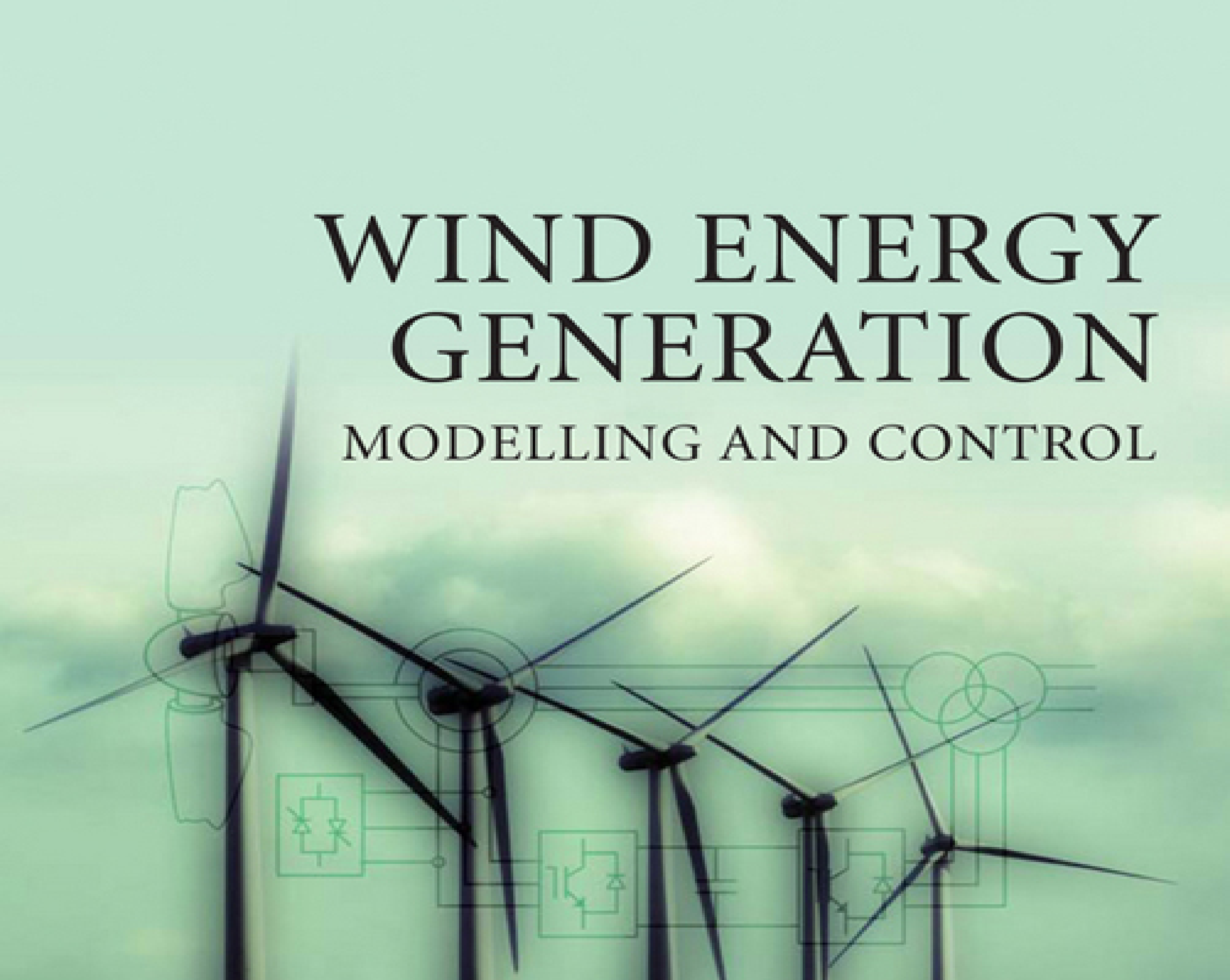
WIND ENERGY GENERATION

MODELLING AND CONTROL



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Contents

Index

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Phill Cartwright has 20 years of industrial experience in the research, analyses, design and implementation of flexible power systems architectures and projects with ABB, ALSTOM and AREVA in Brazil, China, Europe, India and the USA. He is currently the Head of the global Electrical & Automation Systems business for Rolls-Royce Group Plc, providing integrated power systems products and technology for Civil Aerospace, Defence Aerospace, Marine Systems, New Nuclear and emerging Tidal Generation markets and developments. He is a visiting professor in Power Systems at The University of Strathclyde, UK.

