

1

Offshore Wind Energy Systems

1.1 Background

With construction restrictions inhibiting the deployment of wind turbines onshore, offshore installations are more attractive (e.g. in the UK) (The Crown State, 2011). By mid-2012, offshore wind power installed globally was 4620 MW, representing about 2% of the total installed wind power capacity. Over 90% of the offshore wind turbines currently installed across the globe are situated in the North, Baltic and Irish Seas, along with the English Channel. Most of the rest is in two demonstration projects off China's coast. According to the more ambitious projections, a total of 80 GW of offshore wind power could be installed worldwide by 2020, with three quarters of this in Europe (GWEC, 2013).

All current offshore wind installations are relatively close to shore, using well-known onshore wind turbine technology. However, new offshore wind sites located far from shore have been identified, with clusters of wind farms appearing at favourable locations for wind power extraction, like in the UK Dogger Bank and German Bight (Figure 1.1) (European Union, 2011). The depths of the waters at these sites are in excess of 30 m.

1.2 Typical Subsystems

The typical subsystems in an offshore wind farm are shown in Figure 1.2. At first glance, it comprises the same elements of an onshore wind farm. However, the environment in which a turbine operates allows a distinction to be made. Considering that the nature of the sea state will act to prohibit accessibility of wind turbines for repair, there is a greater need for offshore wind turbines to be reliable and not require regular repair. This requirement means that the designs and controllers of offshore wind turbines differ from those seen with onshore wind turbines. This is to ensure that performance is maximised whilst minimising cost (German Energy Agency, 2010).

Offshore Wind Energy Generation: Control, Protection, and Integration to Electrical Systems, First Edition.

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Companion Website: www.wiley.com/go/offshore_wind_energy_generation

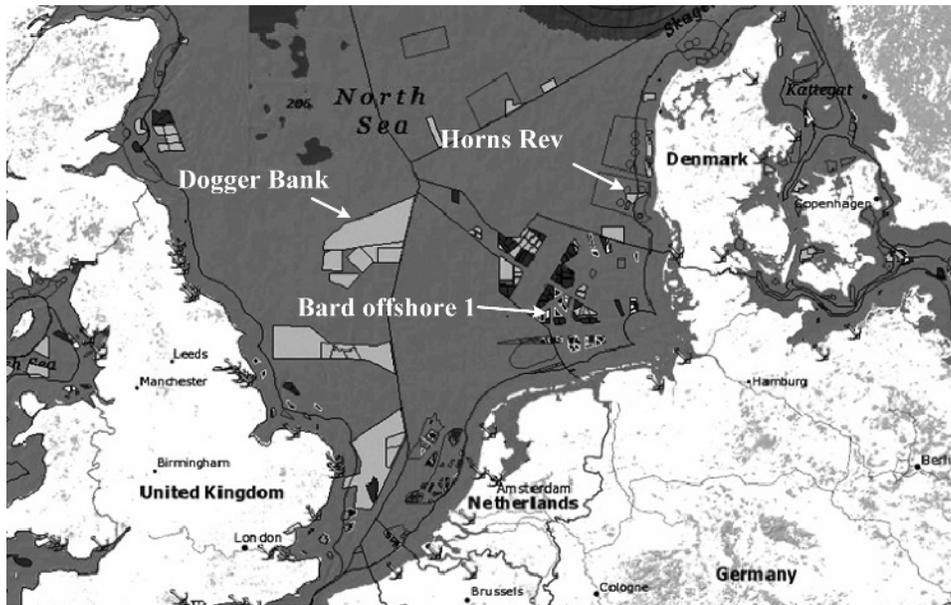


Figure 1.1 Europe's offshore wind farms in operation, construction and planning (Source: www.4coffshore.com/offshorewind).

