3. Wind Generator Topologies

Review of modern wind turbine technologies

Modern wind turbines fall into two basic groups: the horizontal-axis variety and the vertical axis design (Demirbas, 2006). Turbines that rotate around a horizontal axis are most common. Vertical axis turbines are less frequently used (Drewry and Georgiou, 2007). Both types use aerodynamic lift to extract power from the wind. They also have the same sub-systems, as illustrated in Figure 1 (Rizk and Nagrial, 2000).

Horizontal Axis Wind Turbines

Horizontal axis wind turbines (HAWTs) have the main rotor shaft running horizontally and the generator at the top of a tower, and must be pointed into the wind by some means (Babu et al., 2006). Many of these turbines also support independent blade pitch action—each of the blades of the turbine can be pitched about its longitudinal axes (Suryanarayanan and Dixit, 2005). Typical large wind turbines today are massive 3- bladed, horizontal-axis structures with enormous blade spans (70–100 m diameter), tall towers (60–100 m in height), and power ratings in the range 1–5 MW (Suryanarayanan and Dixit, 2007).

Vertical Axis Wind Turbines

Vertical axis wind turbines (VAWTs) have the potential to produce more power than the common HAWT based on their structural superiority (DeCoste et al., 2006). VAWT’s rotating axis is vertical to the wind direction, and there are two types of VAWT: Savonius type using drag force and Darrieus type using lift force (Hwang et al., 2006). VAWTs have several advantages in comparison with the conventional propeller type, HAWTs. For example, the conventional wind turbines have to be set into the wind direction to operate at the maximum efficiency point; however, VAWT operates independently of the wind direction (Fukudome et al., 2005). VAWT capacities are comparable to HAWT, and with a possible shift in technology from horizontal to vertical designs, the potential for VAWT to reach a higher capacity than the HAWT are plausible. Other advantages of the VAWT are that the mechanical power generation equipment can be located at ground level, which makes for easy maintenance (DeCoste et al., 2006).

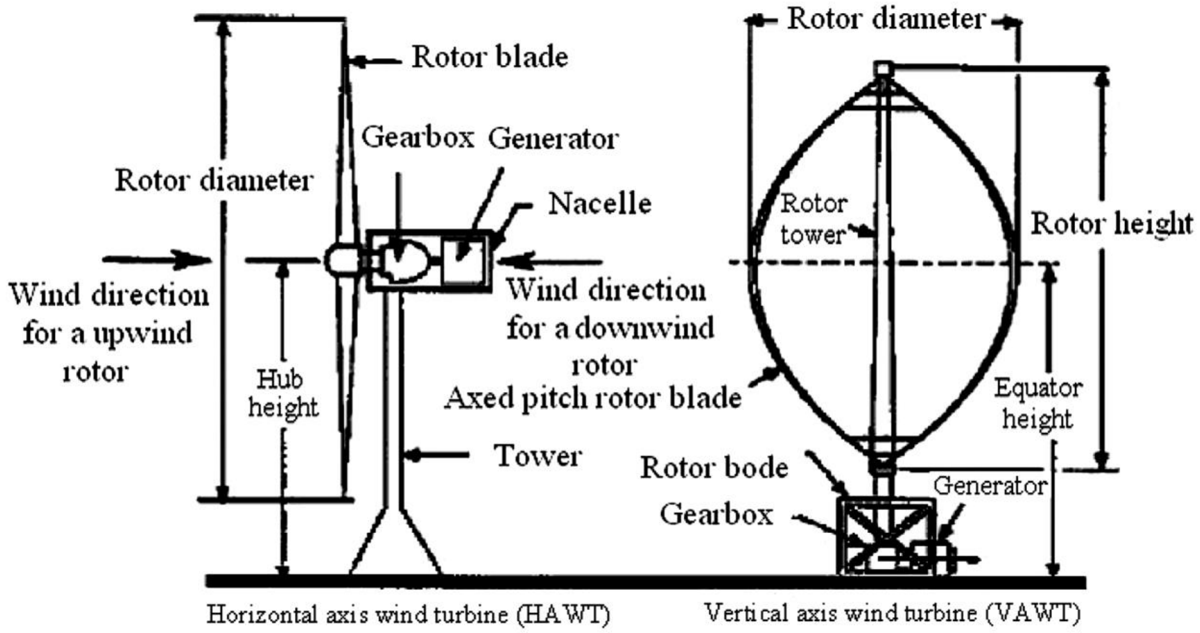


Fig 1. Schematic overview of wind turbine components. (Source: Rizk and Nagrial, 2000.)

Producing Electricity Using Wind Turbines

A wind turbine is a machine for converting the mechanical energy in wind into electrical energy (Babu et al., 2006). A typical wind turbine can produce 1.5 to 4.0 million kWh of electricity a year (Courtney, 2006). At a reasonable wind site, a typical wind turbine will produce electricity 70–85% of the time (Barthelmie, 2007).

The function of a wind turbine is to convert the motion of the wind into rotational energy that can be used to drive a generator, as illustrated in Figure 2. Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power. Wind turbine blades use airfoils to develop mechanical power (Blaabjerg et al., 2004). The cross-sections of wind turbine blades have the shape of airfoils as the one shown in Figure 3. Airflow over an airfoil produces a distribution of forces along the airfoil surface. The resultant of all these pressure and friction forces is usually resolved into two forces and a moment, lift force, drag force, and pitching moment, as shown in Figure 3(Blaabjerg et al., 2004).

Wind turbines are relatively simple systems that generate electricity when wind conditions are between 3 and 4 meters per second (m/s), the speed at which the turbine blades experience sufficient lift to begin rotating, and 25 to 30 m/s, depending on the manufacturer and model (Fitch, 2006). The highest wind speed at which a wind turbine generates electricity is called its furling speed. A wind turbine only provides power when the wind speed is high enough and not too high. The precise values of the lowest and highest wind speeds for power generation depend on the design of wind turbine (Courtney, 2006). The power (P) is related to the air density (ρ) and is proportional to

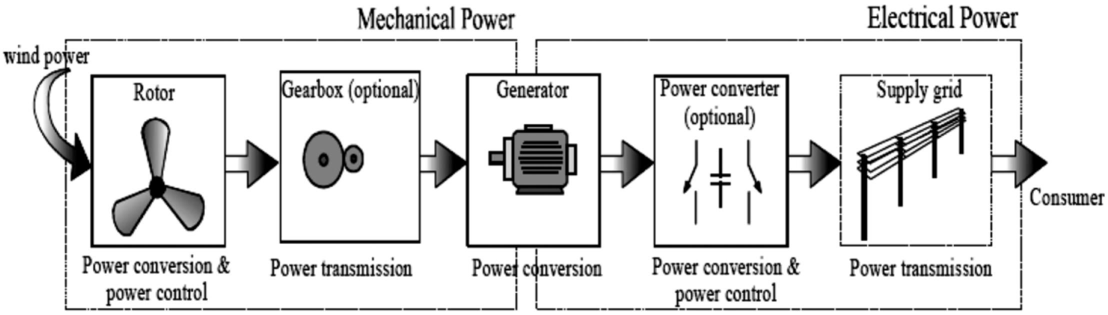


Fig 2.Conversion from wind power to electrical power in a wind turbine. (Source: Blaabjerg et al., 2004.)

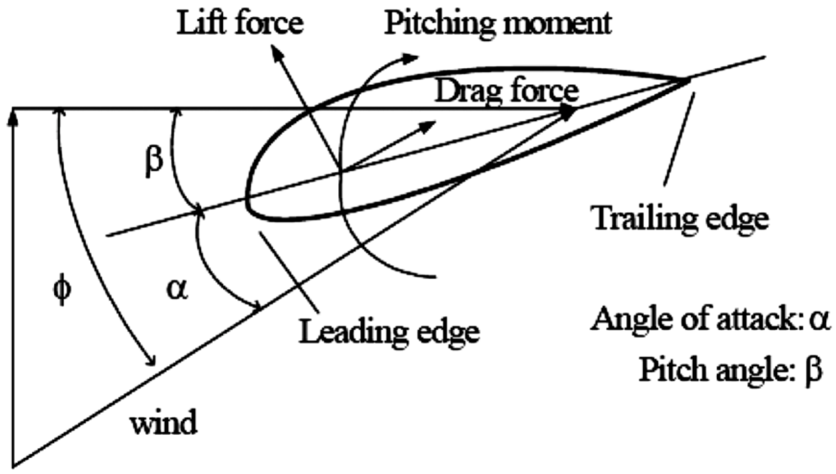


Fig 3. A simple airfoil used in wind turbines. (Source: Blaabjerg et al., 2004.)

the cube of the wind speed (U) and the square of the rotor radius (r) (Barthelmie, 2007):

$$P = \frac{1}{2}\rho \pi r^2 U^3 \qquad (1)$$

The exact amount of electricity produced depends on the wind turbine according to its individual power curve (Figure 4). Once the wind speed increases above the cut-in wind speed, the electricity output increases quickly until the wind speed reaches the “rated wind speed” when the turbine reaches its rated power output and the electricity production is no longer a function of wind speed. For the current generation of wind turbines installed

in a commercial context by a utility company (or other wind farm operator) this will be of the order 1.5 MW at about 12 m/s and above (Barthelmie, 2007). The two-parameter probability density function is used to represent the wind speed probability distribution (Pryor et al., 2005):

$$P(U) \equiv \frac{k}{A}\left[\frac{U}{A}\right]^{k-1} \exp\left[-\left[\frac{U}{A}\right]^{k}\right] for\ U \geq 0, A > 0, k > 0 \qquad (2)$$

where k is the dimensionless shape parameter (a measure of the peakedness of the distribution), A is the scale parameter (a measure of the central tendency), and P.U / is the probability density function. As an approximation, the scale parameter is related to the annual mean wind speed as follows (Morthorst and Andersen, 2005):

$$\overline{U} = \frac{1}{T}\int_0^T U(t)dt = \int_0^\infty UP(U)dU \approx 0.89A \qquad (3)$$

where T is the time over which the average is taken. T should be large, such as one year, or even better, 10–20 years. This is because wind speed varies significantly during the year, and even the annual average wind speed may vary by up to 10–20% between different years.

