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Technical and Regulatory Exigencies for Grid Connection of Wind Generation

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1. Introduction

Pollution problems such as the greenhouse effect as well as the high value and volatility of fuel prices have forced and accelerated the development and use of renewable energy sources. In the three last decades, the level of penetration of renewable energy sources has undergone an important growth in several countries, mainly in the USA and Europe, where levels of 20% have been reached. Main technologies of renewable energies include wind, hydraulic, solar (photovoltaic and thermal), biofuels (liquid biodiesel, biomass, biogas), and geothermal energy. Within this great variety of alternative energy sources, wind energy has experienced a fast growth due to several advantages, such as costs, feasibility, abundance of wind resources, maturity of the technology and shorter construction times (Ackermann, 2005). This trend is expected to be increased even more in the near future, sustained mainly by the cost competitiveness of wind power technology and the development of new power electronics technologies, new circuit topologies and control strategies (Guerrero et al., 2010). However, there are some disadvantages for wind energy, as wind generation is uncontrollably variable because of the intermittency of the primary resource, i.e. the wind. Another important disadvantage is that the best places to install a wind farm, due to the certainty and intensities of suitable wind, are located in remote areas. This aspect requires of additional infrastructure to convey the generated power to the demand centres. Unfortunately, in several countries the regulatory aspect does not follow this fast growth of wind possibilities. Many countries do not have specific rules for wind generators and others do not make the necessary operating studies before installing a wind farm (Heier, 2006).

Power system operators must consider the availability of these power plants which are not dispatchable and are not accessible all the time. Today, developing countries, such as Argentina, are subjected to an analogous situation with wind energy, having perhaps one of the best sources of such energy around the world. Nowadays, there are several operative wind farms and others in stage of building and planning. Similar to other countries, in Argentina there is a lack of regulatory aspects related to this topic (Labriola, 2007).

This chapter thoroughly presents a revision of wind generation, including the following sections. In the first part, a brief history of the wind energy developments is presented. Following, some remarks related to the modern wind energy systems are made. Then, a survey of modern structures of wind turbines is carried out, including towers and foundations, rotor, nacelle with drive train and other equipment, control systems, etc.

Subsequently, major wind turbine concepts related to fixed and variable speed operation and control modes are described. Eventually, technical and regulatory exigencies for the integration of wind generation into the electrical grid are discussed in detail, including a study of selected countries grid codes.

2. Overview of wind energy technology

2.1 A brief history of wind energy development

Since ancient times, man has harnessed the power of the wind for a variety of tasks. Indeed, humans have been using wind energy in their daily work for some 4 000 years. In 1700 B.C., King Hammurabi of Babylon used wind powered scoops to irrigate Mesopotamia. Some other civilizations, like the Persians (500–900 A.D.), used the wind to grind grain into flour, while others used the wind to transport armies and goods across oceans and rivers. Sails revolutionized seafaring, which no longer had to be done with muscle power. More recently, mankind has used the power of the wind to pump water and produce electricity. So the idea of using wind, a natural source, is not new (Rahman, 2003).

The discovery of electricity generated using wind power dates back to the end of last century and has encountered many ups and downs in its more than 100 year history. In the beginning, the primary motivation for essentially all the researches on wind power generation was to reinforce the mechanization of agriculture through locally-made electricity generation. Nevertheless, with the electrification of industrialized countries, the role of wind power was drastically reduced, as it could not compete with the fossil fuel-fired power stations. This conventional generation showed to be by far more competitive in providing electric power on a large scale than any other renewable one.

Lack of fossil fuels during World War I and soon afterward during World War II created a consciousness of the great dependence on fossil fuels and gave a renewed attention to renewable energies and particularly to wind power. Although this concern did not extend for a long time. The prices for electricity generated via wind power were still not competitive and politically nuclear power gained more attention and hence more research and development funds. It took two oil crises in the 1970s with supply problems and price fluctuations on fossil fuels before wind power once again was placed on the agenda. And they were these issues confronting many countries in the seventies which started a new stage for wind power and motivated the development of a global industry which today is characterized by relatively few but very large wind turbine manufacturers (Vestergaard et al., 2004).

Wind turbines that generate electricity today are new and innovative. Their successful history began with a few technical innovations, such as the use of synthetic materials to build rotor blades, and continued with developments in the field of aerodynamics, mechanical/electrical engineering, control technology, and electronics provide the technical basis for wind turbines commonly used today. Since 1980, wind power has been the fastest growing energy technology in the world.

2.2 Modern wind energy systems

The beginning of modern wind turbine development was in 1957, marked by the Danish engineer Johannes Juul and his pioneer work at a power utility (SEAS at Gedser coast in the Southern part of Denmark). His R&D effort formed the basis for the design of a modern AC wind turbine – the well-known Gedser machine which was successfully installed in 1959.

With its 200kW capacity, the Gedser wind turbine was the largest of its kind in the world at that time and it was in operation for 11 years without maintenance. The robust Gedser wind turbine was a technological innovation as it became the hall mark of modern design of wind turbines with three wings, tip brakes, self-regulating and an asynchronous motor as generator. Foreign engineers named the Gedser wind turbine as 'The Danish Concept' (Chen & Blaabjerg, 2009).

Since then, the main aerodynamic concept has been this horizontal axis, three-bladed, upwind wind turbine connected to a three-phase electric grid, although many other different concepts have been developed and tested over the world with dissimilar results. An example of other concepts is the vertical axis wind turbine design by Darrieus, which provides a different mix of design tradeoffs from the conventional horizontal-axis wind turbine. The vertical orientation accepts wind from any direction with no need for adjustments, and the heavy generator and gearbox equipment can rest on the ground instead of on top of the tower (Molina & Mercado 2011).

The aim of wind turbine systems development is to continuously increase output power. Since the rated output power of production-type units reached 200 kW various decades ago, by 1999 the average output power of new installations climbed to 600 kW. Today, the manufactured turbines for onshore applications are specified to deliver 2-3 MW output power. In this sense, the world's first wind park with novel "multi-mega power class" 7 MW wind turbines was manufactured by the German wind turbine producer Enercon (11 E-126 units) and put into partial operation in Estinnes, Belgium, in 2010 (to be completed by July 2012). The key objective of this 77 MW pilot project is to introduce a new power class of large-scale wind energy converters (7 MW WECs) into the market with potential to significantly contribute to higher market penetration levels for wind electricity, especially in Europe. On the other hand, sea-based wind farms are likely to mean bigger turbines than on land, with models that produce up to three times power of standard on-shore models. Series production of offshore wind turbines can reach to date up to 5 MW or more, being the largest onshore wind turbine presently under development a 10 MW unit. At least four companies are working on the development of this "giant power class" 10 MW turbine for sea-based applications, namely American Superconductors (U.S.), Wind Power (U.K.), Clipper Windpower (U.K.) and Sway (Norway). Even more, it is likely that in the near future, power rating of wind turbines will increase further, especially for large-scale offshore floating wind turbine applications.

