1

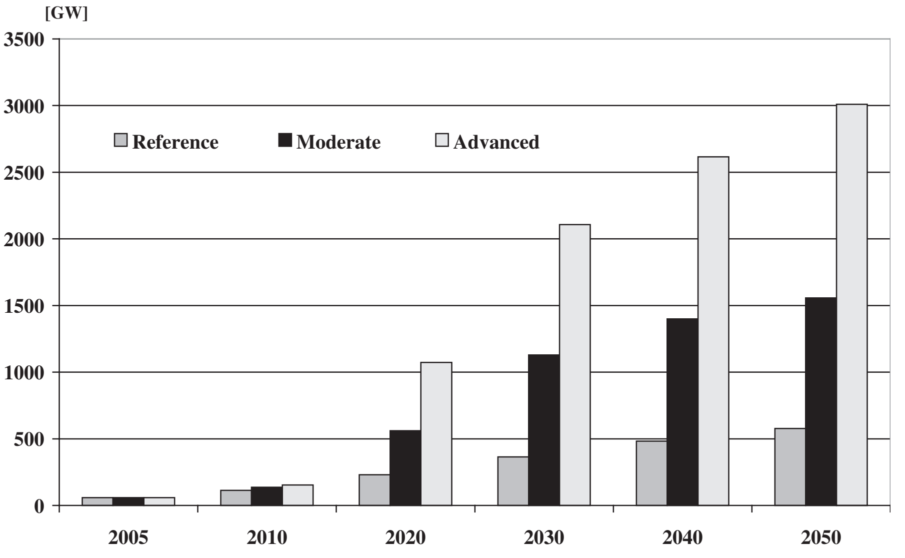
Electricity Generation from Wind Energy

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.

Wind Energy Generation: Modelling and Control Olimpo Anaya-Lara, Nick Jenkins, Janaka Ekanayake, Phill Cartwright and Mike Hughes



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

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

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 ($\leqslant$10 kW)	Intermediate (10–500 kW)	Large (500 kW–5 MW)
• Homes (grid-connected) • Farms • Autonomous remote applications (e.g. battery charging, water pumping, telecom sites)	• Village power • Hybrid systems • Distributed power	• Wind power plants • 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;

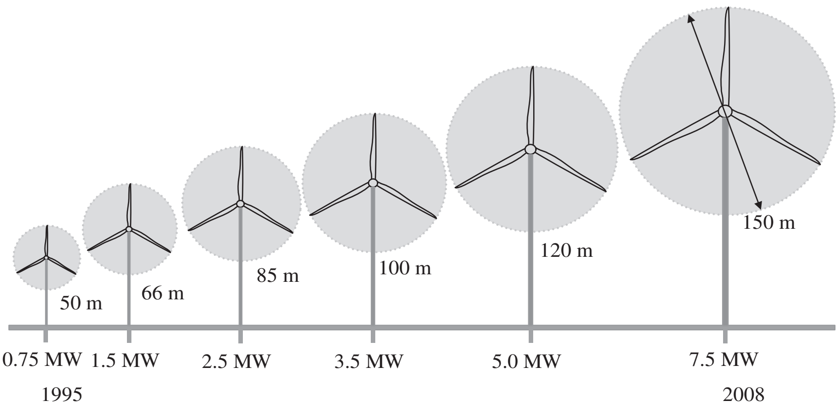


Figure 1.2 Evolution of wind turbine dimensions

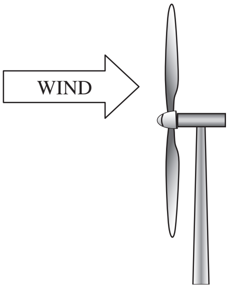


Figure 1.3 Horizontal axis wind turbine

Burton *et al.*, 2001):

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

where

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

$$C_{\text{p}} = \frac{P_{\text{wind turbine}}}{P_{\text{air}}} \tag{1.2}$$

$$P_{\text{wind turbine}} = C_{\text{p}} P_{\text{air}} = C_{\text{p}} \times \frac{1}{2}\rho A v^3 \tag{1.3}$$

A maximum value of C_p 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 C_p values in the range 25–45%.