Mike Hughes graduated from the University of Liverpool in 1961 with first class honours in electrical engineering. His initial career in the power industry was with the Associated Electrical Industries and The Nuclear Power Group, working on network analysis and control scheme design. From 1971 to 1999, he was with the University of Manchester Institute of Science and Technology teaching and researching in the areas of power system dynamics and control. He is currently a part-time Research Fellow with Imperial College, London and a consultant in power plant control and wind generation systems.

Preface

The stimulus for this book is the rapid expansion worldwide of wind energy systems and the implications that this has for power system operation and control. Rapidly evolving wind turbine technology and the widespread use of advanced power electronic converters call for more detailed and accurate modelling of the various components involved in wind energy systems and their controllers. As wind turbine technology differs significantly from that employed by conventional generating plants based on synchronous generators, the dynamic characteristics of the electrical power network may be drastically changed and hence the requirements for network control and operation may also be different. In addition, new Grid Code regulations for connection of large wind farms now impose the requirement that wind farms should be able to contribute to network support and operation as do conventional generation plants based on synchronous generators. To address these challenges good knowledge of wind generation dynamic models, control capabilities and interaction with the power system becomes critical.

The book aims to provide a basic understanding of modelling of wind generation systems, including both the mechanical and electrical systems, and to examine the control philosophies and schemes that enable the reliable, secure and cost-effective operation of these generation systems. The book is intended for later year undergraduate and post-graduate students interested in understanding the modelling and control of large wind turbine generators, as well as practising engineers and those responsible for grid integration. It starts with a review of the principles of operation, modelling and control of the common wind generation systems used and then moves on to discuss grid compatibility and the influence of wind turbines on power system operation and stability.

Chapter 1 provides an overview of the current status of wind energy around the world and introduces the most commonly used wind turbine configurations. Typical converter topologies and pulse-width modulation control techniques used in wind generation systems are presented in Chapter 2. Chapter 3 introduces fundamental knowledge for the mathematical modelling of synchronous machines and their representation for transient stability studies. Chapters 4 to 6 present the mathematical modelling of fixed-speed and variable-speed wind turbines, introducing typical control methodologies. Dynamic performance under small and large network disturbances is illustrated through various case studies. Different representations of shaft and blade dynamics are explained in Chapter 7 to illustrate how structural dynamics affect the performance of the wind turbine during electrical transients. The interaction between bulk wind farm generation and conventional generation and its influence on network dynamic characteristics are explained in Chapter 8. Time response simulation and eigenvalue analysis are used to establish basic transient and dynamic stability characteristics. This then leads into Chapter 9 where more advanced control strategies for variable-speed wind turbines are addressed such as the inclusion of a power system stabiliser. Enabling technologies for wind farm integration are discussed in Chapter 10 and finally Chapter 11 presents different ways in which the wind turbine can be controlled for system contingencies.

The text presented in this book draws together material on modelling and control of wind turbines from many sources, e.g. graduate courses that the authors have taught over many years at universities in the UK, USA, Sri Lanka and Mexico, a large number of technical papers published by the IEEE and IET, and research programmes with which they have been closely associated such as the EPSRC-funded SUPERGEN Future Network Technologies and the DECCfunded UK SEDG. Through these programmes the authors have had the chance to interact closely with industrial partners (utilities, power electronic equipment manufacturers and wind farm developers) and get useful points of view on the needs and priorities of the wind energy sector concerning wind turbine generator dynamic modelling and control. The authors would like to thank Prof. Jim McDonald and Prof. Goran Strbac, co-directors of the UK SEDG. Thanks are also given to Dr. Nolan Caliao and Mr. Piyadanai Pachanapan who assisted in the preparation of drawings, to Dr. Gustavo Quinonez-Varela who provided input into the operation of fixed-speed wind turbines, and to Ms Rose King who provided useful material for Chapter 10. Special thanks go to Dr. Ramtharan Gnanasambandapillai who gave permission to include material from his PhD thesis in Chapter 7.