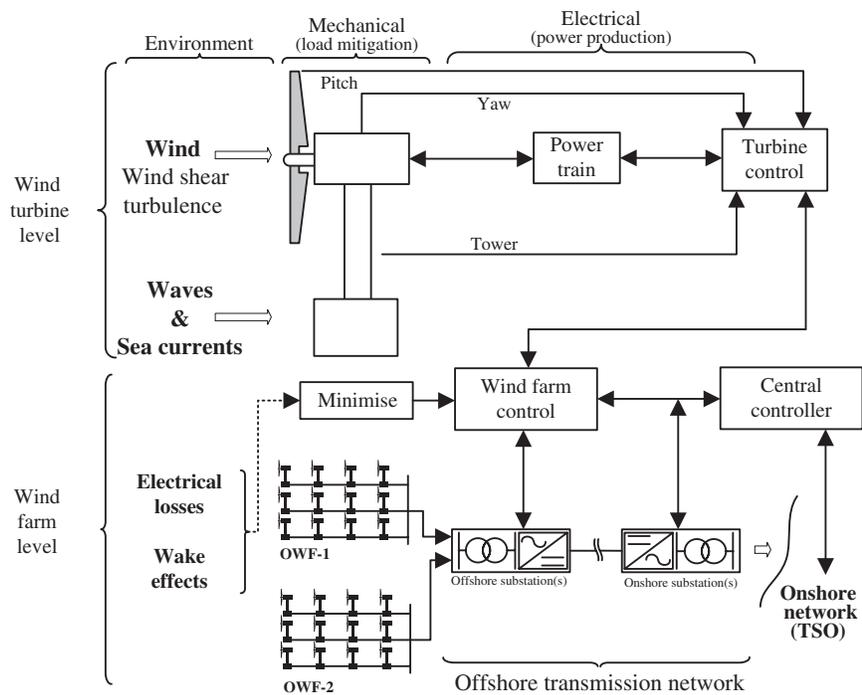


Figure 1.2 Subsystems of an offshore wind farm installation (Anaya-Lara *et al.*, 2013).

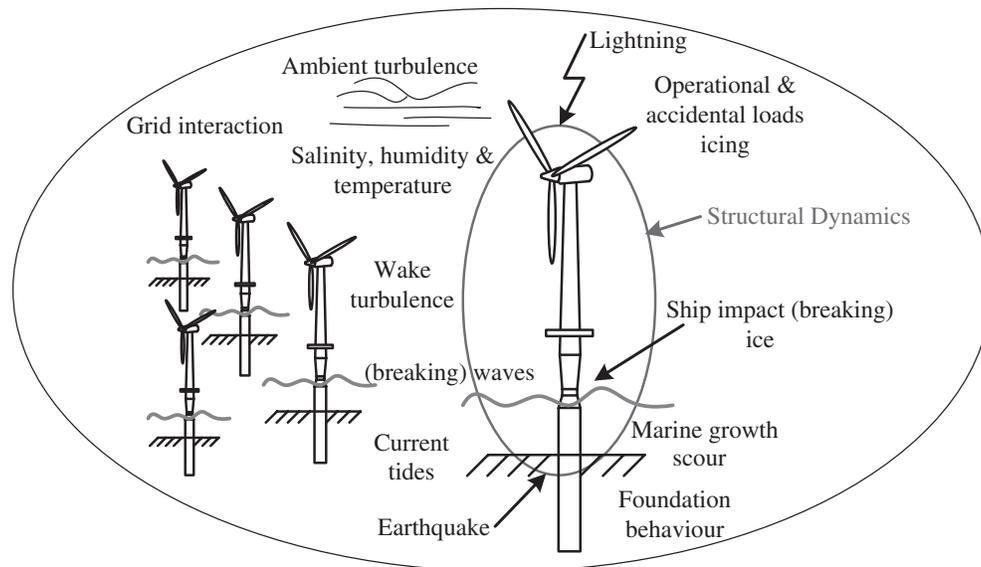


Figure 1.3 Impacts on a bottom-fixed wind turbine (Fischer, 2006).