3. Structure of modern wind turbines

Basically, a wind energy conversion system consists of a turbine tower which carries the nacelle, and the wind turbine rotor, consisting of rotor blades and hub. Most modern wind turbines are horizontal-axis wind turbines (HAWTs) with three rotor blades usually placed upwind of the tower and the nacelle, as illustrated in Fig. 1 (Molina & Mercado, 2011). On the outside, the nacelle is usually equipped with anemometers and a wind vane to measure the wind speed and direction, as well as with aviation lights. The nacelle contains the key components of the wind turbine, i.e. the gearbox, mechanical brake, electrical generator, control systems, yaw drive, etc. The wind turbines are not only installed dispersedly on land, but also combined as wind farms (or parks) with capacities of hundreds MWs which are comparable with modern power generator units.

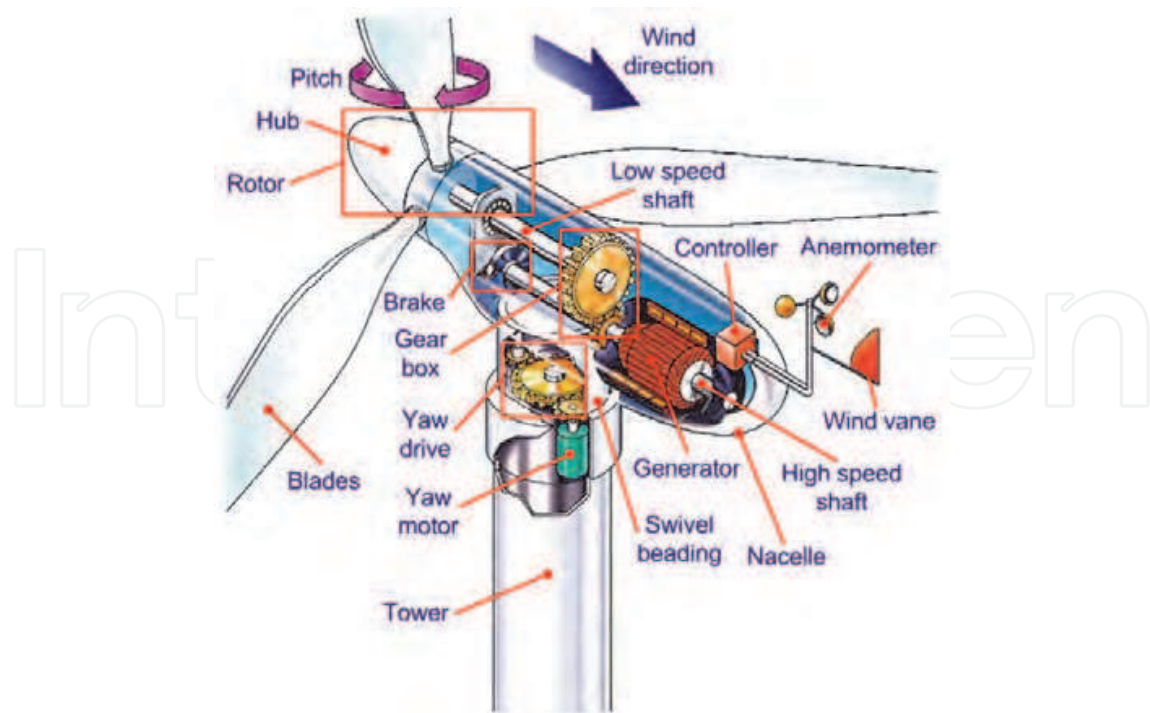


Fig. 1. Major components of a typical horizontal axis, three-bladed, upwind wind turbine

Of the various wind turbine models found around the world, most operate in a similar way and have components that serve very similar functions. Based on this feature, major components that most wind turbines have in common are described below.

3.1 Tower and foundation

One of the most important pieces of the wind turbine assembly is the tower that it is mounted upon. Mounting a wind turbine on the highest possible tower results in increased power production due to the stronger winds present at higher altitudes. In addition, the effects of the wind shear caused by the surrounding terrain is also much less at higher altitudes, providing yet another reason to mount the turbine as high as possible.

Of course, there are some limitations as to how tall of a tower is appropriate for a given application. One such consideration is the structural requirement necessary to support the turbine being considered, included how much the turbine weighs as well as what types of environmental forces (high winds, snow, rain) it will have to sustain over time. Zoning regulations may also play a role in dictating the maximum allowable height that the turbine assembly may be elevated off the ground (Villalobos Jara, 2009).

There are many different types of towers available for a wide variety of turbine sizes. One of the primary categories is the Lattice Tower which is essentially a very narrow, pyramid shaped structure that is strengthened with trusses. Towers of this variety may be self-supporting or they can be further supported by wires.

The other predominant type of tower is the monopole tower. This type of tower consists of a single pole that supports the turbine. As it is expected, lattice towers are much sturdier and can therefore elevate wind turbines to much greater heights than the monopole tower. However, the lattice towers also require more ground space for their larger footprint than what is necessary for a monopole tower. As a result, there is seemingly a tradeoff between strength and the amount of land consumed by the tower foundation. This was true up until

the advent of the now traditional tube tower. As strong, if not stronger, than a lattice tower, the tube tower takes up not much more land than a monopole tower. Due to its immense foundation, located almost entirely underground, tube towers are extremely sturdy structures that can withstand the strongest forces. While not possible until today's modern manufacturing and engineering practices, tube towers have engulfed the entire wind industry and it is rare to see a turbine of any appreciable size erected that is not sited on a tube tower.

The design of the wind turbine foundation in order to guarantee its stability at all operating conditions depends not only of the consistency of the underlying ground but also of the changing weather conditions (e.g. expanse and depth of permafrost in polar regions and where ice is prevalent) to support weight, plus huge static loads and variable forces exerted by the rotating turbine is extremely challenging. Tower foundations must not settle, tilt or be uplifted. Pile foundations may extend 1/3 to 2/3 the height of the tower into the ground. This requires thorough geotechnical research and testing to assess the ground conditions at the site to determine foundation design recommendations.