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2009

Acronyms and Symbols

AC	Alternating current
AVR	Automatic voltage regulator
CB-PWM	Carrier-based PWM
DC	Direct current
DFIG	Doubly fed induction generator
emf	Electromotive force
FC	Fixed capacitor
FMAC	Flux magnitude and angle controller
FRC	Fully rated converter
FRC-SG	Fully rated converter wind turbine using synchronous generator
FRT	Fault ride-through
FSIG	Fixed-speed induction generator
GSC	Generator-side converter
HVAC	High-voltage alternating current
HVDC	High-voltage direct current
IGBT	Insulated-gate bipolar transistor
LCC-HVDC	Line-commutated converter HVDC
NRS-PWM	Non-regular sampled PWM
NSC	Network-side converter
PAM	Pulse-amplitude modulation
PI	Proportional–integral controller
PLL	Phase-locked loop
PM	Permanent magnet
PoC	Point of connection
PPC	Power production control
PSS	Power system stabilizer
pu	Per unit
PWM	Pulse-width modulation
RMS	Root mean square
RPM	Revolutions per minute
RS-PWM	Regular sampled PWM
SFO	Stator flux oriented
SFO-PWM	Switching frequency optimal PWM
SHEM-PWM	Selective harmonic elimination PWM

STATCOM	Static compensator
SVC	Static var compensator
SV-PWM	Space vector PWM
TCR	Thyristor-controlled reactor
TSC	Thyristor-switched capacitor
VSC	Voltage source converter
VSC–HVDC	Voltage source converter HVDC
P_{air}	Power in the airflow
ρ	Air density
A	Swept area of rotor, m^2
ν	Upwind free wind speed, ms^{-1}
C_{p}	Power coefficient
$P_{\text{wind turbine}}$	Power transferred to the wind turbine rotor
λ	Tip-speed ratio
ω	Rotational speed of rotor
R	Radius to tip of rotor
V_{m}	Mean annual site wind speed
V_{DC}	Direct voltage
Over^{-}	Per unit quantity
b	Base quantity
ϕ_{s}	Stator magnetic field
ϕ_{r}	Rotor magnetic field
$i_{d\text{s}}$, $i_{q\text{s}}$	Stator currents in d and q axis
$v_{d\text{s}}$, $v_{q\text{s}}$	Stator voltages in d and q axis
$\psi_{d\text{s}}$, $\psi_{q\text{s}}$	Stator flux linkage in d and q axis
T_{e}	Electromagnetic torque
T_{m}	Mechanical torque
P_{e}	Electrical power
P_{m}	Mechanical power
Q	Reactive power
ω	$_{\text{b}}$ Base synchronous speed
ω_{s}	Synchronous speed

ω_r	Rotor speed
J	Inertia constant
H	Per unit inertia constant
K	Shaft stiffness
f	System frequency
C	Capacitance

Synchronous Generator

i_f	Field current
$i_{\mathrm{k}d}$, $i_{\mathrm{k}q1}$, $i_{\mathrm{k}q2}$	Damper winding d and q axis currents
$L_{\mathrm{lk}d}$, $L_{\mathrm{lk}q}$	Leakage inductance of damper windings in d and q axis
$L_{\mathrm{m}d}$, $L_{\mathrm{m}q}$	Mutual inductance in d and q axis
L_lf	Leakage inductance of the field coil
L_ls	Leakage inductance of the stator coil
r_s	Stator resistance
r_f	Field winding resistance
$r_{\mathrm{k}d}$, $r_{\mathrm{k}q1}$, $r_{\mathrm{k}q2}$	Resistance of damper d and q axis coils
$v_{\mathrm{f}d}$	Field voltage
$v_{\mathrm{k}d}$, $v_{\mathrm{k}q1}$, $v_{\mathrm{k}q2}$	Damper winding voltages in d and q axis
ψ_f	Field flux linkage
$\psi_{\mathrm{k}d}$, $\psi_{\mathrm{k}q1}$, $\psi_{\mathrm{k}q2}$	Damper winding flux linkage in d and q axis
δ_r	Rotor angle
C_s	Synchronizing power coefficient
C_d	Damping power coefficient

Induction Generator

$i_{d\mathrm{r}}$, $i_{q\mathrm{r}}$	Rotor currents in d and q axis
$v_{d\mathrm{r}}$, $v_{q\mathrm{r}}$	Rotor voltages in d and q axis
$\psi_{d\mathrm{r}}$, $\psi_{q\mathrm{r}}$	Rotor flux linkage in d and q axis
e_d , e_q	Voltage behind a transient reactance in d and q axis

L_m	Mutual inductance between stator and rotor windings
X_m	Magnetizing reactance
L_r, L_s	Rotor and stator self-inductance
X_r, X_s	Rotor and stator reactance
L_lr	Rotor leakage inductance
L_ls	Stator leakage inductance
r_r	Rotor resistance
r_s	Stator resistance
s	Slip of an induction generator
p	Number of poles