In the offshore environment, loads are induced by wind, waves, sea currents, and in some cases, floating ice (Figure 1.3), introducing new and difficult challenges for offshore wind turbine design and analysis. Accurate estimation and proper combination of these loads are essential to the turbine and associated controllers design process. Offshore wind turbines have different foundations to onshore wind turbines. The foundations are subjected to hydrodynamic loads. This hydrodynamic loading will inevitably exhibit some form of coupling to the aerodynamic loading seen by the rotor, nacelle and tower. This is an additional problem that must be considered when designing offshore wind turbines. Ideally, the total system composed of rotor/nacelle, tower, substructure and foundation should be analysed using an integrated model (Nielsen, 2006). Development of novel wind turbine concepts optimised for operation in rough offshore conditions along with better O&M strategies is crucial. In addition, turbine control philosophy must be consistent and address the turbine as a whole dynamic element, bearing in mind trade-offs in terms of mechanical performance and power output efficiency (Anaya-Lara *et al.*, 2013).

At the wind farm level, the array layout and electrical collectors must be designed on a site-specific basis to achieve a good balance between electrical losses and wake effects. For power system studies, it is typical to represent the wind farm by an aggregated machine model (and controller). However, more detailed wind farm representations are required to take full advantage of control capabilities, exploring further coordinated turbine control and operation to achieve a better array design. Full exploitation of the great potential offered by offshore wind farms will require the development of reliable and cost-effective offshore grids for collection of power, and its transmission and connection to the onshore network whilst complying with the grid codes. It is anticipated that power electronic equipment (e.g. HVDC and FACTS), and their enhanced control features, will be fundamental in addressing these objectives.

1.3 Wind Turbine Technology

1.3.1 Basics

Wind turbines produce electricity by using the power of the wind to drive an electrical generator (Fox *et al.*, 2007; Anaya-Lara *et al.*, 2009). Wind passes over the blades generating lift and exerting a turning force. The rotating blades turn a shaft that goes into a gearbox, which increases the rotational speed to that which is appropriate for the generator. The generator uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which steps up the generator terminal voltage to the appropriate voltage level for the power collection system.

A wind turbine extracts kinetic energy from the swept area of the blades (Figure 1.4).

The power in the airflow is given by (Burton *et al.*, 2001; Manwell *et al.*, 2002):

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

where ρ is the air density, A is the swept area of the rotor in m^2 , and v is the upwind free wind speed in m/s . The power transferred to the wind turbine rotor is reduced by the power coefficient, C_p :

$$P_{\text{wind turbine}} = C_p P_{\text{air}} = \frac{1}{2} \rho A v^3 C_p \quad (1.2)$$

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 practice, 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

$$\lambda = \frac{\omega R}{v} \quad (1.3)$$

where ω is the rotational speed of the rotor and R is the radius to tip of the rotor.

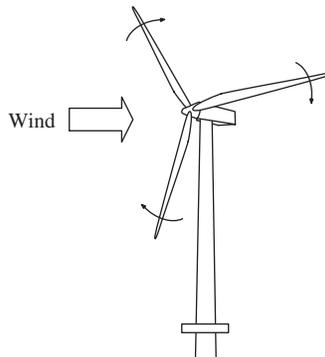


Figure 1.4 Horizontal-axis wind turbine.

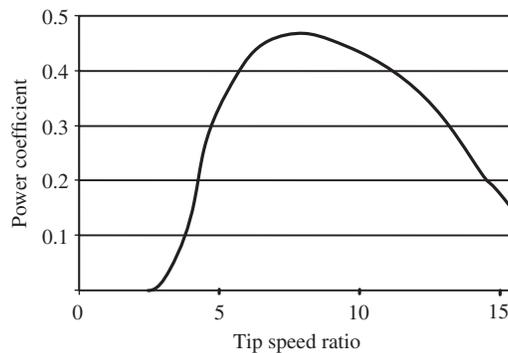


Figure 1.5 Illustration of power coefficient/tip-speed ratio curve, C_p/λ .

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 1.5 shows that the maximum power coefficient is only achieved at a single tip-speed ratio. The implication of this is that fixed rotational speed wind turbines could only operate at maximum efficiency for one wind speed. Therefore, 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. An example of a power curve for a 2-MW wind turbine is given in Figure 1.6.

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.
- 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).