Offshore wind turbine foundation design requires development of highly cost effective concepts, because the share of the cost of the foundation relative to that of the complete wind turbine installation is considerably higher than that of an onshore foundation. Further, environmental and energy gain considerations require of wind farms to be located farther from shore at consequently deeper waters (Villalobos Jara, 2009). With this trend of ever larger turbines in deeper and rougher waters, the design and construction challenges and complexity increase proportionally, and both become closer to or beyond normal experience. Hence, value engineering becomes crucial for development of foundation concepts that are sufficiently robust to be carried through to site installation without impacting the economic viability of the projects.

3.2 Rotor

The rotor is the heart of a wind turbine and consists of multiple rotor blades attached to a hub. It is the turbine component responsible for collecting the energy present in the wind and transforming this energy into mechanical motion. As the overall diameter of the rotor design increases, the amount of energy that the rotor can extract from the wind increases as well. Therefore, turbines are often designed around a certain diameter rotor and the predicted energy that can be drawn from the wind.

The predominant aerodynamic principles that rotor designs are based upon are Drag Design and Lift Design. Drag design rotors operate on the idea of the wind "pushing" the blades out of the way, thereby setting the rotor into motion. Drag design rotors have slower rotational speeds but high-torque capabilities, making them ideal for pumping applications. With Lift design rotors, the blades are designed to function like the wing of an airplane. Each blade is designed as an airfoil, creating lift as the wind moves past the blades. The airfoil operates on the basis of Bernoulli's Principle where the shape of the blade causes a pressure differential between its upper and lower surfaces. This disparity in pressure causes an upward force that lifts the airfoil. In this case, this lift causes the rotor to rotate, once again transforming the energy in the wind into mechanical motion.

In the following, the structure and operation of rotors are discussed and concepts of power control presented (Freris, 1990; Stiesdal, 1999; Thomsen et al., 2007).

3.2.1 Rotor blades

Rotor blades are a crucial and basic part of a wind turbine. The design of the individual blades also affects the overall design of the rotor. Various strains are placed on them, and they must withstand very big loads. Rotor blades take the energy out of the wind; they “capture” the wind and convert its kinetic energy into the rotation of the hub. The profile is similar to that of airplane wings. Rotor blades utilize the same “lift” principle: below the wing, the stream of air produces overpressure; above the wing, the stream of air produces vacuum. These forces make the rotor rotate. Today, most rotors have three blades, a horizontal axis, and a diameter of between 40 and 90 meters. In addition to the currently popular three-blade rotor, two-blade rotors are also used to be common in addition to rotors with many blades, such as the traditional wind mills with 20 to 30 metal blades that pump water. Over time, it was found that three-blade rotor is the most efficient for power generation by large wind turbines.

In addition, the use of three rotor blades allows for a better distribution of mass, which makes rotation smoother and also provides for a “calmer” appearance. The rotor blades mainly consist of synthetic materials reinforced with fiberglass and carbon fibers. The layers are usually glued together with epoxy resin. Wood, wood epoxy and wood-fiber-epoxy compounds are less widely used. One of the main benefits of wooden rotor blades is that they can be recycled. Aluminum and steel alloys are heavier and suffer from material fatigue. These materials are therefore generally only used for very small wind turbines. Each manufacturer has its own rotor blade concepts and conducts research on innovative designs. In general, though, all rotor blades are constructed similarly to airplane wings.

3.2.2 Hub

The hub is the centre of the rotor to which the rotor blades are attached. Cast iron or cast steel is most often used. The hub directs the energy from the rotor blades on to the generator. If the wind turbines have a gearbox, the hub is connected to the slowly rotating gearbox shaft, converting the energy from the wind into rotation energy. If the turbine has a direct drive, the hub passes the energy directly on to the generator. The rotor blade can be attached to the hub in various ways: either in a fixed position, with an articulation, or as a pendulum. The latter is a special version of the two-blade rotor, which swings as a pendulum anchored to the hub. Most manufacturers nowadays use a fixed hub. It has proved to be sturdy, reduces the number of movable components that can fail, and is relatively easy to build.

3.2.3 Power control of the wind turbine

Wind turbines are generally designed to yield maximum power (nominal capacity) at a rated (or nominal) wind speed in the range of 11–15 m/s (around 40–54 km/h, or nearly 25–34 mph) for most commercial units. It does not justify designing turbines that maximize their output at stronger winds, because such strong winds are rare.

In case of stronger winds it is necessary to waste part of the excess energy of the wind in order to ensure that a maximum constant level of power is fed to the grid and thus avoids damaging the wind turbine.

Wind turbines begin generating power at the cut-on speed of around 2.5–4 m/s (about 9–14 km/h, or almost 6–9 mph) and cut off at wind speed of 25–34 m/s (around 90–122 km/h, or nearly 56–76 mph). The maximum wind speed (or survival speed), above which wind

turbines are destroyed, is in the range of 40–72 m/s (144–259 km/h, or 89–161 mph). The most common survival speed of commercial wind turbines is around 60 m/s (216 km/h or 134 mph).

Wind turbines have three modes of operation (Hansen et al., 2004.):

- Below rated wind speed operation
- Around rated wind speed operation (usually at nominal capacity)
- Above rated wind speed operation

If the rated wind speed is exceeded the power has to be limited. Therefore, all wind turbines are designed with a power control that achieves this goal and avoids a run-away situation. There are different ways of doing this safely on modern turbines, namely mainly pitch control and stall control.

3.2.3.1 Pitch control

This control concept was developed between years 1990 and 2000 and operates by turning the rotor blades into or out of the wind according to the control laws. An anemometer mounted atop the nacelle constantly checks the wind speed and sends signals to the pitch actuator, adjusting the angle of the blades to capture the energy from the wind most efficiently.

Standard modern turbines usually pitch the blades at high winds in order to prevent the rotational speed from rising to an unacceptably dangerous level. Since pitching requires acting against the torque on the blade, it requires some form of pitch angle control, which is achieved with a slewing drive. This drive precisely angles the blade while withstanding high torque loads. In addition, many turbines use hydraulic systems. These systems are usually spring loaded, so that if hydraulic power fails, the blades automatically furl. Other turbines use an electric servomotor for every rotor blade. They have a small battery-reserve in case of an electric grid breakdown. Small wind turbines (fewer than some kW) with variable pitching generally use systems operated by centrifugal force, either by flyweights or geometric design, and employ no electric or hydraulic controls.

In a pitch controlled wind turbine, the electronic controller checks the power output of the turbine several times per second. When the power output becomes too high, it sends an order to the blade pitch mechanism which immediately pitches (turns) the rotor blades slightly out of the wind. On the other hand, the blades are turned back into the wind whenever the wind drops again. The rotor blades thus have to be able to turn around their longitudinal axis (to pitch).