1

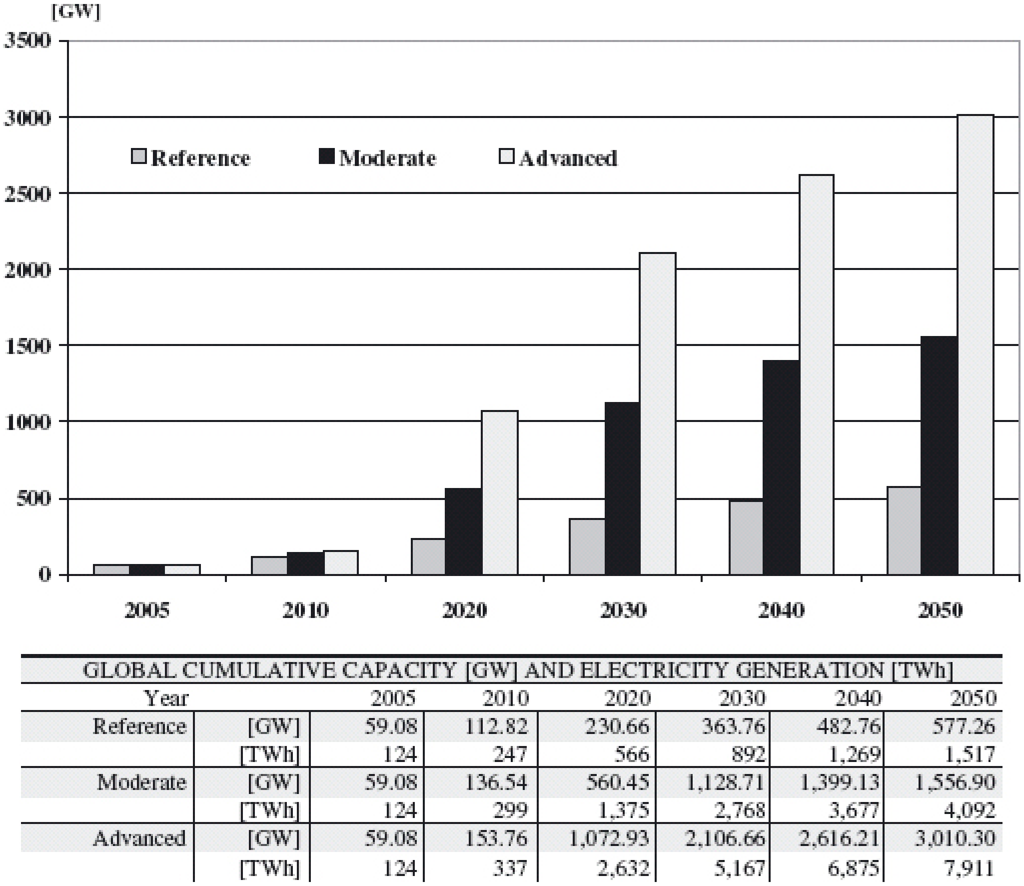
Electricity Generation from Wind Energy

There is now general acceptance that the burning of fossil fuels is having a significant influence on the global climate. Effective mitigation of climate change will require deep reductions in greenhouse gas emissions, with UK estimates of a 60–80% cut being necessary by 2050 (Stern Review, UK HM Treasury, 2006). The electricity system is viewed as being easier to transfer to low-carbon energy sources than more challenging sectors of the economy such as surface and air transport and domestic heating. Hence the use of cost-effective and reliable low-carbon electricity generation sources, in addition to demand-side measures, is becoming an important objective of energy policy in many countries (EWEA, 2006; AWEA, 2007).

Over the past few years, wind energy has shown the fastest rate of growth of any form of electricity generation with its development stimulated by concerns of national policy makers over climate change, energy diversity and security of supply.

Figure 1.1 shows the global cumulative wind power capacity worldwide (GWEC, 2006). In this figure, the 'Reference' scenario is based on the projection in the 2004 World Energy Outlook report from the International Energy Agency (IEA). This projects the growth of all renewables including wind power, up to 2030. The 'Moderate' scenario takes into account all policy measures to support renewable energy either under way or planned worldwide. The 'Advanced' scenario makes the assumption that all policy options are in favour of wind power, and the political will is there to carry them out.

