 2004.

Earnest, Joshua and Wizelius, Tore, *Wind Power Plants and Project Development,* PHI Learning, Delhi, 2011.

Eclareon, *White Paper Wind Generator Technology*, ECI Publications Leonardo Energy, European Copper Institute available at www.leonardo-energy.org/node/156615, 2012.

Eggleston, David, M. and Stoddard, Forrest S., *Wind Turbine Engineering Design*, Van Nostrand Reinhold, New York, USA, 1987.

Engelhardt, Stephan and Geniusz, Andrzej, Optimised Fault Ride Through Performance for Wind Energy Systems with Doubly Fed Induction Generator, *Proceedings of European Wind Energy Conference*, Brussels, 2008.

Fingersh, L., et al., Wind Turbine Design Cost and Scaling Model, Colorado USA, NREL Technical Report NREL/TP-500-40566, 2006.

Frost, W. Aspliden, C., Spera, David, A., Characteristics of the Wind in Wind Turbine Technology, *Fundamental Concepts of Wind Turbine Engineering,* ASME Press, New York, 1998.

Gasch, Robert and Twele, Jochen, *Wind Power Plants: Fundamentals, Design, Construction and Operation*, Solarpraxis, Berlin, 2002.

Gipe, Paul, *Wind Power*, Chelsea Green Publishing Co. Vermont, USA, 2004.

Gottschall, Julia and Peinke, Joachim, Power Curves for Wind Turbines: A Dynamical Approach, *Proceedings of European Wind Energy Conference*, Brussels, April 2008.

Grainger, J.J. and Stevenson, W.D., *Power System Analysis*, McGraw Hill, Singapore, pp. 380–381, 1994.

Grauers, A., Design of Direct Driven Permanent Magnet Generators for Wind Turbines, Technical Report#292, Ph.D. Dissertation, Chalmers University of Technology, Gothenburg, Sweden, 2005.

Hansen, Anca D. and Michalke, Gabriele, et al., Voltage Grid Support of DFIG Wind Turbines During Grid Faults, *Proceedings of European Wind Energy Conference*, Milan, Italy, 2007.

Hansen, Iov, F., Sørensen, A.D., and Cutululis, P., Mapping of Grid Faults and Grid Codes, Risø report, Risø-R-1617(EN), Denmark, 2007.

Hansen, L.H., et al., *Conceptual Survey of Generators and Power Electronics for Wind Turbines*, Risø National Laboratory, Denmark, p. 106, 2001.

Hansen Martin, O.L., *Aerodynamics of Wind Turbines: Rotors, Load and Structure*, James and James, London, 2000.

Harrison, Robert, *Large Wind Turbines: Design and Economics*, Wiley, Chichester, England, 2000.

Hau, Erich, *Wind Turbines—Fundamentals, Technologies, Applications, Economics*—Springer, Germany, 2006.

Heier, Siegfried and Waddington, Rachel, *Grid Integration of Wind Energy Conversion Systems*, John Wiley & Sons, London, 2006.

Henderson, G.M., Referred Generator Inertia: A new and decisive advantage for the Torque Limiting Gearbox (TLG) system, *Proceedings of NZWEA Conference*, Wellington, 2002.

Holttinen, H., The Impact of Large Scale Wind Power Production on the Nordic Electricity System, VTT Publications, Helsinki, 554, 2004.

Holttinen, Hannele, Design and Operation of Power Systems with Large Amounts of Wind Power, First Results of IEA Collaboration, *Proceedings of Global Wind Power Conference*, Adelaide, Australia, 2006.

IEA 2011 Wind Report, IEA, Paris, France, July 2012.

IEC61400-2, Standards for small wind turbines, 2012.

Jauch, Clemens, et al., International Review of Grid Connection Requirements for WPPs, *Proceedings of Nordic Wind Power Conference*, Chalmers University of Technology, 1–2 March, 2004.

Johnson, Gary L., *Wind Energy Systems*, Electronic Edition MAN, 2001.