During normal operation (below or around rated wind speed) the controller generally pitches the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle in order to maximize output at all wind speeds.

3.2.3.2 Stall control

In a stall-regulated wind turbine, the blades are locked in place and do not adjust during operation. Instead the blades are aerodynamically designed and shaped to increasingly “stall” the blade angle of attack with the wind to both maximize power output and protect the turbine from excessive wind speeds. As the actual wind speed in the rotor area increases the angle of attack of the rotor blade also increases, until at some point it starts to stall. Thus, it is ensured that at the moment the wind speed becomes too high, it creates turbulence on the side of the rotor blade which is not facing the wind and prevents the lifting force of the rotor blade from acting on the rotor.

Stalling works by increasing the angle at which the relative wind strikes the blades (angle of attack), and it reduces the induced drag (drag associated with lift). Stalling is simple because it can be made to happen passively (it increases automatically when the winds speed up), or actively (the rotor blade angle is adjusted or pitched in order to create stall along the blades). Active stall regulation allows for power to be regulated more accurately than passive stall regulation does.

The main advantage of stall control is that it avoids moving parts in the rotor itself, and therefore a complex control system since they do not have the same level of mechanical and operational complexity as pitch-regulated turbines. In this way, stall-regulated turbines are often considered more reliable than pitch-regulated ones. On the other hand, stall control represents a very complex aerodynamic design problem, and related design challenges in the structural dynamics of the whole wind turbine, e.g. to avoid stall-induced vibrations. In addition, pitch-regulated wind turbines are generally considered to be slightly more efficient than stall-regulated ones. Around two thirds of the wind turbines currently being installed in the world are stall controlled machines.

3.2.3.3 Other power control methods

Some older wind turbines use ailerons (flaps) to control the power of the rotor, just like aircraft use flaps to alter the geometry of the wings to provide extra lift at takeoff. Another possibility is to yaw the rotor partly out of the wind to decrease power. This technique of yaw control is in practice used only for tiny wind turbines (1 kW or less), as it subjects the rotor to cyclically varying stress which may ultimately damage the entire structure. Braking of a small wind turbine can also be done by dumping energy from the generator into a resistor bank, converting the kinetic energy of the turbine rotation into heat. This method is useful if the kinetic load on the generator is suddenly reduced or is too small to keep the turbine speed within its allowed limit. Cyclically, braking causes the blades to slow down, which increases the stalling effect, reducing the efficiency of the blades. In this way, the turbine rotation can be kept at a safe speed in faster winds while maintaining (nominal) power output. This technique is also used only for tiny wind turbines and cannot be applied for large wind turbines.

3.3 Nacelle with drive train and other equipment

The nacelle contains all the machinery of the wind turbine, i.e. the drive train including the mechanical transmission (rotor shaft, bearings and the gearbox) and the electrical generator, and other equipment such as the power electronic interface, the yaw drive, the mechanical brake, and the control system, among others. Because it requires rotating in order to track the wind direction, it is connected to the tower via bearings. The build-up of the nacelle shows how the manufacturer has decided to place the drive train and other components above this machine bearing.

3.3.1 Drive train

3.3.1.1 Mechanical transmission

The gearbox is the major component of the mechanical transmission. Due to their huge diameters, the rotors of large scale wind turbines tend to have very slow rotational speeds (generally 18–50 rpm). In most cases, these speeds are insufficient to operate their generators at maximum efficiency (for most generators, somewhere in the range of 1200–1800 rpm).

The solution is to include a gearbox transmission between the rotor output shaft and the generator input shaft so that the rotor speed can be geared up to the appropriate rpm required by the generator for maximum power generation. In the case of multi-pole synchronous generators coupled to the electric grid via a full scale power converter, which decouples entirely the generator system from the utility grid, since it can operate at low speeds the gearbox can be omitted. Consequently, a gearless construction represents an efficient and robust solution that is beneficial, especially for offshore applications, where low maintenance requirements are essential. In the case of wind turbines with smaller rotor diameters, the gearbox transmission between the rotor and generator can be also omitted. A decrease in rotor diameter results in a smaller arc-length that the rotor must travel per revolution, eventually causing a comparatively larger rotational speed than that of a larger rotor for a given wind speed. If these larger rotational speeds are appropriate for the type of generator being used, the rotor can be connected straightforwardly to the generator resulting in a direct-driven system in the same way as in the system linked with the power converter. These smaller direct-driven wind turbine systems are predominately used in stand-alone (not grid-connected) DC applications (battery charging, etc).

3.3.1.2 Electrical generator

The generator is the component of the wind turbine responsible for converting the mechanical motion of the rotor into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system, and the generator is the next step in the supply of energy from the wind turbine to the electrical grid.

There are many different types and sizes of electric generators for a wide range of applications. Depending on the size of the rotor and the amount of mechanical energy removed from the wind, a generator may be chosen to produce either AC or DC voltage over a variety of power outputs.

There are two major types of electrical generators for converting mechanical energy. The first is the synchronous generator. The synchronous generator operates on the principle that as a magnet is rotated in the presence of a coil of wire, the changing magnetic field in space induces a current, and therefore a voltage in the coil of wire. In this case, the magnet is attached to the input shaft of the generator and is surrounded by several coils of wire, individually referred to as a pole. As the shaft rotates, so does the permanent magnet which creates a changing magnetic field in the presence of the poles which surround it. This induces a current in each of these poles and electrical energy is produced. Synchronous generators are typically quite simple and can be used in a wide variety of applications.

The second type is the asynchronous generator. At the heart of this design is its rotor, which is essentially a cylindrical cage of copper or aluminium bars that concentrically surround an iron core. This rotor construction looks a bit like a squirrel cage, and accordingly the asynchronous generator is also called a squirrel cage generator. Once again, this rotor is surrounded by a series of poles on its periphery called the stator. One way in which the asynchronous generator varies from the synchronous one is in that it is actually powered by the grid to set itself into motion initially. As the current from the grid passes through the stator, a current is induced in the cage rotor itself; causing opposing magnetic fields that set the rotor in motion at a specific rotational speed (this speed is determined by the frequency of the supply current and the number of poles in the stator). The generation of electricity occurs when the wind causes the rotational speed of the rotor to increase above this idle speed caused by the grid. What is fascinating about this phenomenon is that very large

voltages can be produced for comparatively small increases in rotational speed (considerable voltage for 10–15 rpm increase). With the rotor already in motion, there is little torque applied to the rotor shaft, ultimately resulting in less wear on the transmission. However, the asynchronous generator is much more complex than the synchronous one and also requires an initial source of power to operate. Asynchronous generators are more appropriate for applications where there is a fairly constant wind speed that rarely drops below a certain value.