Figure 1.1 Global cumulative wind power capacity (GWEC, 2006)



GLOBAL CUMULATIVE CAPACITY [GW] AND ELECTRICITY GENERATION [TWh]							
Year		2005	2010	2020	2030	2040	2050
Reference	[GW]	59.08	112.82	230.66	363.76	482.76	577.26
	[TWh]	124	247	566	892	1,269	1,517
Moderate	[GW]	59.08	136.54	560.45	1,128.71	1,399.13	1,556.90
	[TWh]	124	299	1,375	2,768	3,677	4,092
Advanced	[GW]	59.08	153.76	1,072.93	2,106.66	2,616.21	3,010.30
	[TWh]	124	337	2,632	5,167	6,875	7,911

1.1 Wind Farms

Numerous wind farm projects are being constructed around the globe with both offshore and onshore developments in Europe and primarily large onshore developments in North America. Usually, sites are preselected based on general information of wind speeds provided by a wind atlas, which is then validated with local measurements. The local wind resource is monitored for 1 year, or more, before the project is approved and the wind turbines installed.

Onshore turbine installations are frequently in upland terrain to exploit the higher wind speeds. However, wind farm permitting and siting onshore can be difficult as high wind-speed sites are often of high visual amenity value and environmentally sensitive.

Offshore development, particularly of larger wind farms, generally takes place more than 5 km from land to reduce environmental impact. The advantages of offshore wind farms include reduced visual intrusion and acoustic noise impact and also lower wind turbulence with higher average wind speeds.

Table 1.1 Wind turbine applications (Elliot, 2002)

Small (≤10 kW)	**Intermediate (10–500 kW)**	**Large (500 kW–5 MW)**
• Homes (grid-connected)	• Village power	• Wind power plants
• Farms	• Hybrid systems	• Distributed power
• Autonomous remote applica- tions (e.g. battery charging, water pumping, telecom sites)	• Distributed power	• Onshore and offshore wind generation

The obvious disadvantages are the higher costs of constructing and operating wind turbines offshore, and the longer power cables that must be used to connect the wind farm to the terrestrial power grid.

In general, the areas of good wind energy resource are found far from population centres and new transmission circuits are needed to connect the wind farms into the main power grid. For example, it is estimated that in Germany, approximately 1400 km of additional high-voltage and extra-high-voltage lines will be required over the next 10 years to connect new wind farms (Deutsche Energie-Agentur GmbH, 2005).

Smaller wind turbines may also be used for rural electrification with applications including village power systems and stand-alone wind systems for hospitals, homes and community centres (Elliot, 2002).

Table 1.1 illustrates typical wind turbine ratings according to their application.

1.2 Wind Energy-generating Systems

Wind energy technology has evolved rapidly over the last three decades (Figure 1.2) with increasing rotor diameters and the use of sophisticated power electronics to allow operation at variable rotor speed.

1.2.1 Wind Turbines

Wind turbines produce electricity by using the power of the wind to drive an electrical generator. Wind passes over the blades, generating lift and exerting a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox increases the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700 V to the appropriate voltage for the power collection system, typically 33 kV.

A wind turbine extracts kinetic energy from the swept area of the blades (Figure 1.3). The power in the airflow is given by (Manwell *et al.*, 2002; Burton *et al.*, 2001):

Figure 1.2 Evolution of wind turbine dimensions

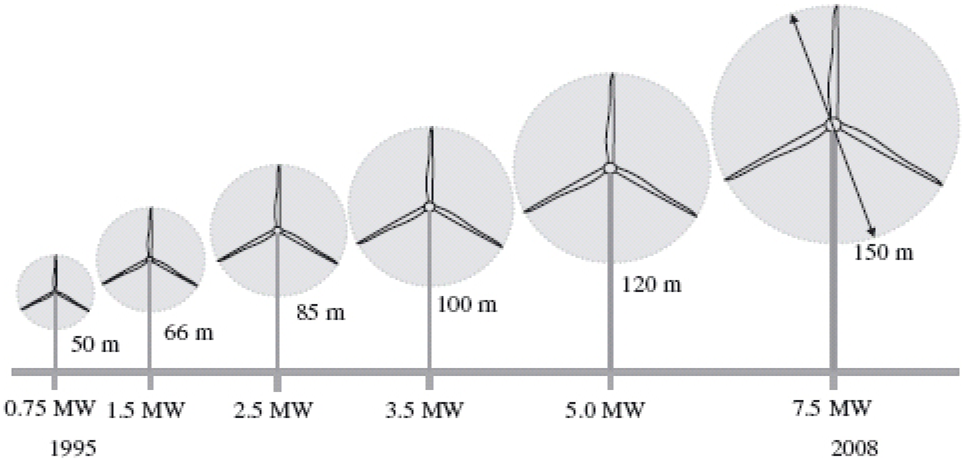
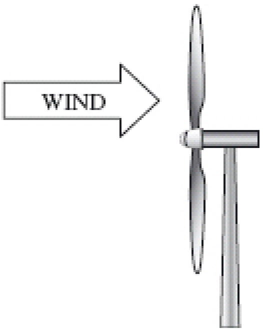