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

$$\lambda = \frac{\omega R}{v} \tag{1.4}$$

where

ω = rotational speed of rotor
R = radius to tip of rotor
v = upwind free wind speed, $\mathrm{m\,s^{-1}}$.

The tip-speed ratio, λ, and the power coefficient, C_p, 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 C_p 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

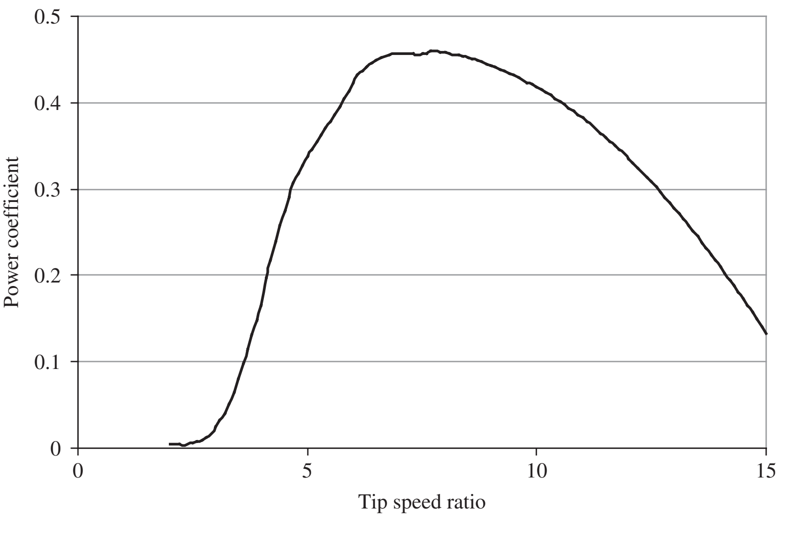


Figure 1.4 Illustration of power coefficient/tip-speed ratio curve, C_p/λ

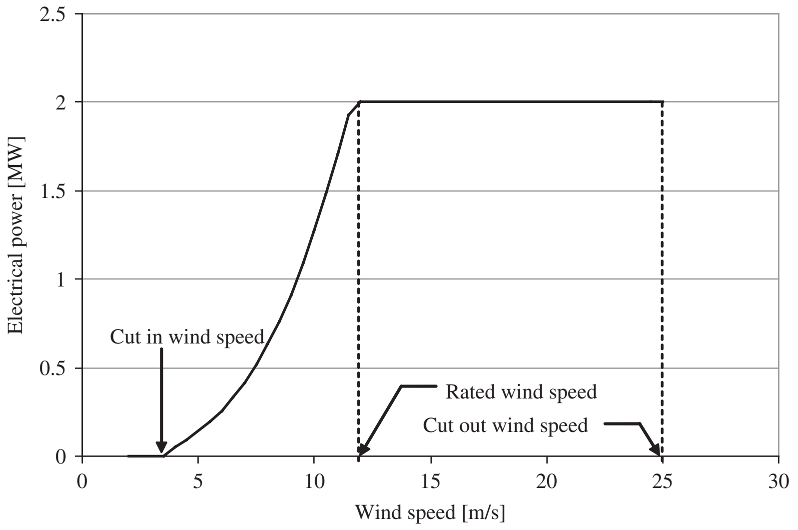


Figure 1.5 Power curve for a 2 MW wind turbine

measured using 10 min average data. An example of a power curve is given in Figure 1.5.

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 $5\,\mathrm{m\,s^{-1}}$, 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 C_p) 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 V_{m} of $8\,\mathrm{m\,s^{-1}}$ typical values will be approximately (Fox *et al.*, 2007):

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

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

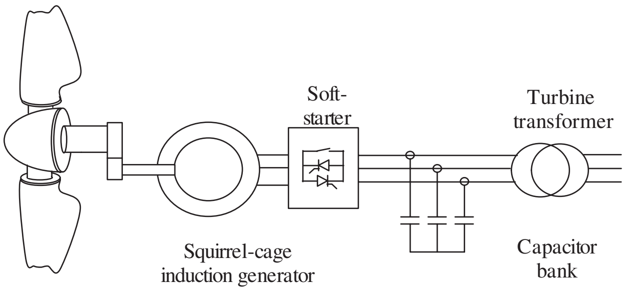


Figure 1.6 Schematic of a fixed-speed wind turbine

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.