3.3.2 Other equipment

3.3.2.1 Power electronic converter

Power electronic systems are used by many wind turbines as interfaces. Wind turbines function at variable rotational speed; thus the generator electric frequency varies and needs to be decoupled from the grid frequency through a power electronic converter system.

The power electronic converter enables wind turbines to operate at variable (or adjustable) speed, and thus permits to provide more effective power capture than the fixed-speed counterparts. In variable speed operation, a control system designed to extract maximum power from the wind turbine and to provide constant grid voltage and frequency is required according to the type of wind turbine used. With the advance of power electronics technology, this objective is easy to be accomplished, as will be noted from description of the subsequent section.

The power converter is an interface found between the load/generator and the grid. Depending on the topology and the applications present in the system, power can flow into the direction of both the generator and the grid. In using converters, three important things must be considered: reliability, efficiency, and cost.

Converters are made by power electronic devices, and circuits for driving, protection and control. Two different types of converter systems are currently in use: grid commutated and self commutated converters. Grid commutated converters are thyristor converters containing 6 or 12 pulse, or even more, that can produce integer harmonics. This kind of converter does not control the reactive power and consume inductive reactive power.

The other type of converter, self-commutated converter systems, are pulse width modulated (PWM) converters that mainly use Insulated Gate Bipolar Transistor (IGBTs). In contrast to grid-commutated, self-commutated converters control both active and reactive powers. PWM-converters, therefore, have the capacity to provide for the demand on reactive power and a high frequency switching that make them produce high harmonics and interharmonics.

3.3.2.2 Yaw drive

The yaw drive is an important component of modern horizontal axis wind turbines yaw system. To ensure the wind turbine is producing the maximum amount of electric energy at all times, the yaw drive is actively controlled to keep the rotor facing into the wind as the wind direction changes. This is accomplished by measured the wind direction by a wind vane situated on the back of the nacelle. The wind turbine is said to have a yaw angle (the misalignment between wind and turbine pointing direction) error if the rotor is not aligned to the wind. A yaw error implies that a lower share of the energy in the wind is running through the rotor area. The power output losses are proportional to the cosine of the yaw error.

3.3.2.3 Mechanical brake

A wind turbine has two different types of brakes. One is the blade tip brake and the other is a mechanical (or stick) brake. The mechanical brake is placed on the small fast shaft between the gearbox and the generator. This mechanical drum brake or disk brake is only used as an emergency brake, if the blade tip brake fails. The brake is also used when the wind turbine is being repaired to eliminate any risk of the turbine suddenly starting. Such brakes are usually applied only after blade furling and electromagnetic braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed.

3.3.2.4 Control system

The wind turbine control system is involved in almost all decision-making processes in the safety of the wind turbine. At the same time, it must supervise the normal operation of the wind turbine and carry out the measurements for monitoring, control, statistical use, etc. The control system is usually based on a number of dedicated computers, specially designed for industrial use, which continuously monitor the condition of the wind turbine and collect statistics on its operation. As the name implies, the controller also controls a large number of switches, hydraulic pumps, valves, and motors within the wind turbine. As wind turbine sizes increase to megawatt machines, it becomes even more important that they have a high availability rate, i.e. that they function reliably all the time.

A series of sensors measure the conditions in the wind turbine. These sensors are usually employed for measuring temperature, wind direction, wind speed, rotational speed of the rotor, the generator, its voltage and current, and many other magnitudes can be found in and around the nacelle (somewhere between 100 and 500 parameter values are sensed in a modern wind turbine), and assist in the turbine control. Computers and sensors are usually duplicated (redundant) in all safety or operation sensitive areas of newer large machines. The controller continuously compares the readings from measurements throughout the wind turbine to ensure that both the sensors and the computers themselves are correctly operating.

4. Wind turbine concepts

Wind turbines can either be designed to operate at fixed speed (actually within a speed range about 1%) or at variable speed. Many low-power wind turbines built to-date were constructed according to the so-called "Danish concept" that was very popular in the 80s, in which wind energy is transformed into electrical energy using a simple squirrel-cage induction machine directly connected to a three-phase power grid (Qiao et al., 2007). The rotor of the wind turbine is coupled to the generator shaft with a fixed-ratio gearbox. At any given operating point, this turbine has to be operated basically at constant speed. On the other hand, modern high-power wind turbines in the 2-10 MW range are mainly based on variable speed operation with blade pitch angle control obtained mainly by means of power electronic equipment, although variable generator rotor resistance could also be used.

Variable speed wind turbine generators permits to provide more effective power capture than the fixed speed counterparts (Timbus et al., 2009). In fact, variable speed wind turbines have demonstrated to capture 8-15% more energy than constant speed machines. In variable speed operation, a control system designed to extract maximum power from the wind turbine and to provide constant grid voltage and frequency is required. As well as becoming

larger, wind turbine designs were progressing from fixed speed, stall-controlled and with drive trains with gear boxes to become pitch controlled, variable speed and with or without gearboxes.

Among variable speed wind turbines, direct-in-line systems and doubly-fed induction generator (DFIG) systems have increasingly drawn more interests to wind turbine manufactures due to their advantages over other variable speed wind turbines and currently have the most significant potential of growth (Molina & Mercado, 2011). Direct-in-line systems consists of a direct-driven (without gearbox) permanent magnet synchronous generator (PMSG) grid-connected via a full-scale power converter, while DFIG systems are built with a common induction generator with slip ring and a partial-scale converter connected to the rotor windings. Both modern pitch-controlled variable speed wind turbines technologies are emerging as the preferred technologies and have become the dominating type of yearly installed wind turbines in recent years (Blaabjerg & Chen, 2006).

4.1 Variable speed wind turbine with partial-scale power converter

This concept, aka doubly-fed induction generator (DFIG), corresponds to a variable speed controlled wind turbine with a wound rotor induction generator (WRIG) and a partial-scale power converter (rated approximately at 30% of nominal generated power) on the rotor circuit (Muller et al, 2002), as shown in Fig. 2. The use of power electronic converters enables wind turbines to operate at variable (or adjustable) speed, and thus permits to provide more effective power capture than the fixed-speed counterparts (Blaabjerg et al. 2004). In addition, other significant advantages using variable speed systems include a decrease in mechanical losses, which makes possible lighter mechanical designs, and a more controllable power output (less dependent on wind variations), cost-effectiveness, simple pitch control, improved power quality and system efficiency, reduced acoustic noise, and island-operation capability.