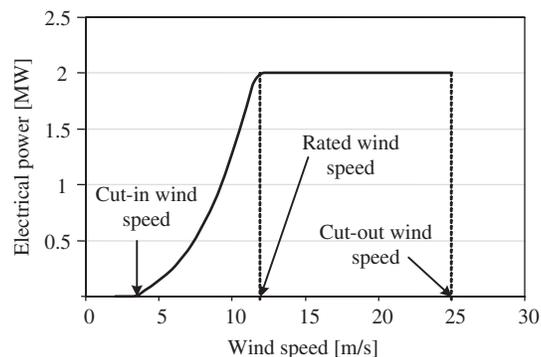


Figure 1.6 Power curve for a 2-MW wind turbine.

Below the cut-in speed of about 4–5 m/s, the wind speed is too low for useful energy production, so the wind turbine remains shut down. When the wind speed is above this value, the wind turbine begins to produce energy; 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 at about 11–12 m/s. 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, typically above 25 m/s, 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 (Anaya-Lara *et al.*, 2009).

1.3.2 Architectures

Figure 1.7 shows the main wind turbine generator concepts which are divided into fixed-speed wind turbines (type A), and variable-speed wind turbines (types B, C and D) (Tande *et al.*, 2007; Fox *et al.*, 2007).

1.3.2.1 Fixed-Speed Wind Turbines

A fixed-speed wind turbine (Type A in Figure 1.7) employs a three-phase squirrel-cage induction generator (SCIG) driven by the turbine via a gearbox and directly connected to the grid through a step-up transformer. Thus, the induction generator will provide an almost

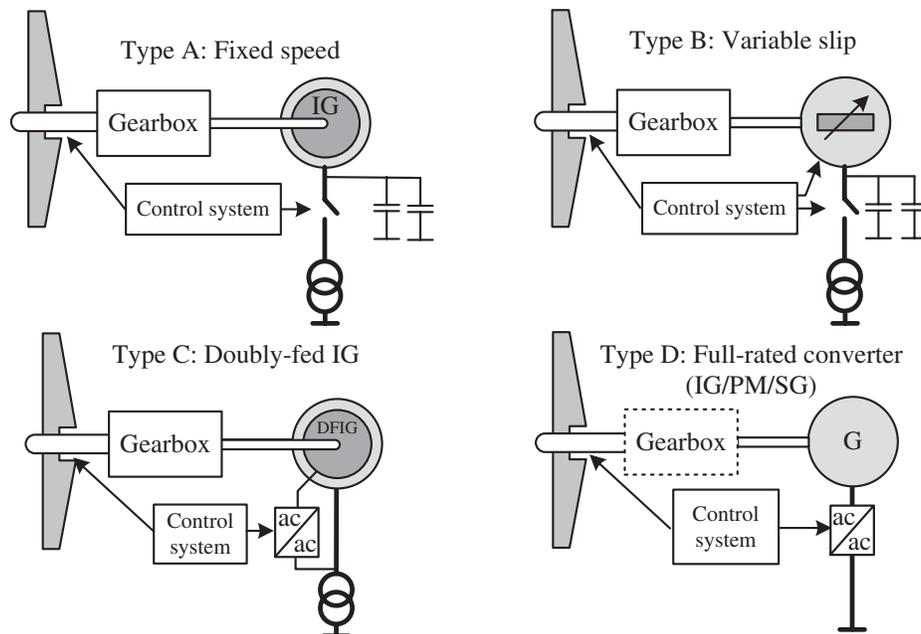


Figure 1.7 Overview of wind turbine concepts (Tande *et al.*, 2007).

constant rotational speed, that is only varying by the slip of the generator (typically about 1%). The reactive power consumption of the induction generator is provided via a capacitors bank, whereas a soft-starter limits the inrush current to the induction generator during start-up. At wind speeds above rated, the output power is limited by natural aerodynamic stall or by active pitching of the blades before the wind turbine is stopped at cut-out wind speed. Modern fixed-speed wind turbines are commonly equipped with capacitors that are connected in steps using power electronic switches for fast reactive power compensation control. A Static VAR Compensator (SVC) can be applied either for controlling the reactive power exchange to a certain value (e.g. zero for unity power factor), or for contributing to voltage control with droop settings just as any other utility-scaled power plant (Tande *et al.*, 2007).