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

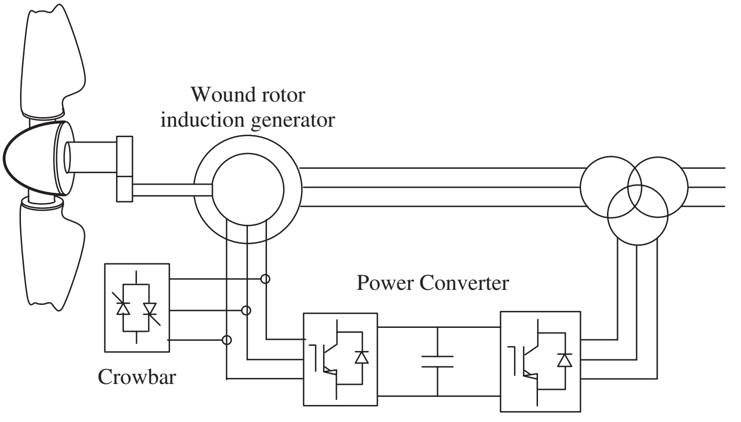


Figure 1.7 Typical configuration of a DFIG wind turbine

obtained by injecting a controllable voltage into the rotor at slip frequency (Müller *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'.

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

The typical configuration of a fully rated converter wind turbine is shown in Figure 1.8. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid (Akhmatov *et al*., 2003; Heier, 2006). The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine.

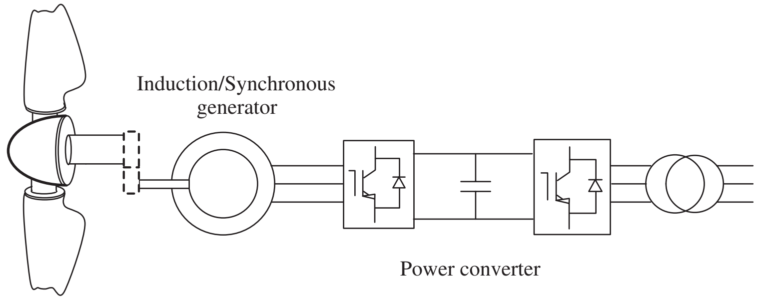


Figure 1.8 Typical configuration of a fully rated converter-connected wind turbine

The power converters can be arranged in various ways. Whereas the generator-side converter (GSC) can be a diode rectifier or a PWM voltage source converter (VSC), the network-side converter (NSC) is typically a PWM VSC. The strategy to control the operation of the generator and the power flows to the network depends very much on the type of power converter arrangement employed. The network-side converter can be arranged to maintain the DC bus voltage constant with torque applied to the generator controlled from the generator-side converter. Alternatively, the control philosophy can be reversed. Active power is transmitted through the converters with very little energy stored in the DC link capacitor. Hence the torque applied to the generator can be controlled by the network-side converter. Each converter is able to generate or absorb reactive power independently.

1.3 Wind Generators Compared with Conventional Power Plant

There are significant differences between wind power and conventional synchronous central generation (Slootweg, 2003):

- Wind turbines employ different, often converter-based, generating systems compared with those used in conventional power plants.
- The prime mover of wind turbines, the wind, is not controllable and fluctuates stochastically.
- The typical size of individual wind turbines is much smaller than that of a conventional utility synchronous generator.

Due to these differences, wind generation interacts differently with the network and wind generation may have both local and system-wide impacts on the operation of the power system. Local impacts occur in the electrical vicinity of a wind turbine or wind farm, and can be attributed to a specific turbine or farm.