In the example depicted in Figure 4, the wind speed distribution has a shape parameter (related to the variability) of 2.0 and a scale parameter (related to the mean wind speed) of 8.0 m/s. Shape parameters can be between about 1 and 4 but are typically between 2 and 3. For the same scale parameter, a larger shape parameter indicates a wider wind speed distribution (Barthelmie, 2007).

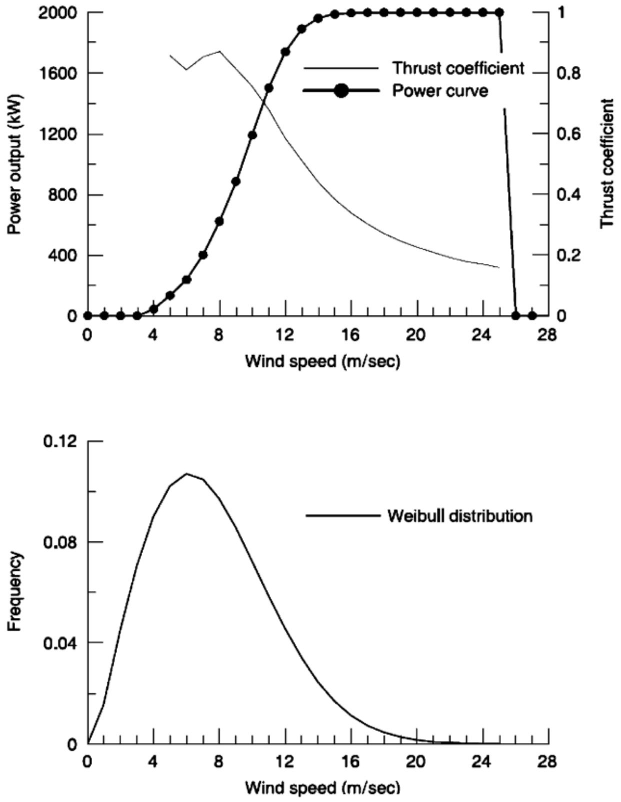


Fig 4. An example power curve for a Bonus 2 MW wind turbine (top) and an example Weibull distribution where the shape parameter, which is related to the variability, is 2.0 and the scale parameter, which is related to the mean, is 8.0 m/sec. (Source: Barthelmie, 2007.)

The “availability” of wind turbines (i.e., the percentage of the time when wind speeds meant that electricity production was possible to the amount of time the turbines were actually operating) typically exceeds 98% for onshore wind farms (Barthelmie, 2007). Future major developments of wind power capacities are likely to take place offshore. As for onshore wind parks, short-term wind power prediction up to 48 h ahead is expected to be of major importance for the management of offshore farms and their secure integration to the grid (Pinson et al., 2004). Higher and more regular wind speeds, as well as the possibility to install numerous and powerful (multi-megawatt) wind turbines, are the main advantages of going offshore to produce electricity. Wind speeds in the power production classes in the offshore environment are more persistent than those onshore. Calms are less frequent and less persistent (Kariniotakis et al., 2004). When inspecting offshore wind power production data averaged at a few-minute rate, one observes variations that are due to slower local atmospheric changes, e.g., frontline passages and rain showers (Pinson et al., 2007).

Wind Turbine Design Characteristics

Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low-speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator (Figure 5) (Drewry and Georgiou, 2007). The design life-time of modern wind turbines is normally thought to be 20 years, and the corresponding number of rotations is of the order 108 to 109. The basic design aspects for a rotor blade are the selection of material and shape. The material should be stiff, strong, and light. The challenge for the designers is thus to go beyond the simple plank and the shape of the blade with pre-twist into a design of the blade structure that is optimized with respect to materials selection and cost-effective production (Babu et al., 2006).

The blades convert the wind energy into rotational forces that drive the generator. Although these blades are rigidly attached to the generator, the pitch angle of the blades is variable. The blades change pitch during operation by passively twisting. The blades start at pitch-up position and flatten-out as the turbine speed increases. This makes the pitch angle be adjusted in such a way as to operate the wind turbine at its optimal performance. Hence, the power extracted from the wind turbine is being maximized in a wide variety of wind speed (Han et al., 2007). The characteristic parameters of a wind turbine are given in Table 1.

Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective, and reliable. The popular size of machines has moved from the small-medium range, 50–100 kW, to much larger 200 kW to 1 MW systems. In the period from the mid 1970s to the mid 1980s, the average power (kWh) per swept area (m2) increased approximately 40% (Lee and Flay, 1999).

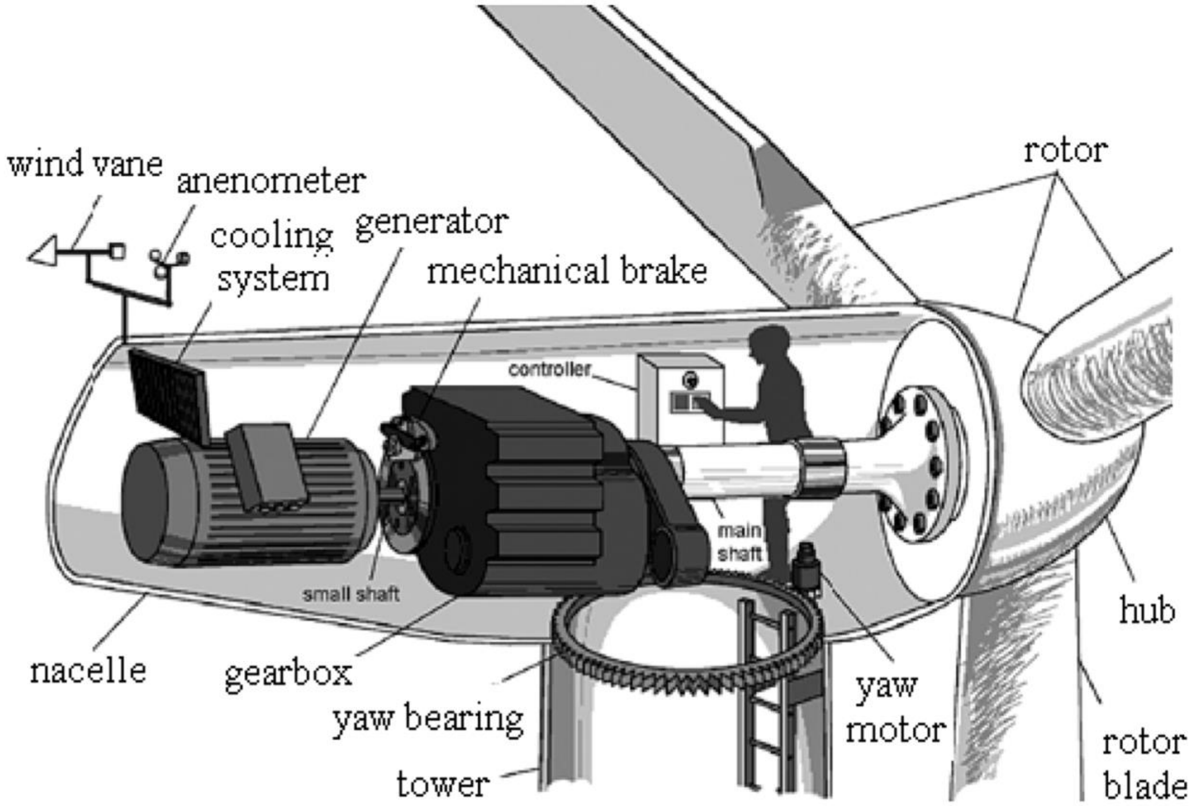


Fig 5. Wind turbine open nacelle. (Source: Drewry and Georgiou, 2007.)

Table 1.

The characteristic parameters of wind turbine

Radius of turbine	24 m
Rated power	750 kW
Cut-in wind speed	4 m/s
Cut-out wind speed	25 m/s
Rated wind speed	16 m/s

Source: Han et al., 2007.