1.3.2.2 Variable-Speed Wind Turbines

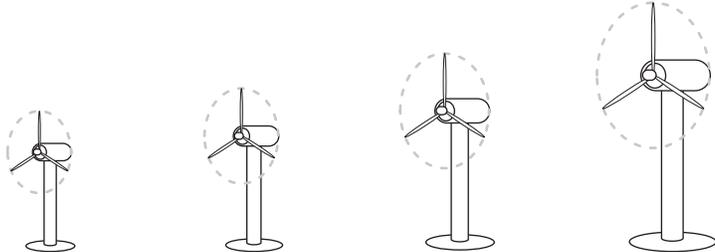
Variable-speed operation offers increased efficiency and enhanced power control. The variable-speed operation is achieved either by controlling the rotor resistance of the induction generator, that is slip control (Type B in Figure 1.7), or by a power electronic frequency converter between the generator and the grid (Types C and D in Figure 1.7). The variable slip concept yields a speed range of about 10%, whereas the use of a frequency converter opens for larger speed variations. All variable-speed concepts are expected to yield quite small power fluctuations, especially during operation above rated wind speed. They are also expected to offer smooth start-up.

In regards to power quality, the basic difference between the three variable-speed concepts is that Type B does not have a power electronic converter and thus reactive power capabilities as a fixed-speed wind turbine, whereas Types C and D each have a converter that offers dynamic reactive power control. The reactive power capability of Types C and D may differ as the Doubly-Fed Induction Generator (DFIG) concept of Type C uses a converter rated typically about 30% of the generator and not 100% as is the case for the Fully-Rated Converter (FRC) wind turbine of the Type D concept. The network-side converters of all major wind turbine suppliers offering Types C or D concepts are voltage source converters (VSCs), allowing independent control of active and reactive power (within the apparent power rating of the converter). The converters are based on fast-switching transistors, for example insulated-gate bipolar transistors (IGBTs); consequently, they are not expected to cause harmonic currents that may significantly distort the voltage waveform (Tande *et al.*, 2007).

1.3.3 Offshore Wind Turbine Technology Status

Currently installed offshore wind turbines are adapted from standard onshore wind turbine designs with significant upgrades to account for sea conditions. These modifications include strengthening the tower to handle the added loading from waves, along with pressurized nacelles and environmental control to keep corrosive sea spray away from critical drive train and electrical components.

Offshore turbine power capacity is greater than standard onshore wind turbines, currently ranging from 2 to 5 MW (Figure 1.8). The current generation of offshore wind turbines typically are three-bladed horizontal-axis, yaw-controlled, active blade-pitch-to-feather controlled, upwind rotors, which are nominally 80 m to approximately 130 m in diameter (E.ON Climate



Project	Scroby Sands	Rødsand II	Robin Rigg	Alpha Ventus
Turbine type	Type C	Type D	Type C	Type C, D
Hub height	60 m	68 m	80 m	90 m
Rotor diameter	80 m	93 m	90 m	126 m / 116 m
Capacity	2 MW	2.3 MW	3 MW	5 MW
Number of turbines	30	90	60	12

Figure 1.8 Offshore wind turbine development (E.ON Climate and Renewables, 2012).

and Renewables, 2012). Offshore wind turbines are generally larger because there are fewer constraints on component and assembly equipment transportation, which limit land-based machine size. In addition, larger turbines can extract more total energy for a given project site area than smaller turbines (Dolan *et al.*, 2009). A critical issue in developing very-large wind turbines is that the physical scaling laws do not allow some of the components to be increased in size without a change in the fundamental technology.

In onshore wind turbines, the drive train is typically designed around a modular, fixed-ratio, three-stage, gearbox speed with planetary stages on the low-speed side and helical stages on the high-speed side. Offshore towers are shorter than onshore ones for the same output because wind shear (the change in wind velocity resulting from the change in elevation) is lower offshore, which reduces the energy capture potential of increasing tower height (Dolan *et al.*, 2009).