System-wide impacts, on the other hand, affect the behaviour of the power system as a whole. They are an inherent consequence of the utilization of wind power and cannot be attributed to individual turbines or farms (UCTE, 2004).

1.3.1 Local Impacts

Locally, wind power has an impact on the following aspects of the power system:

- circuit power flows and busbar voltages
- protection schemes, fault currents, and switchgear rating
- power quality
  - harmonic voltage distortion
  - voltage flicker.

The first two topics are always investigated when connecting any new generator and are not specific to wind power. Harmonic voltage distortion is of particular interest when power electronic converters are employed to interface wind generation units to the network whereas voltage flicker is more significant for large, fixed-speed wind turbines on weak distribution circuits.

1.3.1.1 Circuit Power Flows and Busbar Voltages

The way in which wind turbines affect locally the circuit active and reactive power flows and busbar voltages depends on whether fixed-speed or variable-speed turbines are used. The operating condition of a squirrel-cage induction generator, used in fixed-speed turbines, is dictated by the mechanical input power and the voltage at the generator terminals. This type of generator cannot control busbar voltages by itself controlling the reactive power exchange with the network. Additional reactive power compensation equipment, often fixed shunt-connected capacitors, is normally fitted. Variable-speed turbines have, in principle, the capability of varying the reactive power that they exchange with the grid to affect their terminal voltage. In practice, this capability depends to a large extent on the rating and the controllers of the power electronic converters.

1.3.1.2 Protection Schemes, Fault Currents and Switchgear Rating

The contribution of wind turbines to network fault current also depends on the generator technology employed. Fixed-speed turbines, in common with all directly connected spinning plant, contribute to network fault currents.

However, as they use induction generators, they contribute only sub-transient fault current (lasting less than, say, 200 ms) to balanced three-phase faults but can supply sustained fault current to unbalanced faults. They rely on sequential tripping (over/under-voltage, over/under-frequency and loss of mains) protection schemes to detect when conventional over-current protection has isolated a faulty section of the network to which they are connected.

Variable-speed DFIG wind turbines also contribute to network fault currents with the control system of the power electronic converters detecting the fault very quickly. Due to the sensitivity of the power electronics to over-currents, this type of wind turbine may be quickly disconnected from the network and the crowbar activated to short-circuit the rotor windings of the wound-rotor induction generator, unless special precautions are taken to ensure Grid Code compliance.

Fully rated converter-connected wind turbines generally do not contribute significantly to network fault current because the network-side converter is not sized to supply sustained over-currents. Again, this wind turbine type may also disconnect quickly in the case of a fault, if the Grid Codes do not require a Fault Ride Through capability.

The behaviour of power converter-connected wind turbines during network faults depends on the design of the power converters and the settings of their control systems. There are as yet no agreed international standards for either the fault contribution performance required of converter-connected generators or how such generators should be represented in transient stability or fault calculator simulation programs. A conservative design approach is to assume that such generators do contribute fault current when rating switchgear and other plant, but not to rely on such fault currents for protection operation.

1.3.1.3 Power Quality

Two local effects of wind power on power quality may be considered, voltage harmonic distortion and flicker. Harmonic distortion is mainly associated with variable-speed wind turbines because these contain power electronic converters, which are an important source of high-frequency harmonic currents. It is increasingly of concern in large offshore wind farms, where the very extensive cable networks can lead to harmonic resonances and high harmonic currents caused by existing harmonic voltages already present on the power system or by the wind turbine converters.

In fixed-speed wind turbines, wind fluctuations are directly translated into output power fluctuations because there is no energy buffer between the mechanical input and the electrical output. Depending on the strength of the grid connection, the resulting power fluctuations can result in grid voltage fluctuations, which can cause unwanted and annoying fluctuations in electric light bulb brightness. This problem is referred to as 'flicker'. In general, flicker problems do not occur with variable-speed turbines, because in these turbines wind speed fluctuations are not directly translated into output power fluctuations. The stored energy of the spinning mass of the rotor acts as an energy buffer.