Modern wind turbines are large to maximize interaction with the air and, thus, gain efficiency. Modern wind technology takes advantage of advances in materials, engineering, electronics, and aerodynamics. A typical wind turbine can produce 1.5 to 4.0 million kWh of electricity a year. Wind turbines are relatively simple systems that generate electricity when wind conditions are between 3 and 4 meters per second (m/s), the speed at which the turbine blades experience sufficient lift to begin rotating, and 25 to 30 m/s, depending on the manufacturer and model.

Most wind turbines have upwind rotors that are actively yawed to preserve alignment with wind direction. The three-bladed rotor is the most popular and, typically, has a separate front bearing with a low speed shaft connected to a gearbox which provides an output speed suitable for a four-pole generator. The design life-time of modern wind turbines is normally thought to be 20 years, and the corresponding number of rotations is of the order 108 to 109.

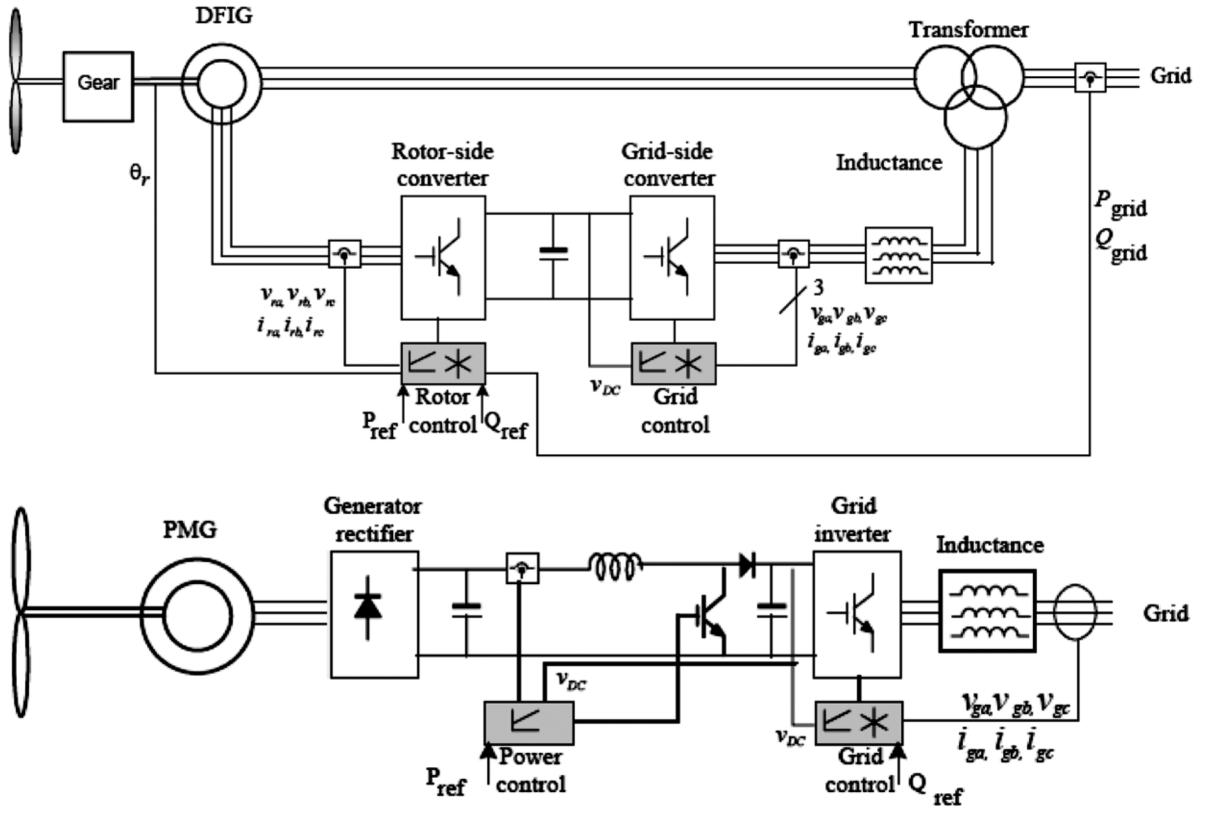


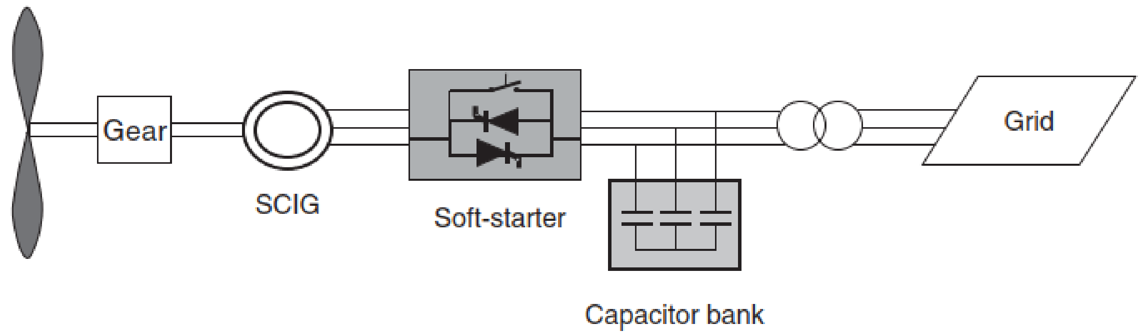
Fig 6. Basic control of active and reactive power in a wind turbine: (a) Doubly-fed induction generator system and (b) multi-pole synchronous generator system. (Source: Blaabjerg et al., 2004.)

Reliable and powerful control strategies are needed for wind energy conversion systems to achieve maximum performance. Wind turbines can operate either with a fixed speed or a variable speed. Variable speed control of wind turbines is of practical interest. For a variable speed wind turbine with a pitch control system, which regulates the effective rotor blade angle, optimum power can be obtained using appropriate control methods. The blade pitch control is relatively fast, however, and can be better used to regulate power flow especially when near the high speed limit.

Fixed and Variable speed wind turbines

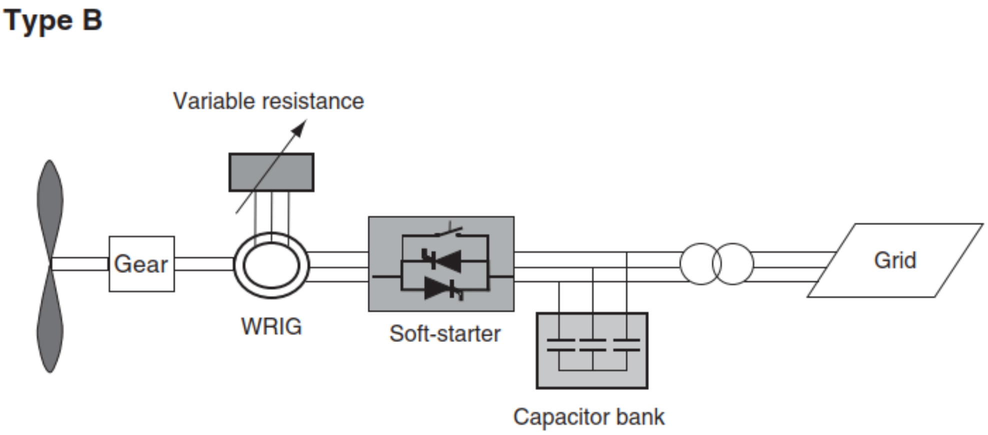
This configuration denotes the fixed-speed wind turbine with an asynchronous squirrel cage induction generator (SCIG) directly connected to the grid via a transformer. Since the SCIG always draws reactive power from the grid, this configuration uses a capacitor bank for reactive power compensation. A smoother grid connection is achieved by using a soft-starter. Regardless of the power control principle in a fixed-speed wind turbine, the wind fluctuations are converted into mechanical fluctuations and consequently into electrical power fluctuations. In the case of a weak grid, these can yield voltage fluctuations at the point of connection. Because of these voltage fluctuations, the fixed-speed wind turbine draws varying amounts of reactive power from the utility grid (unless there is a capacitor bank), which increases both the voltage fluctuations and the line losses. Thus the main drawbacks of this concept are that it does not support any speed control, it requires a stiff grid and its mechanical construction must be able to tolerate high mechanical stress.