The rotor stator is directly connected to the electric grid, while a partial-scale power converter controls the rotor frequency and consequently the rotor speed. The partial-scale power converter is composed of a back-to-back four-quadrant AC/DC/AC converter design based on insulated gate bipolar transistors (IGBTs), whose power rating defines the speed range (typically around $\pm 30\%$ of the synchronous speed). Moreover, this converter allows controlling the reactive power compensation and a smooth grid connection (Carrasco et al., 2006). The partial-scale power converter makes this concept attractive from an economical point of view. However, its main drawbacks are the use of slip rings, which needs brushes and maintenance, and the complex protection schemes in the case of grid faults.

4.2 Direct-in-line variable speed wind turbine with full-scale power converter

This configuration corresponds to the direct-in-line full variable speed controlled wind turbine, with the generator connected to the electric grid through a full-scale power converter, as illustrated in Fig 3 (Li et al., 2009). A synchronous generator is used to produce variable frequency AC power. The power converter connected in series (or in-line) with the wind turbine generator transforms this variable frequency AC power into fixed-frequency AC power. This power converter also allows controlling the reactive power compensation locally generated, and a smooth grid connection for the entire speed range. The generator can be electrically excited (wound rotor synchronous generator, WRSG) or permanent magnet excited type (permanent magnet synchronous generator, PMSG). Recently, due to

the development in power electronics technology, the squirrel-cage induction generator (SCIG) has also started to be used for this concept. The generator stator is connected to the grid through a full-scale power converter, which is composed of a back-to-back four-quadrant AC/DC/AC converter design based on insulated gate bipolar transistors (IGBTs).

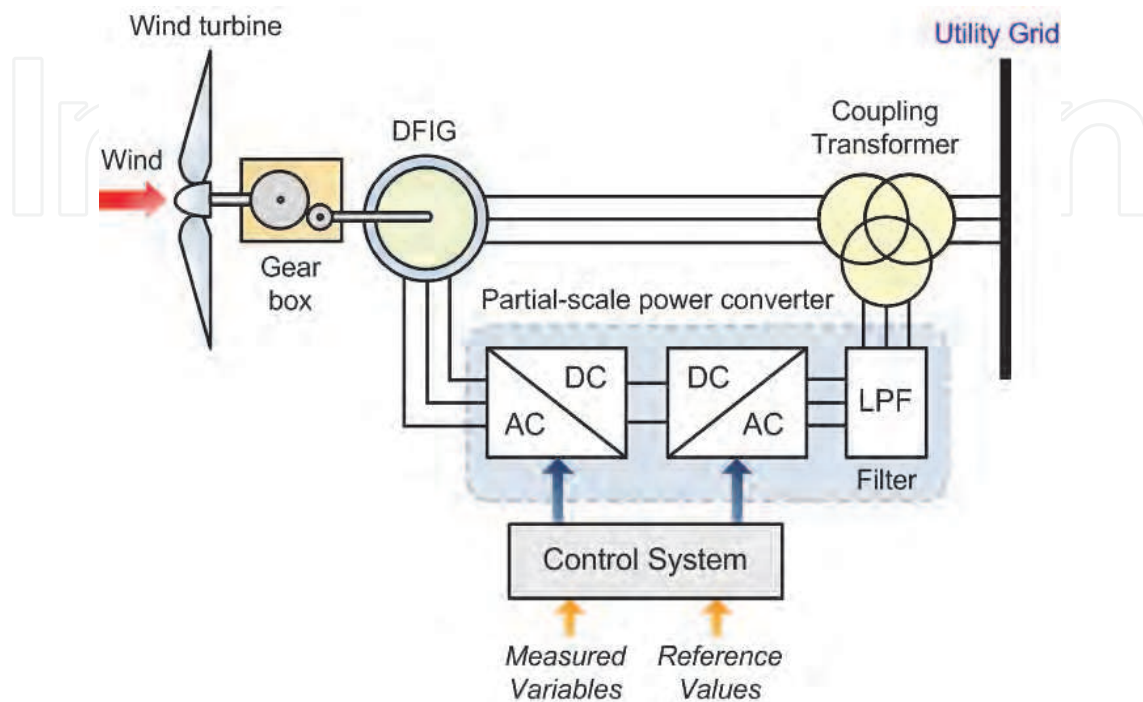


Fig. 2. Variable speed wind turbine with doubly-fed induction generator (DFIG) controlled with a partial-scale power converter

Some full variable speed wind turbine systems have no gearbox (shown in dotted lines in Fig. 3) and use a direct driven multi-pole generator.

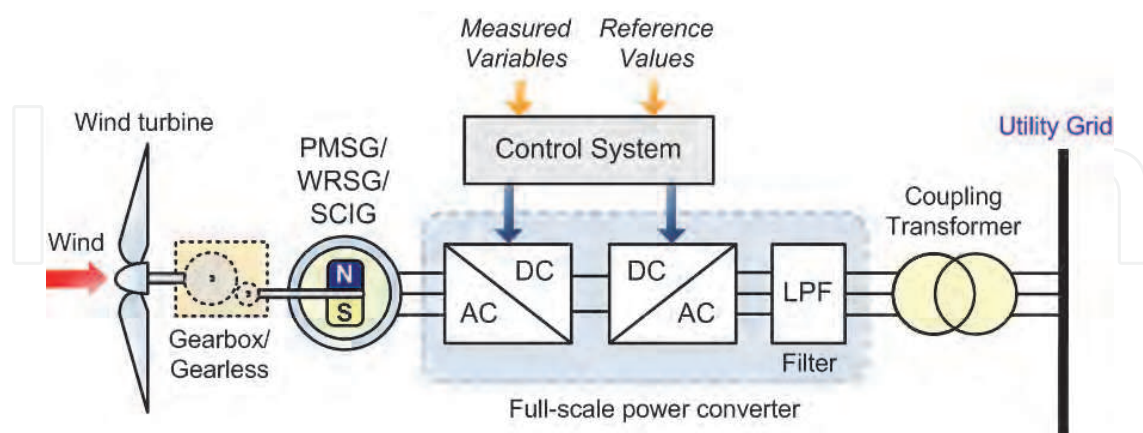


Fig. 3. Variable speed wind turbine with permanent magnet synchronous generator (PMSG) controlled with a full-scale power converter

Direct-in-line variable speed wind turbines have several drawbacks respect to the former variable speed DFIG concepts, which mainly include the power converter and output filter ratings at about 1 p.u. of the total system power. This feature reduces the efficiency of the

overall system and therefore results in a more expensive device. However, as the full scale power converter decouples entirely the wind turbine generator from the utility grid, grid codes such as fault ride through and grid support are easier to be accomplished, as required from modern applications. In addition, since a direct-in-line system can operate at low speeds, the gearbox can be omitted (direct-driven). Consequently, a gearless construction represents an efficient and robust solution that is beneficial, especially for offshore applications, where low maintenance requirements are essential. Moreover, using a permanent magnet synchronous generator, the DC excitation system is eliminated and allows reducing weight, losses, costs, and maintenance requirements (no slip rings are required). Even more, due to the intensified grid codes around the world, direct-driven PMSG wind turbine systems could be favoured in the future compared to DFIG wind turbine concepts (Li et al., 2009).