1.4 Offshore Transmission Networks

Recent research has produced a number of proposals for a future integrated European transmission network (Supergrid), where large quantities of new offshore wind farms in the North Sea are connected to each other and to major load centres (Figure 1.9). In the long term, benefits of the operation of renewable energy sources are predicted to arise from better interconnection. Energy derived from renewable sources such as wind is inherently variable; that is, their energy output is variable and often difficult to accurately predict. If wind farms from different geographical regions are connected to a single transmission system, in addition to inputs from solar and hydroelectric schemes, then the total output from the renewable sources is expected to become ‘smoother’ and easier to predict.

It is anticipated that the development of the Supergrid will involve complex interconnections integrating wind farms into clusters and wind power plants. By way of example, Figure 1.10 presents a schematic of a generic ideal scenario interconnecting wind generation, and oil and gas platforms with various onshore grids (Anaya-Lara *et al.*, 2011).

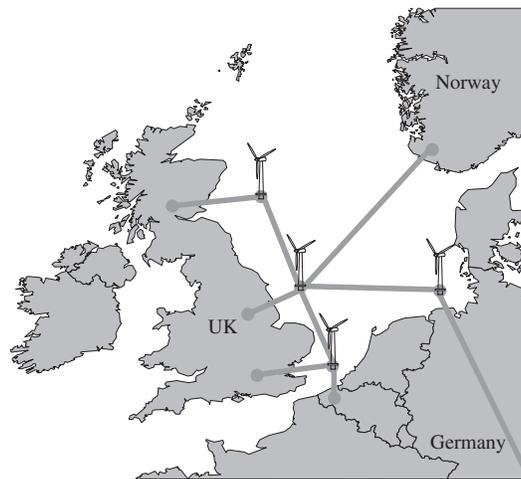


Figure 1.9 Phase 1 Supergrid (Source: www.friendsofthesupergrid.eu).

1.5 Impact on Power System Operation

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

- Wind turbines use different, often converter-based, generating systems compared with those used in synchronous generation.

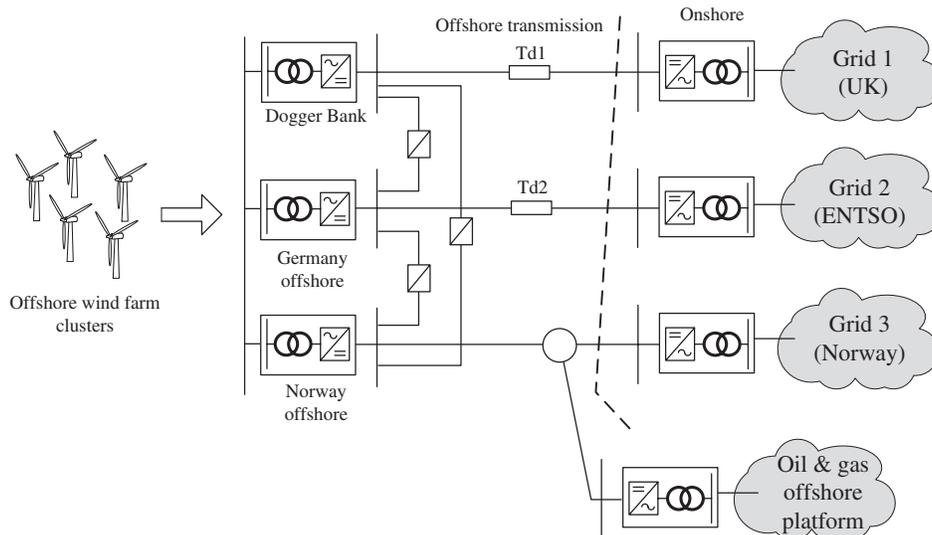


Figure 1.10 Generic offshore power network (Td stands for transmission distance) (Anaya-Lara *et al.*, 2011).

- 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 energy systems interact differently with the power system and may have both local and system-wide impacts on operation. Local impacts, such as busbar voltages and power quality, 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, such as power system dynamics and stability and frequency support, affect the behaviour of the power system as a whole (UCTE, 2004).

1.5.1 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 grid 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, these machines absorb reactive power, further depressing the network voltage. If the voltage does not recover quickly enough, the wind turbines continue to accelerate and to consume larger amounts of reactive power. This eventually leads to voltage and rotor speed instability. In contrast to synchronous generators, whose exciters 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 (Anaya-Lara *et al.*, 2009).