Figure 1.3 Horizontal axis wind turbine



(1.1) $P_{\text{air}} = \frac{1}{2}\rho A v^3$

where

ρ = air density (approximately 1.225 kg m^{-3}) A = swept area of rotor, m^2

ν = upwind free wind speed, m s^{-1}.

Although Eq. (1.1) gives the power available in the wind the power transferred to the wind turbine rotor is reduced by the power coefficient, Cp:

(1.2) $C_p = \frac{P_{\text{wind turbine}}}{P_{\text{air}}}$

(1.3) $P_{\text{wind turbine}} = C_p P_{\text{air}} = C_p \times \frac{1}{2}\rho A v^3$

A maximum value of Cp is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum Cp values in the range 25–45%.

It is also conventional to define a tip-speed ratio, λ,as

(1.4) $$\lambda = \frac{\omega R}{\nu}$$

where

ω = rotational speed of rotor

R = radius to tip of rotor

ν = upwind free wind speed, m s^{-1}.

The tip-speed ratio, λ, and the power coefficient, Cp, are dimensionless and so can be used to describe the performance of any size of wind turbine rotor. Figure 1.4 shows that the maximum power coefficient is only achieved at a single tip-speed ratio and for a fixed rotational speed of the wind turbine this only occurs at a single wind speed. Hence, one argument for operating a wind turbine at variable rotational speed is that it is possible to operate at maximum Cp over a range of wind speeds.

The power output of a wind turbine at various wind speeds is conventionally described by its power curve. The power curve gives the steady-state electrical power output as a function of the wind speed at the hub height and is generally measured using 10 min average data. An example of a power curve is given in Figure 1.5.

Figure 1.4 Illustration of power coefficient/tip-speed ratio curve, Cp/λ

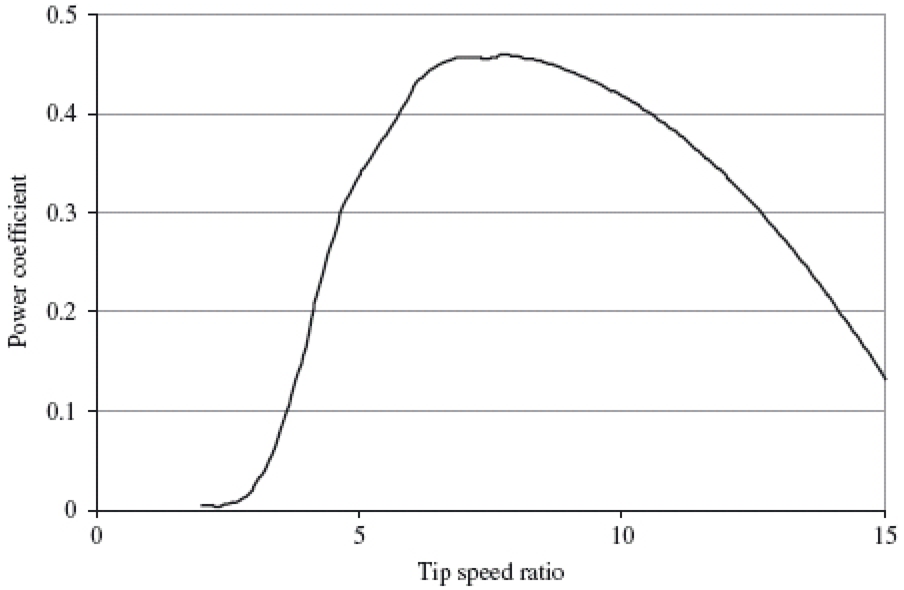
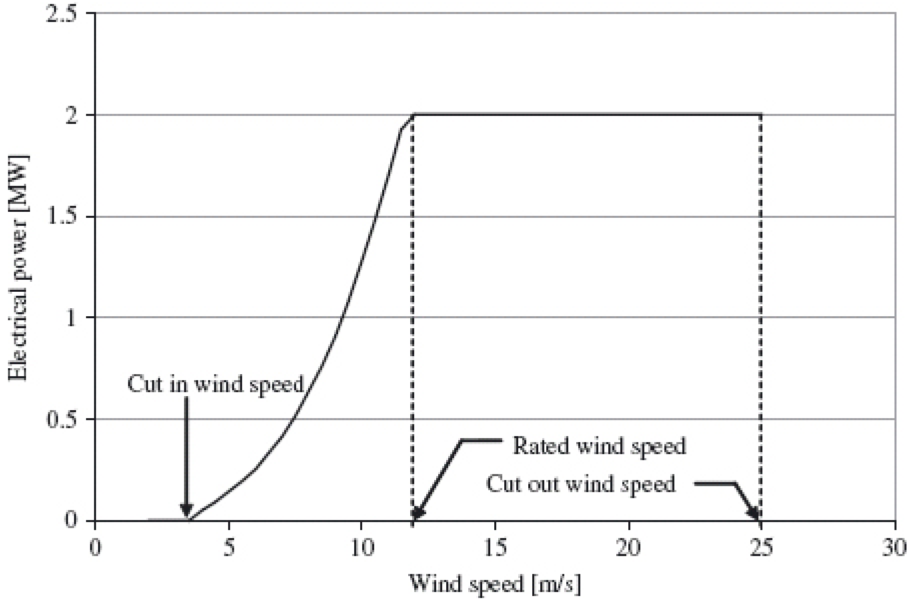