Type A



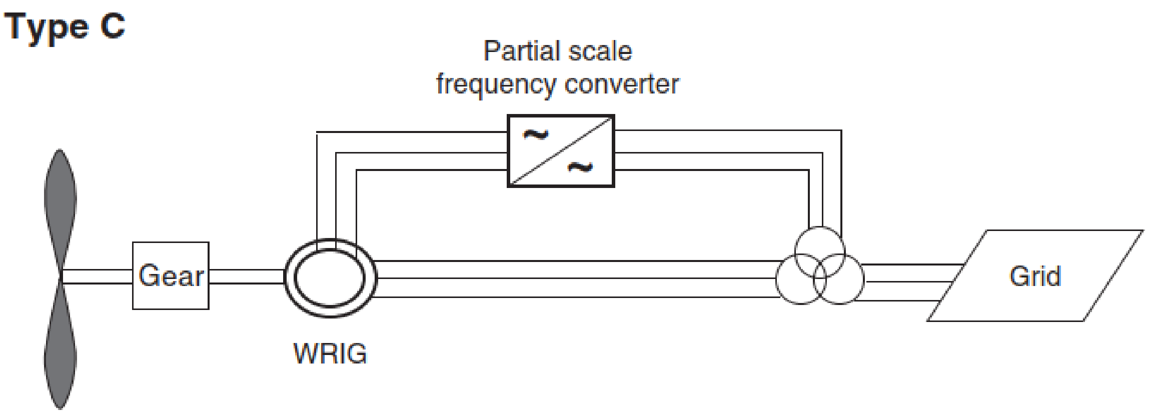
Type B: limited variable speed

This configuration corresponds to the limited variable speed wind turbine with variable generator rotor resistance, known as OptiSlip. It uses a wound rotor induction generator (WRIG) and has been used by the Danish manufacturer Vestas since the mid-1990s. The generator is directly connected to the grid. A capacitor bank performs the reactive power compensation. A smoother grid connection is achieved by using a soft-starter. The unique feature of this concept is that it has a variable additional rotor resistance, which can be changed by an optically controlled converter mounted on the rotor shaft. Thus, the total rotor resistance is controllable. This optical coupling eliminates the need for costly slip rings that need brushes and maintenance. The rotor resistance can be changed and thus controls the slip. This way, the power output in the system is controlled. The range of the dynamic speed control depends on the size of the variable rotor resistance. Typically, the speed range is 0–10 % above synchronous speed. The energy coming from the external power conversion unit is dumped as heat loss. Wallace and Oliver (1998) describe an alternative concept using passive components instead of a power electronic converter. This concept achieves a 10 % slip, but it does not support a controllable slip.



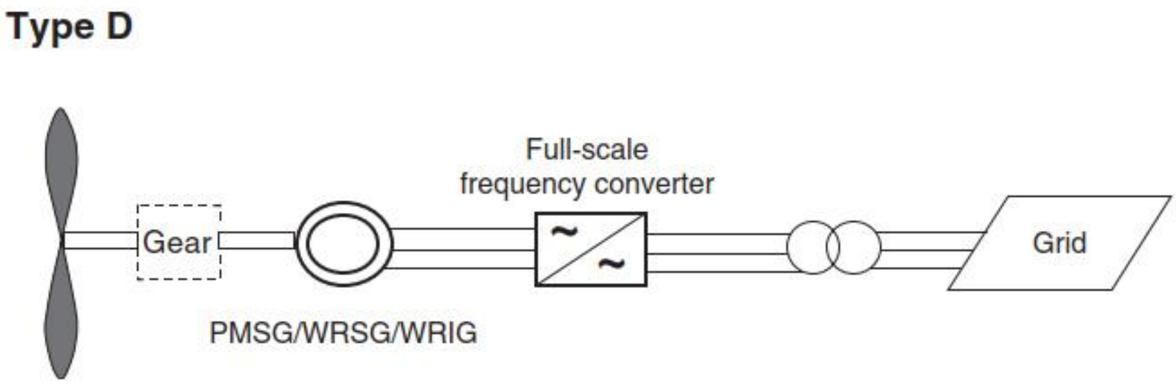
Type C: variable speed with partial scale frequency converter

This configuration, known as the doubly fed induction generator (DFIG) concept, corresponds to the limited variable speed wind turbine with a wound rotor induction generator (WRIG) and partial scale frequency converter (rated at approximately 30 % of nominal generator power) on the rotor circuit .The partial scale frequency converter performs the reactive power compensation and the smoother grid connection. It has a wider range of dynamic speed control compared with the OptiSlip, depending on the size of the frequency converter. Typically, the speed range comprises synchronous speed - 40 % to +30 %. The smaller frequency converter makes this concept attractive from an economical point of view. Its main drawbacks are the use of slip rings and protection in the case of grid faults.



Type D: variable speed with full-scale frequency converter

This configuration corresponds to the full variable speed wind turbine, with the generator connected to the grid through a full-scale frequency converter. The frequency converter performs the reactive power compensation and the smoother grid connection. The generator can be excited electrically [wound rotor synchronous generator (WRSG) or WRIG) or by a permanent magnet [permanent magnet synchronous generator (PMSG)]. Some full variable-speed wind turbine systems have no gearbox. In these cases, a direct driven multipole generator with a large diameter is used. The wind turbine companies Enercon, Made and Lagerwey are examples of manufacturers using this configuration.



Induction Generators, Doubly-Fed Induction Generators and their characteristics

Basically, a wind turbine can be equipped with any type of three-phase generator. Today, the demand for grid-compatible electric current can be met by connecting frequency converters, even if the generator supplies alternating current (AC) of variable frequency or direct current (DC). Several generic types of generators may be used in wind turbines:

Asynchronous (induction) generator:

– squirrel cage induction generator (SCIG);

– wound rotor induction generator (WRIG):

OptiSlip induction generator (OSIG),

Doubly-fed induction generator (DFIG).

Synchronous generator:

– wound rotor generator (WRSG);

– permanent magnet generator (PMSG).

Other types of potential interest:

– high-voltage generator (HVG);

– switch reluctance generator (SRG);

– transverse flux generator (TFG).

In this section, we will summarise the essential properties of these generic generator types. For a detailed analysis of generator types, see the standard literature on this field (Heier, 1998; Krause, Wasynczuk and Sudhoff, 2002).

Asynchronous (induction) generator

The most common generator used in wind turbines is the induction generator. It has several advantages, such as robustness and mechanical simplicity and, as it is produced in large series, it also has a low price. The major disadvantage is that the stator needs a reactive magnetising current. The asynchronous generator does not contain permanent magnets and is not separately excited. Therefore, it has to receive its exciting current from another source and consumes reactive power. The reactive power may be supplied by the grid or by a power electronic system. The generator’s magnetic field is established only if it is connected to the grid.

In the case of AC excitation, the created magnetic field rotates at a speed determined jointly by the number of poles in the winding and the frequency of the current, the synchronous speed. Thus, if the rotor rotates at a speed that exceeds the synchronous speed, an electric field is induced between the rotor and the rotating stator field by a relative motion (slip), which causes a current in the rotor windings. The interaction of the associated magnetic field of the rotor with the stator field results in the torque acting on the rotor.

The rotor of an induction generator can be designed as a so-called short-circuit rotor

(squirrel cage rotor) or as a wound rotor.

Squirrel cage induction generator

So far, the SCIG has been the prevalent choice because of its mechanical simplicity, high efficiency and low maintenance requirements (for a list of literature related to SCIGs, see L. H. Hansen et al., 2001).

As illustrated in Figure Type A , the SCIG of the configuration Type A is directly grid coupled. The SCIG speed changes by only a few percent because of the generator slip caused by changes in wind speed. Therefore, this generator is used for constant-speed wind turbines (Type A). The generator and the wind turbine rotor are coupled through a gearbox, as the optimal rotor and generator speed ranges are different.

Wind turbines based on a SCIG are typically equipped with a soft-starter mechanism and an installation for reactive power compensation, as SCIGs consume reactive power. SCIGs have a steep torque speed characteristic and therefore fluctuations in wind power are transmitted directly to the grid. These transients are especially critical during the grid connection of the wind turbine, where the in-rush current can be up to 7–8 times the rated current. In a weak grid, this high in-rush current can cause severe voltage disturbances. Therefore, the connection of the SCIG to the grid should be made gradually in order to limit the in-rush current.

During normal operation and direct connection to a stiff AC grid, the SCIG is very robust and stable. The slip varies and increases with increasing load. The major problem is that, because of the magnetising current supplied from the grid to the stator winding, the full load power factor is relatively low. This has to be put in relation to the fact that most power distribution utilities penalise industrial customers that load with low power factors. Clearly, generation at a low power factor cannot be permitted here either. Too low a power factor is compensated by connecting capacitors in parallel to the generator. In SCIGs there is a unique relation between active power, reactive power, terminal voltage and rotor speed. This means that in high winds the wind turbine can produce more active power only if the generator draws more reactive power. For a SCIG, the amount of consumed reactive power is uncontrollable because it varies with wind conditions. Without any electrical components to supply the reactive power, the reactive power for the generator must be taken directly from the grid. Reactive power supplied by the grid causes additional transmission losses and in certain situations, can make the grid unstable. Capacitor banks or modern power electronic converters can be used to reduce the reactive power consumption. The main disadvantage is that the electrical transients occur during switching-in.

In the case of a fault, SCIGs without any reactive power compensation system can lead to voltage instability on the grid (Van Custem and Vournas, 1998). The wind turbine rotor may speed up (slip increases), for instance, when a fault occurs, owing to the imbalance between the electrical and mechanical torque. Thus, when the fault is cleared, SCIGs draw a large amount of reactive power from the grid, which leads to a further decrease in voltage. SCIGs can be used both in fixed-speed wind turbines (Type A) and in full variable speed wind turbines (Type D). In the latter case, the variable frequency power of the machine is converted to fixed-frequency power by using a bidirectional full-load back- to-back power converter.