With variable-speed wind turbines, the sensitivity of the power electronics to over-currents caused by the 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 reduction, a voltage drop over a wide geographic area can lead to a large generation deficit. Such a voltage drop could, for instance, be caused 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 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.

1.5.2 Reactive Power and Voltage Support

The voltage on a transmission network is determined mainly by the interaction of reactive power flows with the reactive inductances of such 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 network voltage is to reduce the reactive power drawn from the network by using shunt compensators. Variable-speed wind turbines have the capability of reactive power control and may be able to support the voltage of the network. In many situations, 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 compensators (STATCOMs).

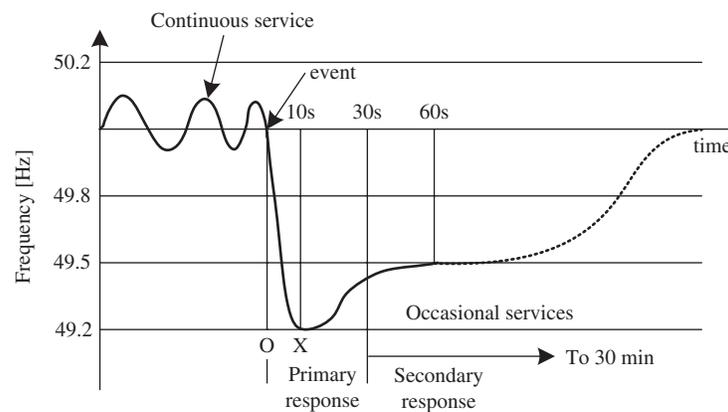


Figure 1.11 Frequency control in England and Wales (Erinmez *et al.*, 1999).

1.5.3 Frequency Support

With the projected increase in wind generation, a potential concern for transmission system operators is the capability of wind farms to provide dynamic frequency support in the event of sudden changes in power network frequency (see Figure 1.11). To provide frequency support from a generation unit, the generator power must increase or decrease as the system frequency changes. Thus, 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 (Anaya-Lara *et al.*, 2009).

1.5.4 Wind Turbine Inertial Response

A FSIG wind turbine acts in a similar manner to a synchronous machine when a sudden change in frequency occurs. For a drop in frequency the machine starts decelerating. This results in the conversion of kinetic energy of the machine to electrical energy, thus giving a power surge. The inverse is true for an increase in system frequency. In the case of a DFIG wind turbine, equipped with conventional controls, the control system operates to apply a restraining torque to the rotor according to a pre-determined curve against rotor speed. This is decoupled from the power system frequency so there is no contribution to the system inertia.

With a large number of DFIG and/or FRC wind turbines connected to the network, the angular momentum of the system will be reduced and the frequency may drop very rapidly during the phase OX in Figure 1.11. Therefore, it is important to reinstate the effect of the machine inertia within these wind turbines. It is possible to emulate the inertia response by manipulating their control actions. The emulated inertia response provided by these generators is referred to as fast primary response (also called ‘virtual’ or ‘synthetic’ inertia).

1.6 Grid Code Regulations for the Connection 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 (Anaya-Lara *et al.*, 2009). 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 electricity supply. The additional services that a power plant should provide are normally 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.

Grid Codes specify the levels and time period of the output power of a generating plant that should be maintained within the specified values of grid frequency and grid voltages. Typically this requirement is defined as shown in Figure 1.12 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 1.13 shows the operational regions as specified in the Great Britain and Ireland Grid Codes.

Traditionally, wind turbine generators were tripped off once the voltage at their terminals reduced to less than 20% retained voltage. However, with the penetration of wind generation increasing, Grid Codes now generally demand Fault Ride-Through (FRT) – or Low-Voltage Ride-Through (LVRT) – capability for wind turbines connected to transmission networks. Figure 1.14 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 indicated in Figure 1.14.