Figure 1.5 Power curve for a 2MW wind turbine



The power curve has three key points on the velocity scale:

- Cut-in wind speed – the minimum wind speed at which the machine will deliver useful power.
- Rated wind speed – the wind speed at which rated power is obtained (rated power is generally the maximum power output of the electrical generator).

- Cut-out wind speed – the maximum wind speed at which the turbine is allowed to deliver power (usually limited by engineering loads and safety constraints).

Below the cut-in speed, of about 5 m s^{-1}, the wind turbine remains shut down as the speed of the wind is too low for useful energy production. Then, once in operation, the power output increases following a broadly cubic relationship with wind speed (although modified by the variation in Cp) until rated wind speed is reached. Above rated wind speed the aerodynamic rotor is arranged to limit the mechanical power extracted from the wind and so reduce the mechanical loads on the drive train. Then at very high wind speeds the turbine is shut down.

The choice of cut-in, rated and cut-out wind speed is made by the wind turbine designer who, for typical wind conditions, will try to balance obtaining maximum energy extraction with controlling the mechanical loads (and hence the capital cost) of the turbine. For a mean annual site wind speed Vm of 8ms^{-1}typical values will be approximately (Fox *et al*., 2007):

- cut-in wind speed: 5 m s^{-1}, 0.6 Vm
- rated wind speed: 12–14ms^{-1},1.5–1.75 Vm
- cut-out wind speed: 25 m s^{-1}, 3Vm.

Power curves for existing machines can normally be obtained from the turbine manufacturer. They are found by field measurements, where an anemometer is placed on a mast reasonably close to the wind turbine, not on the turbine itself or too close to it, since the turbine may create turbulence and make wind speed measurements unreliable.

1.2.2 Wind Turbine Architectures

There are a large number of choices of architecture available to the designer of a wind turbine and, over the years, most of these have been explored (Ackermann, 2005; Heier, 2006). However, commercial designs for electricity generation have now converged to horizontal axis, three-bladed, upwind turbines. The largest machines tend to operate at variable speed whereas smaller, simpler turbines are of fixed speed.