5. Technical exigencies for grid connection of wind generation

Any customer connected to a public utility electric network, whether generator or consumer, have to comply with agreed technical exigencies (aka demands or requirements) in order for the power grid to operate securely and efficiently. Electric power systems rely on generators to provide many of the control functions, and so the technical exigencies for generators are inevitably more complex than for demand customers. These technical requirements are often called “grid codes”, although the term should be used with care, as there are often different codes, depending on the voltage level of connection or the size of the application. In addition, there may be technical requirements that are not referred to the grid code, but which apply to the project through the connection agreement or the power purchase agreement or in some other way. Grid codes or interconnection guidelines can be summarized as a technical document containing the rules governing the operation, maintenance and development of the transmission system.

Large-scale penetration of wind generation may present a significant power contribution to the electric grid, and thus play an important role in power system operation and control (Slootweg & Kling, 2003). Consequently, high technical demands are expected to be met by these generation units. The purpose of these technical requirements is to define the technical characteristics and obligations of wind generators and the system operator (Martínez de Alegría et al. 2007), meaning that:

- Electric system operators can be confident that their system will be secure regardless of the wind generation projects and technologies applied.
- The amount of project-specific technical negotiation and design is minimised.
- Equipment manufacturers can design their equipment in the knowledge that the requirements are clearly defined and will not change without warning or consultation.
- Project developers have a wider range of equipment suppliers to choose from.
- Equivalent projects are treated fairly.
- Different wind generator technologies are treated equally.

This section includes the technical exigencies encountered in the majority of grid codes concerning wind generation interconnection. These include fault ride-through capability, system voltage and frequency operating range, reactive power and voltage regulation, active power regulation and frequency control as well as voltage flicker emission and harmonics emission.

5.1 Fault Ride-Through (FRT) capability

An important issue when integrating large-scale wind generation is the impact on the system stability and the transient behaviour. System stability is mainly associated with power system faults in the network such as tripping of transmission lines, loss of generation (generating unit failure) and short circuit. These failures disrupt the balance of power (active and reactive) and change the power flow. Although the capacity of the operating generators can be suitable, large voltage drops can occur suddenly and can propagate over very wide areas, affecting a great number of wind generators. The unbalance and re-distribution of active and reactive power in the network can force the voltage to vary beyond the boundary of stability. A period of low voltage (brownout) can occur and possibly be followed by a complete loss of power (blackout). (Jauch et al., 2004; Chen & Blaabjerg, 2009; Tsili & Papathanassiou, 2009).

Many faults in the power system are cleared by relay protections either by disconnection or by disconnection plus fast reclosing. In all the situations the result is a short period of low or no voltage followed by a period of voltage recovering. Some decades ago, when just a few wind turbines were connected to the grid, if a fault somewhere in the grid caused a short voltage drop at the wind turbine (aka voltage sag or dip), the wind turbine was simply disconnected from the electrical grid and had to be reconnected again when the fault was cleared and the voltage returned to the normal values. Because the penetration of wind generation in those days was low, the sudden disconnection of a wind turbine or even a wind farm from the grid did not cause a significant impact on the stability of the power system. With the increasing penetration of wind generation, the contribution of power generated by wind turbines is becoming a significant issue. If a large wind farm (or park) is abruptly disconnected when operates at full-rate, the power system will lose further production capability. Unless the remaining operating power plants have enough spinning reserve, in order to replace the lost power within very short time, a large power disturbance can occur and possibly be followed by a complete loss of power. It is, therefore, an essential requirement that wind generation is able to remain connected to the system during a power system fault, where the voltage on all three phases could fall to prevent extra generation losses. If wind generators are not able to ride-through voltage dips, the system will need a larger spinning reserve with consequent higher operating costs in order to avoid the system collapse because of the increasingly frequency drop.

The large increase in the installed wind capacity in transmission systems, especially in the last decade, requires that wind generation remains in operation in the case of disturbances and faults in the power system. For this reason, grid codes issued during the last years invariably demand that wind generation (especially those connected to high voltage grids) withstand voltage dips to a certain percentage of the nominal voltage (down to 0-15%) and for a specified duration (according to the country regulations). Such requirements are known as Fault Ride-Through (FRT) or Low Voltage Ride-Through (LVRT) capabilities and are described by a voltage vs. time characteristic such as the one shown in Fig. 4, denoting the minimum required immunity of the wind power generator (Kim & Dah-Chuan Lu, 2010). The FRT requirements under voltage dip is one of the main focuses of the grid codes and also include fast active and reactive power restoration to the pre-fault values, after the system voltage returns to its normal operation levels. Some codes impose increased reactive power generation by the wind turbines during the disturbance, in order to provide voltage support, a requirement that resembles the behaviour of conventional synchronous

generators in over-excited operation. The requirements depend on the specific characteristics of each power system and the protection employed and they deviate significantly from each other.

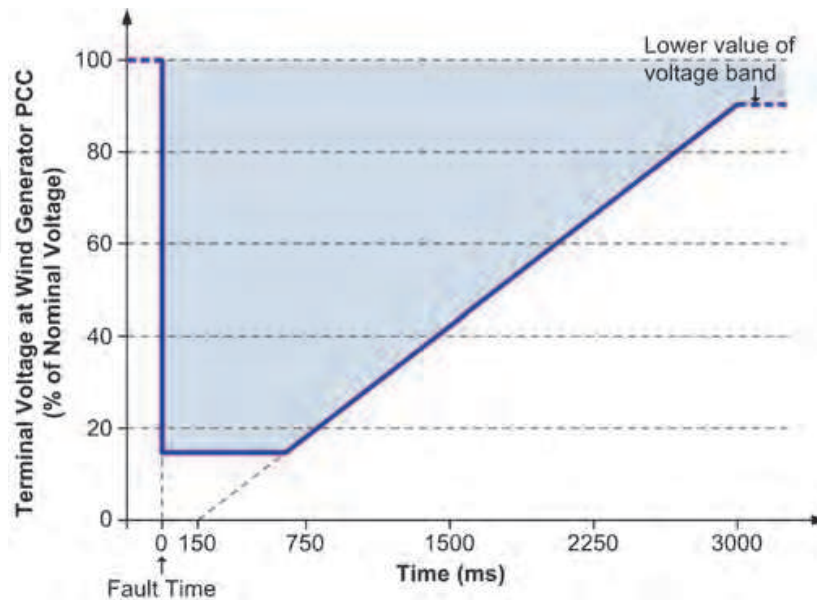


Fig. 4. Typical fault ride-through capability of a wind power generator

As previously described, the latest grid codes require that wind farms must remain in operation during severe grid disturbances, ensure fast restoration of active power to the pre-fault levels, as soon as the fault is cleared, and in certain cases produce reactive current in order to support grid voltage during disturbances. Depending on their type and technology, wind turbines can fulfil these requirements to different degrees.