Wound rotor induction generator

In the case of a WRIG, the electrical characteristics of the rotor can be controlled from the outside, and thereby a rotor voltage can be impressed. The windings of the wound rotor can be externally connected through slip rings and brushes or by means of power electronic equipment, which may or may not require slip rings and brushes. By using power electronics, the power can be extracted or impressed to the rotor circuit and the generator can be magnetised from either the stator circuit or the rotor circuit. It is thus also possible to recover slip energy from the rotor circuit and feed it into the output of the stator. The disadvantage of the WRIG is that it is more expensive and not as robust as the SCIG. The wind turbine industry uses most commonly the following WRIG configurations: (1) the OptiSlip induction generator (OSIG), used in the Type B concept and (2) the doubly-fed induction generator (DFIG) concept, used in the Type C configuration.

OptiSlip induction generator

The OptiSlip feature was introduced by the Danish manufacturer Vestas in order to minimise the load on the wind turbine during gusts. The OptiSlip feature allows the generator to have a variable slip (narrow range) and to choose the optimum slip, resulting in smaller fluctuations in the drive train torque and in the power output. The variable slip is a very simple, reliable and cost-effective way to achieve load reductions compared with more complex solutions such as full variable-speed wind turbines using full-scale converters.

OSIGs are WRIGs with a variable external rotor resistance attached to the rotor windings (see Figure). The slip of the generator is changed by modifying the total rotor resistance by means of a converter, mounted on the rotor shaft. The converter is optically controlled, which means that no slip rings are necessary. The stator of the generator is connected directly to the grid. The advantages of this generator concept are a simple circuit topology, no need for slip rings and an improved operating speed range compared with the SCIG. To a certain extend, this concept can reduce the mechanical loads and power fluctuations caused by gusts. However, it still requires a reactive power compensation system.

The disadvantages are: (1) the speed range is typically limited to 0–10 %, as it is dependent on the size of the variable rotor resistance; (2) only poor control of active and reactive power is achieved; and (3) the slip power is dissipated in the variable resistance as losses.

Doubly-fed induction generator

The concept of the DFIG is an interesting option with a growing market. The DFIG consists of a WRIG with the stator windings directly connected to the constant-frequency three-phase grid and with the rotor windings mounted to a bidirectional back-to-back IGBT voltage source converter. The term ‘doubly fed’ refers to the fact that the voltage on the stator is applied from the grid and the voltage on the rotor is induced by the power converter. This system allows a variable-speed operation over a large, but restricted, range.

The converter compensates the difference between the mechanical and electrical frequency by injecting a rotor current with a variable frequency. Both during normal operation and faults the behaviour of the generator is thus governed by the power converter and its controllers. The power converter consists of two converters, the rotor-side converter and grid-side converter, which are controlled independently of each other. It is beyond the scope of this chapter to go into detail regarding the control of the converters (for more detail, see Leonhard, 1980; Mohan, Undeland and Robbins, 1989; Pena, Clare and Asher, 1996).

The main idea is that the rotor-side converter controls the active and reactive power by controlling the rotor current components, while the line-side converter controls the DC-link voltage and ensures a converter operation at unity power factor (i.e. zero reactive power). Depending on the operating condition of the drive, power is fed into or out of the rotor: in an over synchronous situation, it flows from the rotor via the converter to the grid, whereas it flows in the opposite direction in a sub synchronous situation. In both cases – sub synchronous and over synchronous – the stator feeds energy into the grid.

The DFIG has several advantages. It has the ability to control reactive power and to decouple active and reactive power control by independently controlling the rotor excitation current. The DFIG has not necessarily to be magnetised from the power grid, it can be magnetised from the rotor circuit, too. It is also capable of generating reactive power that can be delivered to the stator by the grid-side converter. However, the grid-side converter normally operates at unity power factor and is not involved in 68 Generators and Power Electronics the reactive power exchange between the turbine and the grid. In the case of a weak grid, where the voltage may fluctuate, the DFIG may be ordered to produce or absorb an amount of reactive power to or from the grid, with the purpose of voltage control. The size of the converter is not related to the total generator power but to the selected speed range and hence to the slip power. Thus the cost of the converter increases when the speed range around the synchronous speed becomes wider. The selection of the speed range is therefore based on the economic optimisation of investment costs and on increased efficiency. A drawback of the DFIG is the inevitable need for slip rings.

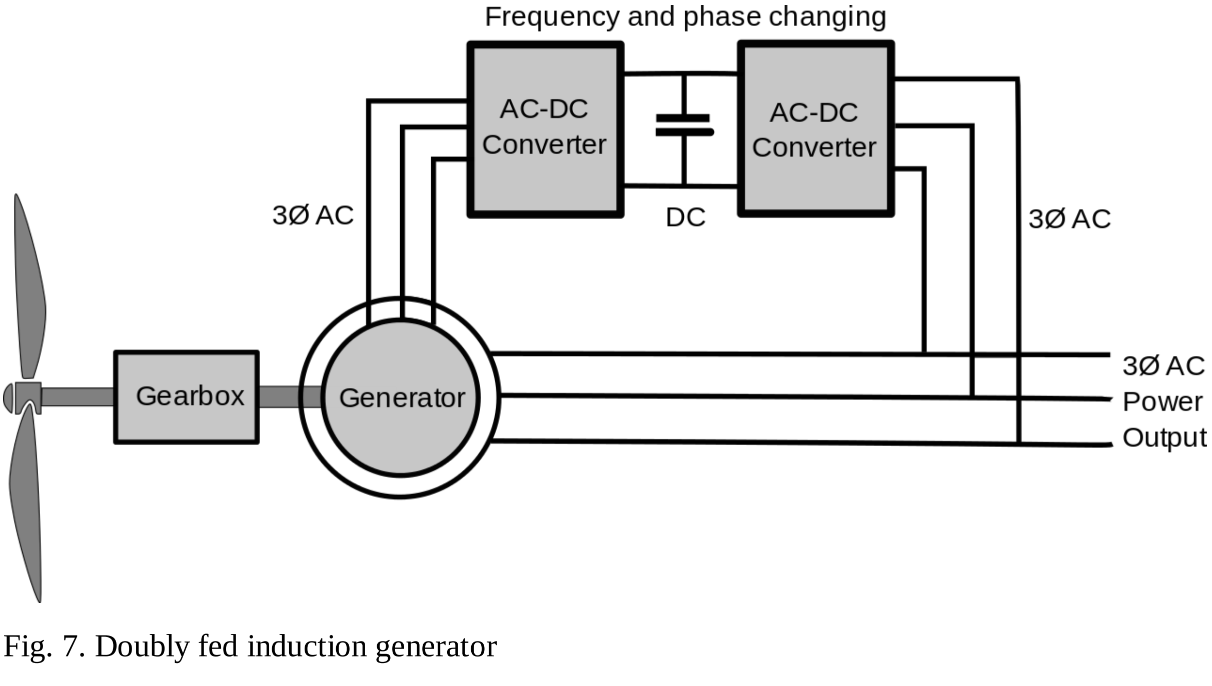


Fig. 7. Doubly fed induction generator

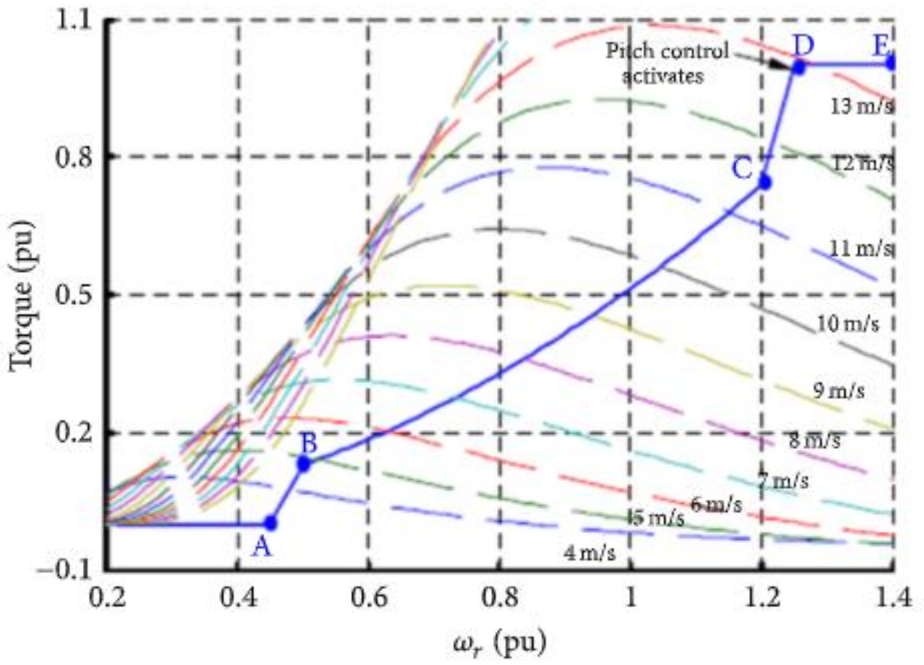


Fig.8. Turbine torque characteristics

The synchronous generator

The synchronous generator is much more expensive and mechanically more complicated than an induction generator of a similar size. However, it has one clear advantage compared with the induction generator, namely, that it does not need a reactive magnetising current. The magnetic field in the synchronous generator can be created by using permanent magnets or with a conventional field winding. If the synchronous generator has a suitable number of poles (a multipole WRSG or a multipole PMSG), it can be used for direct-drive applications without any gearbox. As a synchronous machine, it is probably most suited for full power control as it is connected to the grid through a power electronic converter. The converter has two primary goals: (1) to act as an energy buffer for the power fluctuations caused by an inherently gusting wind energy and for the transients coming from the net side, and (2) to control the magnetisation and to avoid problems by remaining synchronous with the grid frequency. Applying such a generator allows a variable-speed operation of wind turbines.