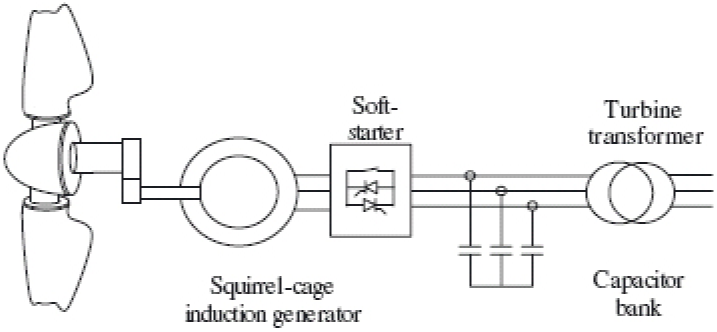
Modern electricity-generating wind turbines now use three-bladed upwind rotors, although two-bladed, and even one-bladed, rotors were used in earlier commercial turbines. Reducing the number of blades means that the rotor has to operate at a higher rotational speed in order to extract the wind energy passing through the rotor disk. Although a high rotor speed is attractive in that it reduces the gearbox ratio required, a high blade tip speed leads to increased aerodynamic noise and increased blade drag losses. Most importantly, three-bladed rotors are visually more pleasing than other designs and so these are now always used on large electricity-generating turbines.

1.2.2.1 Fixed-speed Wind Turbines

Fixed-speed wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator. From the electrical system viewpoint they are perhaps best considered as large fan drives with torque applied to the low-speed shaft from the wind flow.

Figure 1.6 illustrates the configuration of a fixed-speed wind turbine (Holdsworth *et al.*, 2003; Akhmatov, 2007). It consists of a squirrel-cage induction generator coupled to the power system through a turbine transformer. The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, because the operating slip variation is generally less than 1%, this type of wind generation is normally referred to as fixed speed.

Figure 1.6 Schematic of a fixed-speed wind turbine



Squirrel-cage induction machines consume reactive power and so it is conventional to provide power factor correction capacitors at each wind turbine. The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator. Also, by applying the network voltage slowly to the generator, once energized, it brings the drive train slowly to its operating rotational speed.

1.2.2.2 Variable-speed Wind Turbines

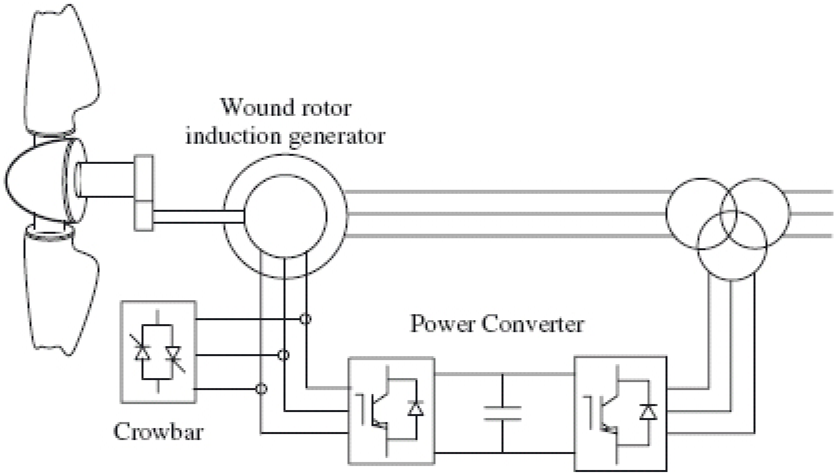
As the size of wind turbines has become larger, the technology has switched from fixed speed to variable speed. The drivers behind these developments are mainly the ability to comply with Grid Code connection requirements and the reduction in mechanical loads achieved with variable-speed operation. Currently the most common variable-speed wind turbine configurations are as follows:

- doubly fed induction generator (DFIG) wind turbine
- fully rated converter (FRC) wind turbine based on a synchronous or induction generator.

Doubly Fed Induction Generator (DFIG) Wind Turbine

A typical configuration of a DFIG wind turbine is shown schematically in Figure 1.7. It uses a wound-rotor induction generator with slip rings to take current into or out of the rotor winding and variable-speed operation is obtained by injecting a controllable voltage into the rotor at slip frequency (Muller¨*et al*., 2002; Holdsworth *et al*., 2003). The rotor winding is fed through a variable-frequency power converter, typically based on two AC/DC IGBT-based voltage source converters (VSCs), linked by a DC bus. The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling variable-speed operation of the wind turbine. The generator and converters are protected by voltage limits and an over-current 'crowbar'.

Figure 1.7 Typical configuration of a DFIG wind turbine



A DFIG system can deliver power to the grid through the stator and rotor, while the rotor can also absorb power. This depends on the rotational speed of the generator. If the generator operates above synchronous speed, power will be delivered from the rotor through the converters to the network, and if the generator operates below synchronous speed, then the rotor will absorb power from the network through the converters.

Fully Rated Converter (FRC) Wind Turbine