Koessler, R.J.S., et al., Integration of Large Wind Farms into Utility Grids (Part 1—Modeling of DFIG), *Proceedings of the IEEE PES*, Dallas U.S.A., 2003.

Lange, B. et al., Operational Control of Wind Farm Clusters for Transmission System Operators, *Proceedings of European Wind Energy Conference*, Brussels, 2008.

Ledesma, P., et al., Transient Stability of a Fixed Speed Wind Farm, *Journal Renewable Energy 28*, pp. 1341–1355, 2003.

Lilja Matti and Rissannen, Ilka, Multibrid Low Speed Synchronous Generator with Frequency Converter, *Proceedings of Nordic Wind Power Conference*, 1–2 March, Chalmers University of Technology, 2004.

Manwell, J.F., et al., *Wind Energy Explained—Theory, Design and Application,* John Wiley & Sons, Chichester, England, 2002.

McGovin, C. and Steeley, W., *Wind Power Integration: Smoothing Short-Term Power Fluctuations*, Final Report 1008852, EPRI, Palo Alto, CA, USA, 2005.

Michalke, Gabriele, et al., Control Strategy of a Variable Speed Wind Turbine with Multipole Permanent Magnet Synchronous Generator, *Proceedings of European Wind Energy Conference*, Milan, Italy, 2007.

Michalke, Gabriele, et al., Dynamic Behaviour of a DFIG Wind Turbine Subjected to Power System Faults, *Proceedings of European Wind Energy Conference*, Brussels, 2008.

Muljadi, E., Power Quality Aspects in a Wind Power Plant, Conference Paper, NREL/CP-500-39183, NREL, USA, 2006.

Muller, H. et al., Grid Compatibility of Variable Speed Wind Turbines with Directly Coupled Synchronous Generator and Hydro-Dynamically Controlled Gearbox, *Proceedings of 6th International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms*, 26–28 October, Delft, Netherlands, 2006.

Næss, B.I., Methods for Reduction of Voltage Unbalance in Weak Grids Connected to Wind Plants: Wind Power and the Impacts on Power Systems, *Proceedings of IEEE Workshop*, Oslo, 17–18 June, 2002.

Newman, et al., A Dynamic Voltage Restorer (DVR) with Selective Harmonic Compensation at Medium Voltage Level, *IEEE Transactions on Industry Applications*, Vol. 41, No. 6, pp. 1744–1753, 2005.

Newton, Christopher, Trends in Electrical System Technology for Wind Turbines, *Proceedings of European Wind Energy Conference*, Athens, Greece February-March, 2006.

Nielsen, J.G., et al., Control and testing of a dynamic voltage restorer (DVR) at medium voltage level, *IEEE Transactions on Power Electronics*, Vol. 19, No. 3, pp. 806–813, 2004.

Olson, Jon, (Siemens) and Botha, Paul (Meridian), High Wind Ride Through, *Proceedings of 2013 NZ Wind Energy Conference and Exhibition at Wellington*, New Zealand, 20–22 March, 2013.

Pasqualetti, M. et al., *Windpower in View*, Academic Press, London, 2002.

Peter, Christiansen, Wind Turbine Grid Connection and Interaction, Tech-wise A/S; DM Energy; Denmark, 2001.

Polinder, H. Bank, Deok-je, et al., Review of Generator Systems for Direct-Drive Wind Turbines, *Proceedings of European Wind Energy Conference*, Brussels, April 2008.

Polinder, H. et al., 10 MW Wind Turbine Direct-Drive Generator Design with Pitch or Active Speed Stall Control, *Proceedings of IEEE Int. Electric Machines and Drives Conference*, Antalya, Turkey, 3–5 May, 2007.

Polinder, H. et al., Comparison of direct-drive and geared generator concepts for wind turbines, *Proceedings of the IEEE Int. Electric Machines and Drives Conference*, San Antonio (Tx), pp. 543–550, 2005.