Two classical types of synchronous generators have often been used in the wind turbine industry: (1) the wound rotor synchronous generator (WRSG) and (2) the permanent magnet synchronous generator (PMSG).

Wound rotor synchronous generator

The WRSG is the workhorse of the electrical power industry. Both the steady-state performance and the fault performance have been well-documented in a multitude of research papers over the years, (see L. H. Hansen et al., 2001).

The stator windings of WRSGs are connected directly to the grid and hence the rotational speed is strictly fixed by the frequency of the supply grid. The rotor winding is excited with direct current using slip rings and brushes or with a brushless exciter with a rotating rectifier. Unlike the induction generator, the synchronous generator does not need any further reactive power compensation system. The rotor winding, through which direct current flows, generates the exciter field, which rotates with synchronous speed. The speed of the synchronous generator is determined by the frequency of the rotating field and by the number of pole pairs of the rotor. The wind turbine manufacturers Enercon and Lagerwey use the wind turbine concept Type D (see Figure) with a multipole (low-speed) WRSG and no gearbox. It has the advantage that it does not need a gearbox. But the price that has to be paid for such a gearless design is a large and heavy generator and a full-scale power converter that has to handle the full power of the system. The wind turbine manufacturer Made also applies the wind turbine concept Type D, but with a four-pole (high-speed) WRSG and a gearbox.

Permanent magnet synchronous generator

Many research articles have suggested the application of PMSGs in wind turbines because of their property of self-excitation, which allows an operation at a high power factor and a high efficiency, (see Alatalo, 1996). In the permanent magnet (PM) machine, the efficiency is higher than in the induction machine, as the excitation is provided without any energy supply. However, the materials used for producing permanent magnets are expensive, and they are difficult to work during manufacturing. Additionally, the use of PM excitation requires the use of a full scale power converter in order to adjust the voltage and frequency of generation to the voltage and the frequency of transmission, respectively. This is an added expense. However, the benefit is that power can be generated at any speed so as to fit the current conditions. The stator of PMSGs is wound, and the rotor is provided with a permanent magnet pole system and may have salient poles or may be cylindrical. Salient poles are more common in slow-speed machines and may be the most useful version for an application for wind generators. Typical low-speed synchronous machines are of the salient-pole type and the type with many poles.

There are different topologies of PM machines presented in the literature. The most common types are the radial flux machine, the axial flux machine and the transversal flux machine. A detailed description of all these types is given in Alatalo (1996). The synchronous nature of the PMSG may cause problems during startup, synchronisation and voltage regulation. It does not readily provide a constant voltage (Mitcham and Grum, 1998). The synchronous operation causes also a very stiff performance in the case of an external short circuit, and if the wind speed is unsteady. Another disadvantage of PMSGs is that the magnetic materials are sensitive to temperature; for instance, the magnet can lose its magnetic qualities at high temperatures, during a fault, for example. Therefore, the rotor temperature of a PMSG must be supervised and a cooling system is required. Examples of wind turbine manufacturers that use configuration Type D with PMSGs are Lagerwey, WinWind and Multibrid.

Power electronics converters

It includes the following:

(a) RSC. This is a voltage source converter (VSC) type, chosen over current source type due to its faster response to system changes and lower losses in the DC-link.

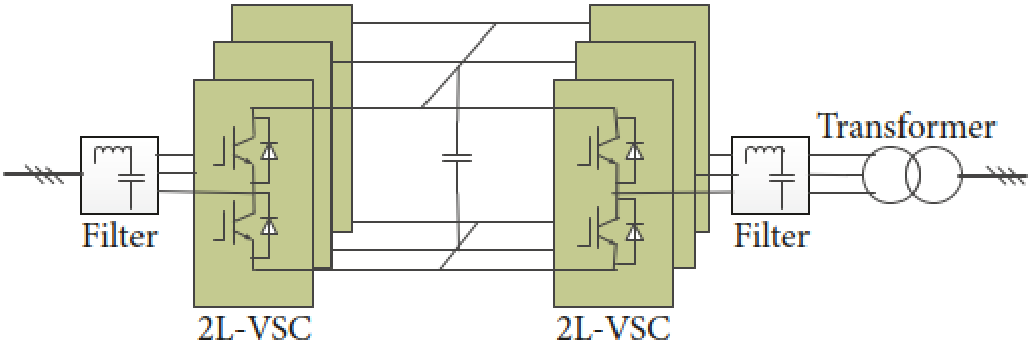


Fig . 9. Two-level back-to-back voltage source converter

It is composed of a rectifier bridge utilizing insulated gate bipolar transistors (IGBT) and diodes. It supplies magnetization current to the rotor. It also controls active and reactive generator power output by injecting currents of varying amplitude and frequency into the rotor windings. Slip power is also sent to the DC-link. The IGBTs switching is controlled by pulses which are generated by either sinusoidal pulse width modulation (SPWM) or space vector modulation (SVM) techniques. (b) DC-Link. It links the RSC to the GSC as shown in Figure. It is composed of an energy storage capacitor or combination of several capacitors that try to maintain constant voltage at their terminals. A VSC is characterized by a high value of capacitance in the DC-link. (c) Grid Side Converter (GSC). The GSC is a bidirectional rectifier bridge, utilizing IGBTs as the switching device, responsible for maintaining the DC bus voltage within certain limits by transferring the power from the rotor, which is stored in the DC-link capacitor, to the grid. It also exchanges reactive power with the grid by either absorbing reactive power from the grid or exporting reactive power to the grid as per the set value. Usually, its power factor is set at unity to minimize current flowing in it.

As DFIG WECS increase in individual size, the high power ratings have resulted in different converter configurations to accommodate the high currents and voltages with existing semiconductor device ratings. These include the following.

(a) Two-Level Back-to-Back VSC. This is the most established solution with a simple structure and few components. Bulky filters are required to limit the high dv/dt stresses on generator and transformer due to the only two voltage levels and to reduce the total harmonic distortion (THD) of grid voltages and currents.

(b) Parallel Connection of Two-Level Back-to-Back VSCs. This is as shown in Figure.9. It has the advantage of redundancy and hence increases reliability of the converter.

(c) Multilevel Topology. This is classified into the following:

(i) Three-level neutral point diode clamped (NPC) structure

(ii) Four-level flying capacitor clamped structure

(iii) Five-level cascade H-bridge (CHB) connection which

is bulky and complex as it requires many isolated DC sources

(d) Matrix Converters. A matrix converter, also called a cycloconverter, transfers AC supply directly into an AC load of a different frequency. It does not utilize a DC-link capacitor. It has lower harmonics and lower switching losses.

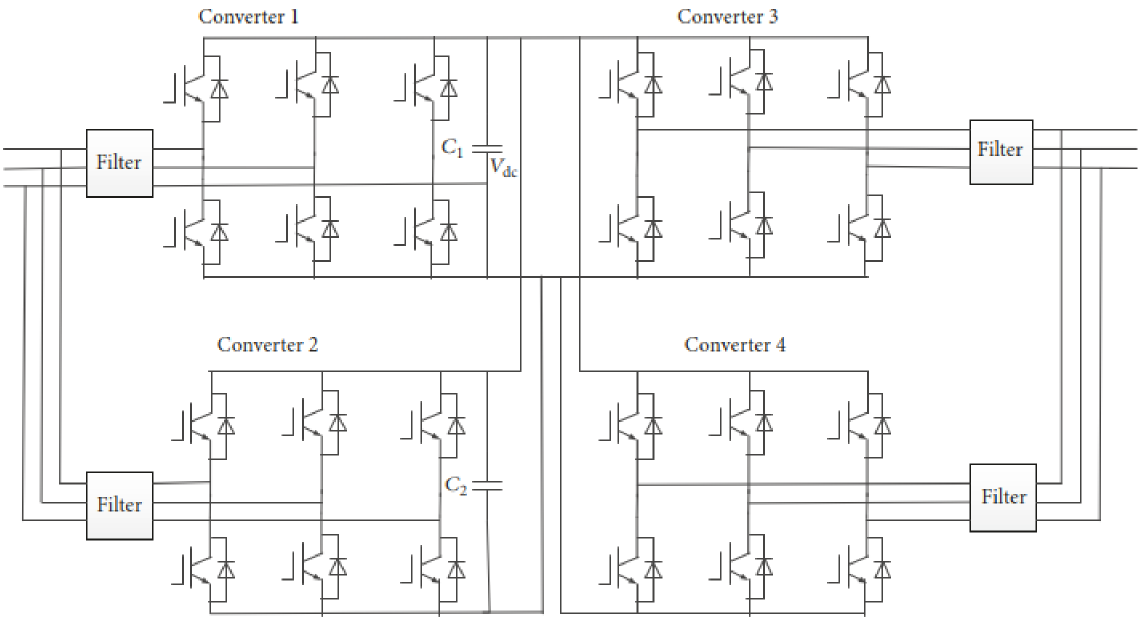


Fig .10. Two-level back-to-back VSC in parallel connection

It however has higher conduction losses, limitation on output voltage, and poor protection during faults.