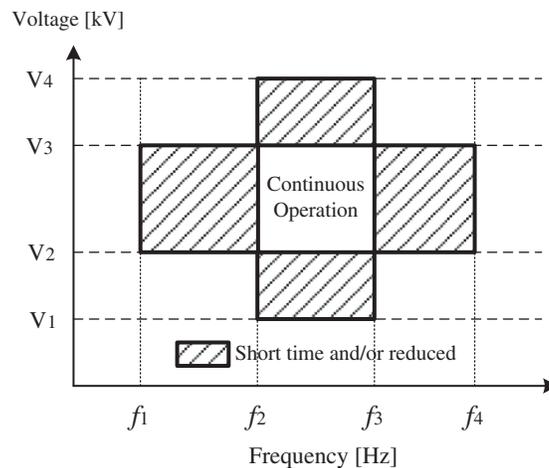


Figure 1.12 Typical shape of continuous and reduced output regions (after GB and Irish Grid Codes).

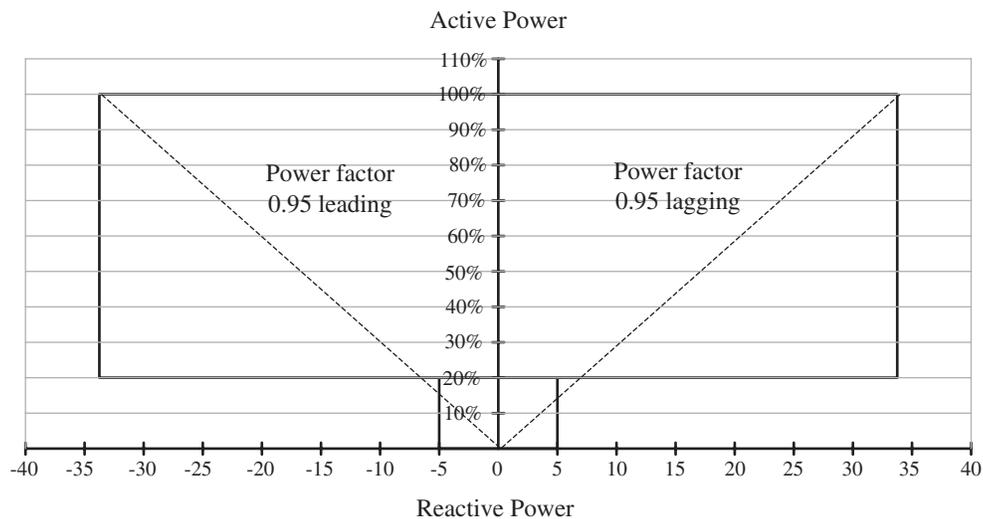


Figure 1.13 Typical steady-state operating region (after GB and Irish Grid Codes).

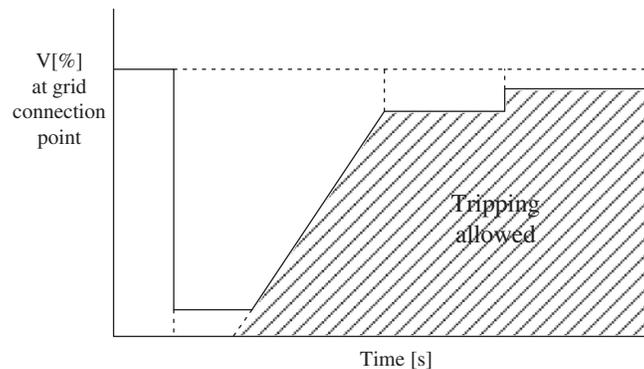


Figure 1.14 Typical shape of Fault Ride-Through capability plot (after GB and Irish Grid Codes).

The large-scale deployment of offshore wind turbines in the North Sea will potentially involve various wind turbine providers, introducing different turbine designs, with varying specifications and performance characteristics. It is envisaged that control requirements and dynamic performance of these future offshore wind power systems, with such a variety of technology and complex grid arrangements, may be significantly different from conventional and comparatively simpler existing power networks. Consequently, the establishment of suitable Grid Codes satisfying so many variables is a difficult challenge that needs to be addressed.

Acknowledgements

The material in Sections 1.3.1, 1.5 and 1.6 of this chapter is adapted from that originally published in Anaya-Lara *et al.*, 2009.

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