Polinder, H., Wind Turbine Generator Systems, *Proceedings of International Conference on Energy: Trends and Issues*, WETI-2006, pp. IP.1–15, 2006.

Polinder, H. et al., Comparison of Direct-Drive and Geared Generator Concepts for Wind Turbines, *IEEE Trans. Energy Conversion*, Vol. 21, pp. 725–733, September 2006.

Poller, Markus A., Impact of Wind Generation on Power System Stability Farms, *Proceedings of GTZ-TERNA Expert Workshop: Grid and System Integration of Wind Energy*, Berlin/Germany, 10–12 November, 2009.

Quarton, D.C., Wind Turbine Design Calculations: The State of the Art, *Proceedings European Union Wind Energy Conference*, Göteborg, 1996.

Quaschning, V., *Understanding Renewable Energy Systems*, Earthscan, London, 2005.

Ramsden, V.S., et al., High Performance Electric Machines for Renewable Energy Generation and Efficient Drives, *Journal of Renewable Energy,* Vol. 22, No. 1–3, pp. 159–167, 2001.

Robles, E., et al., Power Electronics Solutions for Grid Connection of Wind Farms, *Proceedings of European Wind Energy Conference*, Milan, Italy, May 2007.

Romero, Elena Giménez, Voltage Control in a Medium Voltage System with Distributed Wind Power Generation, Thesis, Departmental of Industrial Electrical Engineering and Automation, Lund University, Sweden, 2007.

Ruin, Sven and Whale, Jonathan, Consumer Labelling for Small Wind Turbines, *WindTech International Magazin*e, Groningen, Netherlands, January/February 2012.

Samuelsson, O. and S. Lindahl, On Speed Stability, *IEEE Trans. Power System,* Vol. 20, No. 2, pp. 1179–1180, May 2005.

Slootweg, J.G. and Kling, W.L., Modeling and Analysing Impacts of Wind Power on Transient Stability of Power Systems, *Wind Engineering,* Vol. 25, No. 6, pp. 3–20, 2001.

Smith, J. Charles, Wind Integration in North America, *Proceedings of NE System's Operators Wind Integration Seminar*, Montreal, Quebec, 12–13 February, 2008.

Sørensen, P., et al., Wind Farms Connected to Weak Grids in India, *Journal of Wind Energy,* pp. 137–149, 2001.

Soter, Stefan and Wegener, Ralph, Development of Induction Machines in Wind Power Technology, *Proceedings of European Wind Energy Conference*, Athens, Greece, February–March 2006.

Spera, David, A., *Wind Turbine Technology: Fundamental Concepts of Wind Turbine Engineering,* ASME Press, New York, 1998.

Spruce, C.J., Power Control of Active Stall Wind Turbines, *Proceedings of European Wind Energy Conference*, London, UK, 2004.

Suvire, Gastón Orlando (Editor), *Wind Farm—Technical Regulations, Potential Estimation and Siting Assessment,* InTechweb.org, Croatia, 2011.

Tande, Olav John, *System Requirements of Wind Power Plants,* Sintef Energy Research, Trondheim, Norway, 2007.

Transpower, *Connection and Dispatch Guide*, Version 3.0, Transpower New Zealand Limited Wellington, 2004.

Tsili, Marina, et al., Grid Code Requirements for Large Wind Farms: A Review of Technical Regulations and Available Wind Turbine Technologies, *Proceedings of European Wind Energy Conference*, Brussels, 2008.

Venkatesh, R., Power Quality Issues and Grid Interfacing of Wind Electric Generators, Monograph, Crompton Greaves, Mumbai, India, 2000.

Villate, J.L. et al., Innovative Solutions in Power Electronics for Variable Speed Wind Turbines, *Proceedings of European Wind Energy Conference*, February–March, Athens, Greece, 2006.

Voith, Old Tricks for New Dogs—The Latest Developments for Wind Turbines Rely on Proven Technologies, *Journal of Power Transmission Engineering*, June, Germany; www.powertransmission.com, 2008.