(e) **Resonant Converters**. The main topology, the natural clamped converter, consists of two two-level back-to-back VSCs with a circuit to provide resonance in between them.

(f) **Tandem Converters**. These consist of a two-level back-to- back current source converter (CSC), designated the primary converter, in parallel with a two-level back-to-back VSC, and designated the secondary converter.

Harmonic Filter. The VSC produces harmonics, in multiples of the switching frequency, which cause distortion of the grid voltages and currents. The harmonics can be reduced by use of filters, either active, passive, or hybrid, and by control that utilizes RSC or GSC capacity.

Electromagnetic Compatibility (EMC) Filter. The switching on and off of IGBTs causes interference over a wide signal spectrum. The interference signals can be transmitted or received by electrical connections through impedances between the emitting source and the susceptible equipment, through magnetic and electric fields causing capacitive and inductive connections, and by radiation. The EMC filter reduces these emissions to a level where other electrical devices can be operated in the vicinity without problems. The PEC itself must also not be affected by low levels of external interference to avoid giving rise to cases of dangerous operating states.

Converter Control Unit (CCU). It carries out the control of the various elements in the rotor circuit for coordinated, reliable, and accurate operation. The CCU is a programmable electronic device with various inputs from its own measurements and the WECS controller, and it sends out output signals to the elements to be controlled. It also has communication channels for remote sensing and control. Controls for the RSC and GSC under both normal conditions and grid disturbance conditions must ensure that predetermined set-points are met.

Converter Control

Grid Utility Operator’s Specifications. Control for DFIG WECS is aimed at power production that meets the grid utility operator’s specifications. These usually vary as to the operator, based on the complexity of the grid system. IEEE standard 1549 defines the basic requirements for integrating distributed generation units including wind power to the utility grids. Common grid connection requirements include the following.

(a) Fault Ride-Through (FRT). DFIG WECS are impacted by faults from the grid. These include frequency fluctuations, voltage sags, and voltage swells. FRT capability is critical system requirements for wind farms as disconnection of the wind farm on occurrence of a fault is no longer an option since the sudden loss of a large source of active power can result in cascade trip of other plants due to under voltage and/or under frequency due to power-load mismatch in the system. Thus, the main aim of FRT requirement is the instantaneous resumption of active power as soon as the fault is cleared. IEEE std. 1159/95 defines voltage sag as a reduction of between 0.1 to 0.9 p.u. of the voltage and current (on an rms basis) at the power frequency for any duration ranging from 0.5 cycles to 1 minute. The amplitude is the remaining voltage value during the sag. On the other hand, IEC defines a voltage dip as a sudden voltage reduction at any point in the electrical system lasting from anywhere between half a cycle to a few seconds. Figure 11.shows the waveform of a voltage sag.

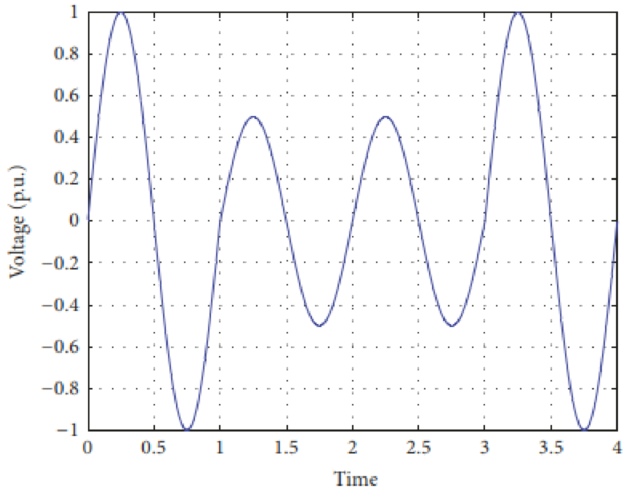


Fig. 11. Waveform of a voltage sag

Voltage swell as defined by IEEE 1159/95 is the increase in the RMS voltage level to 1.1 p.u–1.8 p.u. of nominal, at the power frequency, for durations of 0.5 cycles to 1 minute. Figure 12.shows the waveform of a voltage swell.

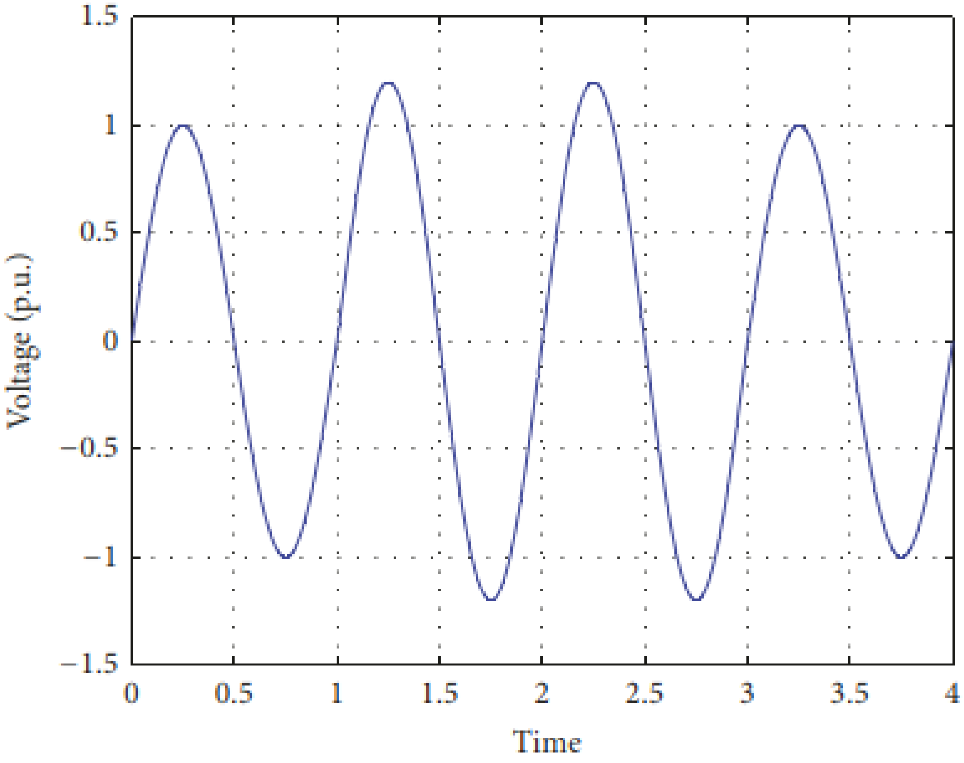


Fig .12. Voltage Swell

There are two subtypes of FRT.

(i) Low-Voltage Ride-Through (LVRT). Some grid codes also include zero-voltage ride-through (ZVRT), where the nominal voltage drops to zero, under LVRT. Voltage sags result from sudden loss of large generating units, switching in of large loads such as induction motors, and energizing of transformers and system faults such as short circuits and faults to ground. On occurrence of voltage sag, the WECS must remain connected for a given set time before disconnecting. In some cases, the WECS must help support grid voltage during the fault. LVRT curves for four countries are given in Figure 13.

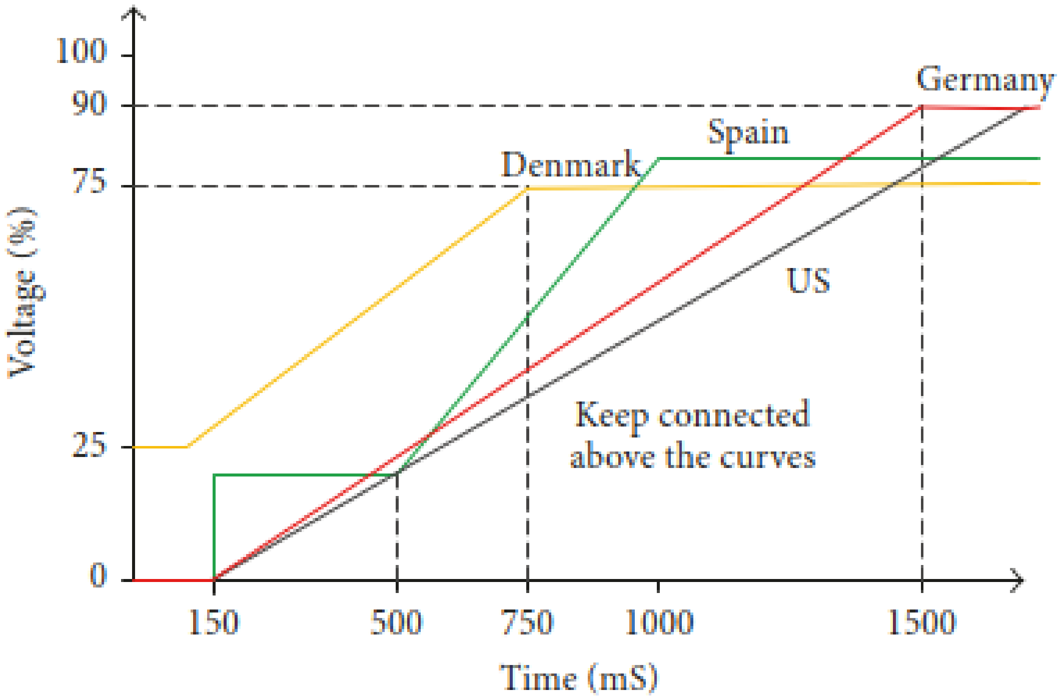


Fig .13. Curves for low-voltage ride-through requirements for different countries