1.3.2 System-wide Impacts

In addition to the local impacts, wind power also has a number of system-wide impacts as it affects the following (Slootweg, 2003; UCTE, 2004):

- power system dynamics and stability
- reactive power and voltage support
- frequency support.

1.3.2.1 Power System Dynamics and Stability

Squirrel-cage induction generators used in fixed-speed turbines can cause local voltage collapse after rotor speed runaway. During a fault (and consequent network voltage depression), they accelerate due to the imbalance between the mechanical power from the wind and the electrical power that can be supplied to the grid. When the fault is cleared, they absorb reactive power, depressing the network voltage. If the voltage does not recover quickly enough, the wind turbines continue to accelerate and to consume large amounts of reactive power. This eventually leads to voltage and rotor speed instability. In contrast to synchronous generators, the exciters of which increase reactive power output during low network voltages and thus support voltage recovery after a fault, squirrel-cage induction generators tend to impede voltage recovery.

With variable-speed wind turbines, the sensitivity of the power electronics to over-currents caused by network voltage depressions can have serious consequences for the stability of the power system. If the penetration level of variable-speed wind turbines in the system is high and they disconnect at relatively small voltage reductions, a voltage drop over a wide geographic area can lead to a large generation deficit. Such a voltage drop could be caused, for instance, by a fault in the transmission grid. To prevent this, grid companies and transmission system operators require that wind turbines have a Fault Ride Through capability and are able to withstand voltage drops of certain magnitudes and durations without tripping. This prevents the disconnection of a large amount of wind power in the event of a remote network fault.

1.3.2.2 Reactive Power and Voltage Support

The voltage on a transmission network is determined mainly by the interaction of reactive power flows with the reactive inductance of the network. Fixed-speed induction generators absorb reactive power to maintain their magnetic field and have no direct control over their reactive power flow. Therefore, in the case of fixed-speed induction generators, the only way to support the voltage of the network is to reduce the reactive power drawn from the network by the use of shunt compensators.

Variable-speed wind turbines have the capability of reactive power control and may be able to support the voltage of the network to which they are connected. However, individual control of wind turbines may not be able to control the voltage at the point of connection, especially because the wind farm network is predominantly capacitive (a cable network).

On many occasions, the reactive power and voltage control at the point of connection of the wind farm is achieved by using reactive power compensation equipment such as static var compensators (SVCs) or static synchronous compensators (STATCOMs).

1.3.2.3 Frequency Support

To provide frequency support from a generation unit, the generator power must increase or decrease as the system frequency changes. Hence, in order to respond to low network frequency, it is necessary to de-load the wind turbine leaving a margin for power increase. A fixed-speed wind turbine can be de-loaded if the pitch angle is controlled such that a fraction of the power that could be extracted from wind will be ‘spilled’. A variable-speed wind turbine can be de-loaded by operating it away from the maximum power extraction curve, thus leaving a margin for frequency control.

1.4 Grid Code Regulations for the Integration of Wind Generation

Grid connection codes define the requirements for the connection of generation and loads to an electrical network which ensure efficient, safe and economic operation of the transmission and/or distribution systems. Grid Codes specify the mandatory minimum technical requirements that a power plant should fulfil and additional support that may be called on to maintain the second-by-second power balance and maintain the required level of quality and security of the system. The additional services that a power plant should provide are normally

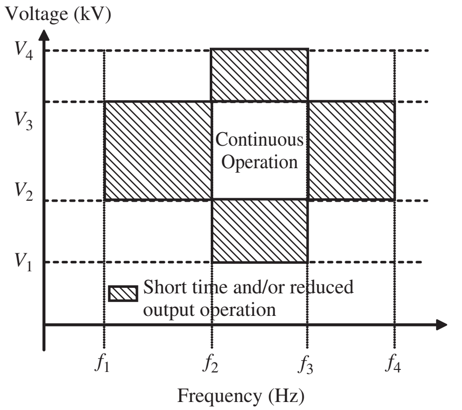


Figure 1.9 Typical shape of continuous and reduced output regions (after Great Britain and Ireland Grid Codes; ESB National Grid, 2008; National Grid, 2008)

agreed between the transmission system operator and the power plant operator through market mechanisms.