Walker, John F. and Jenkins, Nicholas, *Wind Energy Technology*, UNESCO, John Wiley & Sons, Chichester, UK, 1997.

Zavadil, R., N. Miller, A. Ellis, and E. Muljadi, Making Connections, *IEEE Power Energy Mag*., pp. 26–37, November 2005.

Zumarkalea, Urkixo, Grid Connection of Doubly Fed Induction Generator WPPs: A Survey, Monograph, Spain, 2003.

WEB LINKS

http://climatetechwiki.org/technology/biomass accessed on February 2013

http://cwel-windenergy.com accessed on February 2009

http://en.wikipedia.org/wiki/IEC_61400 accessed on January 2013

http://indianpowersector.com/ last accessed 2011, 2 January 2013

http://openbookproject.net/electricCircuits/accessed on January 2013

http://powermin.nic.in/indian_electricity_scenario/introduction.htm accessed on February 2013

http://renet-eu-india.com/energywave.php accessed on February 2013

www.awsopenwind.org/ accessed on March 013

www.ades.tv/en/products/pendular-wind-turbine/id/24 accessed on 11th January 2013

www.aircon-international.de accessed on July 2012

www.allaboutcircuits.com/vol_2/chpt_13/8.html accessed on May 2012

www.altenergymag.com/emagazine.php?art_id=1478 accessed on 16 March 2011

www.alternative-energy-tutorials.com accessed on 24 July 2012

www.aquaret.com accessed accessed on February 2013

www.clipperwind.com/ accessed on September 2008

www.controleng.com/single-article/direct-drive-wind-turbines-flex-muscles/4be132ffb053a53fc4ab10b2c9c57340.html on 24 July 2012

www.cygnuspower.com accessed on September 2012

www.endurancewindpower.com accessed on May 2012

www.enercon.de/en/_home.html accessed on January 2013

www.energywise.govt.nz/how-to-be-energy-efficient/generating-renewable-energy-at-home/small-wind-turbines accessed on January 2013

www.eocycle.com accessed on November 2012

www.ewea.org/events/past-events-and-proceedings on September 2013

www.ewea.org/wind-energy-basics/wind-energy-faq/ accessed on October 2013

www.ewtdirectwind.com/technology/direct-drive-technology.html accessed on November 2012

www.fuhrlaender.de, accessed on June 2008

www.gamesa.es/en, accessed on June 2007

www.greenspec.co.uk/small-wind-turbines.php accessed on April 2012

www.gwec.net/, accessed on January 2013

www.houseofjapan.com/electronics/hitachi-permanent-magnet-type-generator accessed on 18 July 2012

www.iea.org/topics/windpower/ accessed on January 2013

www.ieabcc.nl/overview.html accessed on February 2013

www.intechopen.com accessed on February 2013

www.kenersys.com accessed on February 2007

www.mhi.co.jp/en/products/pdf/MWT100_24.pdf accessed on January 2013

www.mtorres.es/pdf/TWT%20165-82%20IN.pdf accessed on February 2013

www.nordex-online.com/en/produkte-service/wind-turbines/n117-24-mw.html?no_cache=1 accessed on January 2008

www.nordicwindpower.com/products.html accessed on January 2013

www.powerhousewind.co.nz/products.htm-1-bladed SWT accessed on 11 January 2013

www.renewableenergyworld.com/rea/magazine/story?id=52086 accessed on August 2008.