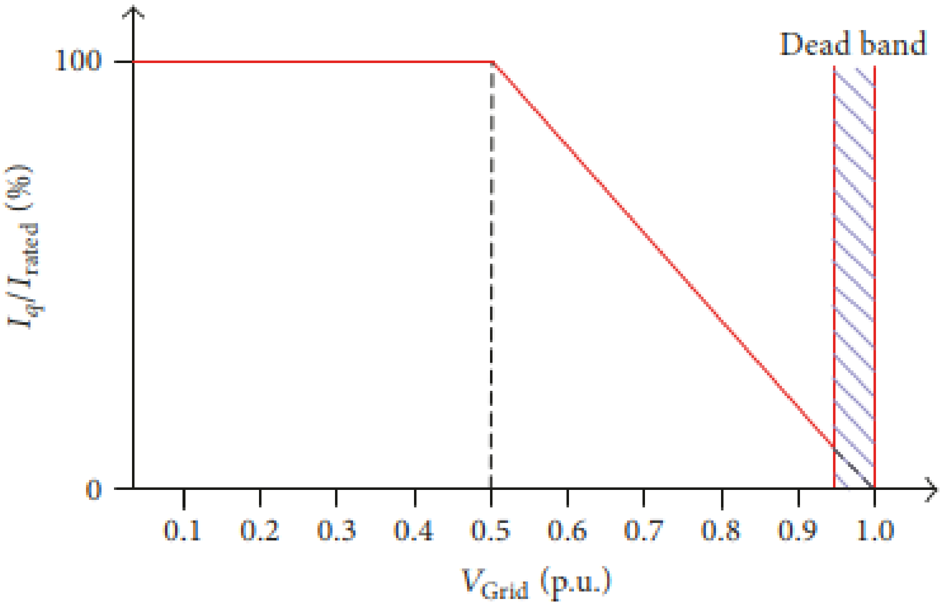


Fig .14. German and Danish grid code reactive current requirements during sags

(ii) High-Voltage Ride-Through (HVRT). Voltage swells result from single-phase short-term interruptions, reactive power overcompensation from capacitor banks, lightning strikes, or switching off of large loads such as in response to voltage sag . When voltage goes above its upper limit, usually at 1.1% though being set at 1.3% for Spain and Australia, the WECS must stay connected for a given period of time before disconnecting. Since voltage sags are more frequent than swells, LVRT is given greater focus than HVRT.

(b) Active Power (P) Control.

The WECS must provide active power control to ensure stable system frequency and avoid overloading of transmission lines. The ramp rate should also be within the set range.

(c) Reactive Power (Q) Control.

Dynamic reactive power control capability is required as the power factor and reactive power balance must be maintained in the desired range.

(d) Voltage Regulation.

The voltage at each WECS terminal must be maintained at a constant value.

(e) Voltage Operating Ranges.

The WECS must operate within typical grid voltage limits.

(f) Frequency Control.

This entails frequency regulation capability so as to maintain desired grid frequency.

(g) Frequency Operating Ranges.

The WECS must operate within typical grid frequency limits.

(h) Power Quality.

The WECS outputs in terms of voltage fluctuations which could result in flicker and voltage/current harmonics are limited to within set ranges.

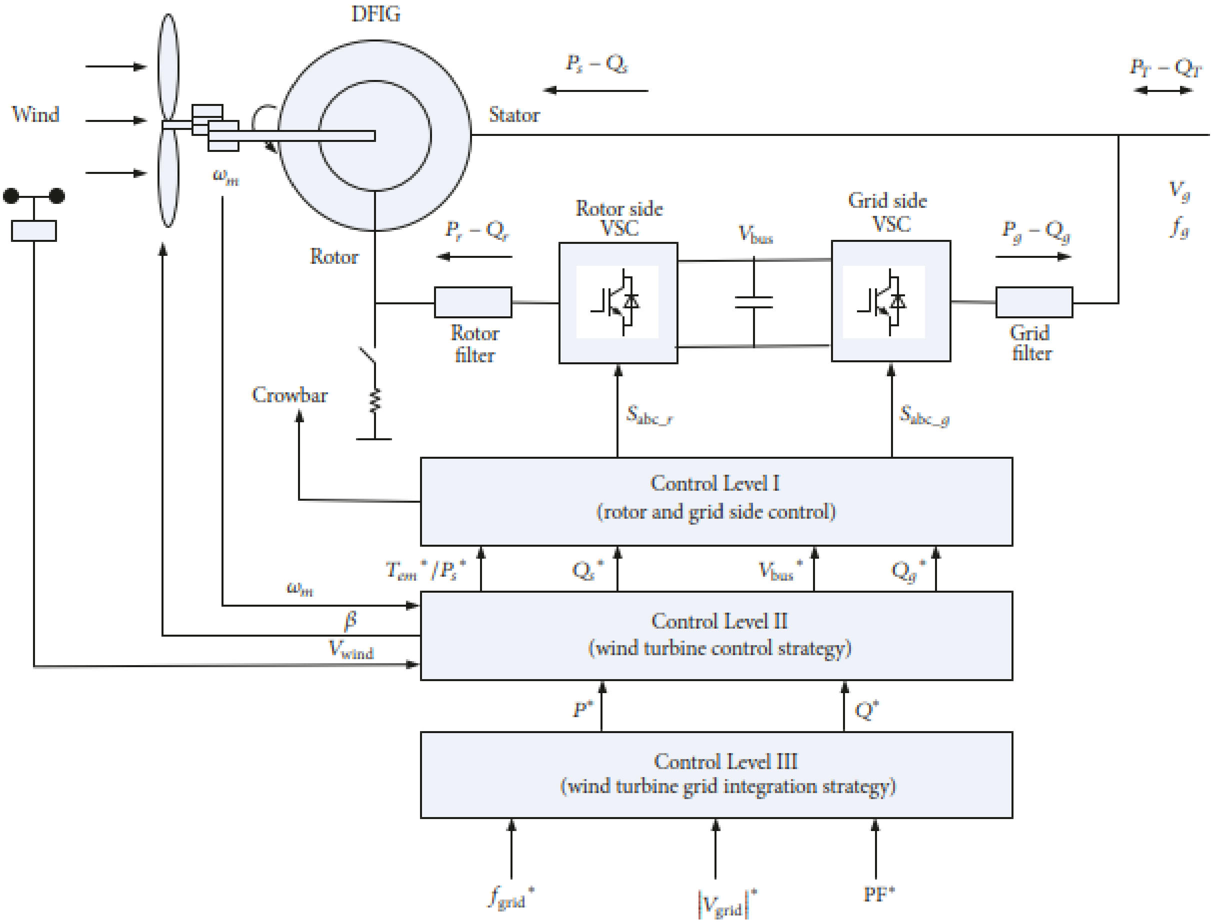


Fig .15. Conceptual diagram for DFIG wind turbine with partial scale power converter showing control strategy levels.

(a) Level I. This controls power flow from the DFIG, both from stator and from rotor, to the grid using the PEC. The converter control is divided into RSC control and GSC control.

(i) RSC control: RSC has decoupled control of stator active power (electromechanical torque) and the stator reactive power. It has a two-stage controller, oriented on either stator flux or grid/stator voltage reference frame. It has a faster inner current control loop and a slower outer power control loop.

(ii) GSC control: it aims at maintaining the DC-link capacitor voltage at a set value in addition to maintaining the desired converter power factor. It has a two-stage controller on grid/stator voltage oriented reference frame where the *d*-axis current component controls the active power and hence the DC-link voltage on the outer slower loop while the q-axis current component controls the reactive power on the faster inner loop.

(b) Level II. This handles control of conversion of wind energy in the airflows into mechanical energy by the turbine rotor, always aiming at maximum power production except when a reserve capacity is ordered by Level III control. It receives its set-points from Level III control and sends control set-points to Level I control.

(c) Level III. This is the highest level of control as it controls integration with the grid and provides control related to the grid voltage, power factor, and frequency as well as responding to grid operator requirements in terms of active and reactive power demands. It is similar to the wind farm control system but deals only with individual WECS values.