The connection codes normally focus on the point of connection between the public electricity system and the new generation. This is very important for wind farm connections, as the Grid Codes demand requirements at the point of connection of the wind farm not at the individual wind turbine generator terminals. The grid connection requirements differ from country to country and may differ from region to region. They have many common features but some of the requirements are subtly different, reflecting the characteristics of the individual grids.

As a mandatory requirement, the levels and time period of the output power of a generating plant should be maintained within the specified values of grid frequency and grid voltage as specified in Grid Codes. Typically, this requirement is defined as shown in Figure 1.9, where the values of voltage, V_1 to V_4, and frequency, f_1 to f_4, differ from country to country.

Grid Codes also specify the steady-state operational region of a power plant in terms of active and reactive power requirements. The definition of the operational region differs from country to country. For example, Figure 1.10 shows the operational regions as specified in the Great Britain and Ireland Grid Codes.

Almost all Grid Codes now impose the requirement that wind farms should be able to provide primary frequency response. The capability profile typically specifies the minimum required level of response, the frequency deviation at which it should be activated and time to respond.

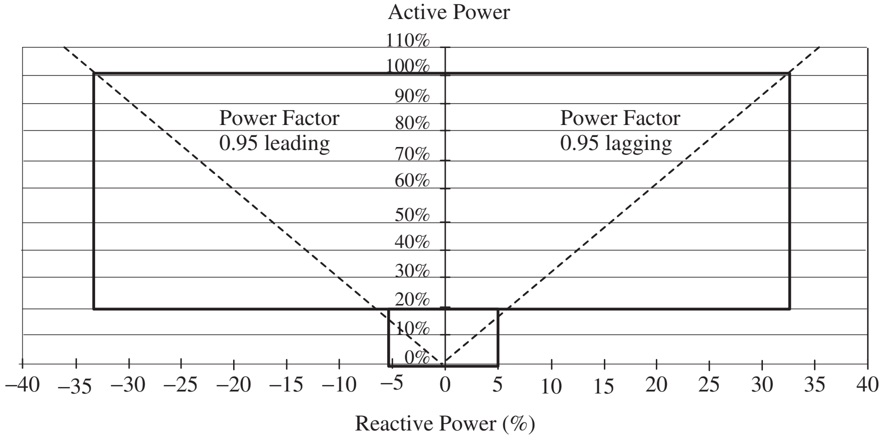


Figure 1.10 Typical steady-state operating region (after Great Britain and Ireland Grid Codes; ESB National Grid, 2008; National Grid, 2008)

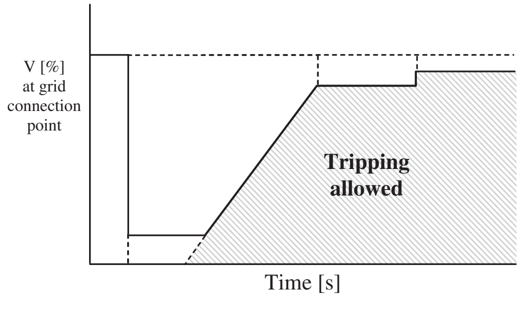


Figure 1.11 Typical shape of Fault Ride Through capability plot (after Great Britain and Ireland Grid Codes; ESB National Grid, 2008; National Grid, 2008)

Traditionally, wind turbine generators were tripped off once the voltage at their terminals reduced to a specified level. However, with the penetration of wind generation increasing, Grid Codes now generally demand Fault Ride Through capability for wind turbines connected to transmission networks. Figure 1.11 shows a plot illustrating the general shape of voltage tolerance that most grid operators demand. When reduced system voltage occurs following a network fault, generator tripping is only permitted when the voltage is sufficiently low and for a time that puts it in the shaded area shown in Figure 1.11. Grid Codes are under continual review and, as the level of wind power increases, are likely to become mode demanding.

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