www.renewbl.com/2010/05/05/india-implementing-geothermal-energy-rd-and-demonstration-program.html accessed on 27 February 2013

www.repoweringsolutions.com/english/index.htm accessed on January 2013

www.rrbenergy.com accessed on September 2012

www.rsvp.nrel.gov/wind_resources.html accessed on February 2008

www.scritube.com/limba/engleza/physics/why-wind-energy15816211.php accessed on February 2013

www.siemens.com/powergeneration/windpower accessed on April 2012

www.solardropshipping.com/charge_controller.php accessed on February 2013

www.suzlon.com accessed on November 2012

www.thewindpower.net accessed on January 2013

www.turbowinds.com/index.php?page=products accessed on October 2012

www.unison.co.kr/Eng/Cyber/New_pro_data/Pro_list.aspx accessed on January 2013

www.vawtpower.blogspot.in/ accessed on January 2013

www.vergnet.com/en/gev-hp.php accessed on September 2012

www.vestas.com accessed on February 2013

www.voith.com/en/products-services/power-transmission/variable-speed-gearboxes/windrive-technology-26688.html accessed on January 2013

www.windenergy.com accessed on September 2012

www.windenergysolutions.nl/products-introduction accessed on September 2012

www.wind-energy-the-facts.org/en accessed on January 2013

www.windflow.co.nz/news/published-papers accessed on January 2013

www.windpower.org/en/knowledge.html accessed on February 2013

www.windpowerindia.com accessed on May 2012

www.windturbines.net/wiki accessed on Oct. 2012 accessed on March 2012

www.winwind.com accessed on May 2012

www.wwindea.org/technology/ch01/estructura-en.htm accessed on August 2012

Index

Wind Power Technology Third Edition

Joshua Earnest
Sthuthi Rachel

I encourage all those who will read this book, will promote both directly and indirectly the use and awareness of wind energy as a clean and viable source of electric power.

—THOMAS ACKERMAN, Ph.D., Wind Power Author and Founder,Energynautics GmbH, Germany

Those who will read this book, will be well prepared to work in the wind power sector and participate in the important task to develop a renewable energy system which can stop the global climate change.

—TORE WIZELIUS, Wind Power Author,Teacher and Wind Project Developer, Sweden

This book provides a valuable technical information on small wind turbines that will allow students to become amateur wind engineers and entrepreneurs in this growing industry.

—Urban Green Energy, USA

This comprehensive textbook, now in its third edition, incorporates significant improvements based on the readers' suggestions and demands. It provides engineering students with the principles of different types of grid connected renewable energy sources and, in particular, the detailed underpinning knowledge required to understand the different types of grid connected wind turbines.

New to the Third Edition

- Revised Chapter 1 providing considerable amount of current information and technologies related to various types of renewable energy technologies
- One new chapter on 'Electronics in Renewable Energy Systems' (Chapter 15)

Designed as a textbook for Renewable Energy courses offered in the most of the Indian universities, the book not only serves for the one-semester stream-specific course on Renewable Energy or Wind Energy for diploma and senior level undergraduate students of electrical, mechanical, electronics and instrumentation engineering, but also for the postgraduate engineering students undertaking energy studies.

The Authors

Joshua Earnest, Ph.D., is Professor in the Department of Electrical and Electronics Engineering, as well as Dean, Planning and Monitoring at National Institute of Technical Teachers' Training and Research (NITTTR), Bhopal. He has about six years of industrial experience and thirty-three years of teaching and training experience. Besides being a trainer–educator of engineering teachers at the university and tertiary levels, he also trains executives of the industry. He has been the convener of India's First International Wind Energy Conference at NITTTR, Bhopal in January 2006 and later in 2011 as well. Besides being a guest professor for wind power at Gotland University (now Uppsala University), Sweden, he has been the online wind power education resource person to CEPRI, Beijing, China. He is also the wind power resource person for LIFE Academy, Karlstad, Sweden, University of Namibia, Windhoek and for other organizations too. He has also to his credit a considerable number of papers and articles published at the national and international levels. Dr. Joshua has co-authored a book on *Wind Power Plant and Project Development*, 2nd ed., published by PHI Learning.

Sthuthi Rachel is with the Department of Electronics Engineering at Ramrao Adik Institute of Technology (RAIT), DY Patil University, Nerul, Navi-Mumbai. She has several papers published to her credit and is also interested in the clean and green renewable energy, the hope for this planet Earth.

ISBN:978-81-203-5166-0
9 788120 351660

www.phindia.com