In the case of fixed (constant) speed wind turbines, their low voltage behaviour is dominated by the presence of the direct grid-connected induction generator. In the event of a voltage dip, the generator torque reduces considerably (roughly by the square of its terminal voltage) resulting in the acceleration of the rotor, which may result in rotor instability, unless the voltage is restored fast or the accelerating mechanical torque is rapidly reduced. Further, operation of the machine at increased slip values results in increased reactive power absorption, particularly after fault clearance and partial restoration of the system voltage. This effectively prevents fast voltage recovery and can affect other neighbouring generators, whose terminal voltage remains depressed. Since the dynamic behaviour of the induction generator itself cannot be improved, a measure that can be employed in order to enhance the FRT capabilities of constant speed wind turbines is to supply reactive power through switched capacitors or static compensation devices connected at the wind turbine or wind farm terminals.

On the other hand, variable speed wind turbines, present the distinct advantages of direct generator torque and reactive current control and the possibility to endure large rotor speed variations without stability implications. For this reason, grid disturbances affect much less their operation and, generally, they are capable of meeting strict technical requirements.

In case of voltage disturbances, rotor overspeed becomes an issue of much smaller significance, since a limited increase of speed is possible (e.g. 10-15% above rated), the rotor inertia acting as an energy buffer for the surplus accelerating power, until the pitch

regulation becomes effective. In case of severe voltage dips, an energy surplus may occur in the electrical part, potentially leading to DC overvoltages. This is dealt with via proper redesign of the converter controllers, increase of the local energy storage capacity (e.g. capacitor size) or even by providing local power dissipation means. However, even with variable speed wind turbines there still exist LVRT issues affecting their response. In the case of DFIG wind turbines, the direct connection of the generator stator to the grid inevitably results in severe transients in case of large grid disturbances. Hence, the stator contributes a high initial short circuit current, while large currents and voltages are also induced in the rotor windings, as a consequence of the fundamental flux linkage dynamics of the generator. Furthermore, the depressed terminal voltage reduces accordingly the power output of the grid side rotor converter, leading to an increase of the DC bus capacitor voltage. To protect the power converters from overvoltages and overcurrents, DFIGs are always equipped with a device known as a crowbar that short-circuits the rotor terminals as soon as such situations are detected. Once the crowbar is activated, the DFIG behaves like a conventional induction machine, i.e. control is lost over the generator. Notably, crowbar activation is possible not only at the instant of a voltage depression, but also in case of abrupt voltage recovery, after clearance of a fault. Hence, although voltage dips inevitably cause torque and power transients in the DFIG wind turbine, which excite the rotor crowbar protection for a limited time interval, the various implementations of the active crowbar can improve the stability of the wind turbine and its response to sudden voltage changes.

Variable speed wind turbines with full-scale power converter present the distinct advantage that the converter totally decouples the generator from the grid. Hence, grid disturbances have no direct effect on the generator, whose current and torque variations during voltage dips are much lower compared to the DFIG and the respective transients fade out faster. From the point of view of the reactive output power, the grid side converter has the ability to produce reactive current during the voltage dip, up to its rated current. Notably, this wind turbine type can exhibit better voltage control capabilities even than conventional synchronous generators. Another notable advantage of this type against the DFIG-based wind turbines is related with the behaviour of the latter in case of unbalanced disturbances. In such situations, the low negative sequence impedance of the induction generator may give rise to large rotor currents, whose frequency lies outside the controllers bandwidth, resulting in the activation of the crowbar (or the disconnection of the stator) until the disturbance is cleared. Wind turbines can control their active power output by pitch control, while variable speed wind turbines have the additional capability for such control via variation of their rotor speed. Hence, power restriction, ramp rate limitations and contribution to frequency regulation is possible, even for constant speed machines. However, in the latter case the grid frequency is directly related to the generator slip and hence a change in frequency will transiently affect the active power produced by the wind turbine. In contrast, in the case of variable speed machines the generator power is directly controlled and therefore their primary frequency response is entirely adjustable via proper design of the control systems.

5.2 Voltage and frequency operating range

Wind farms must be capable of operating continuously within the voltage and frequency variation limits encountered in normal operation of the system. In addition, they should remain in operation in case of voltage and frequency excursions outside the normal operation limits, for a limited time and in some cases at reduced output power capability.

Tolerance to voltage variations in power systems depends on the level at the point of common coupling (PCC) of the wind power generator connected to the network. Transmission level voltages are usually considered to be 115 kV and above. Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages. Voltages less than 33 kV are usually used for distribution. Voltages above 230 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages.

The operating voltages at each voltage level are highly dependent on the local conditions and can be different in various countries. The lowest values are reached during operational disturbances and are usually not lower than 90% of the nominal voltage in the transmission level and can be down in some countries to 70% of the initial voltage for duration of up to 10 seconds, which must not lead to instability of the wind farm. Voltages above the upper limit for full-load voltage range is rarer and occurs for instance by reestablishment of the supply after major operational disturbances. These highest values are typically not higher than 113% in the transmission level. The system voltage operating range is generally narrower for higher voltage levels.

The frequency is one of the most important parameters in all power networks. The frequency of the electrical system varies by country; most electric power is generated at either 50 or 60 Hz. All the generating equipments in the electric system are designed to operate within very strict frequency margins. Grid codes specify that all generating plants should be able to operate continuously between a frequency range around the nominal frequency of the grid, usually between 49.5 and 50.5 Hz (for 50 Hz systems such as in Europe), and to operate for different periods of time when lower/higher frequencies down/up to a minimum/maximum limit, typically 47.5 and 52 Hz. Operation outside these limits would damage the generating plants, so even very short duration deviations from the nominal frequency values would trip load shedding relays and generation capacity would be lost. The lost of generation leads to further frequency deviation and a blackout can occur.

Wind farms have to be dimensioned to generate power at voltages and frequencies deviated from rated values in the way indicated in Fig. 5, showing the power restriction in different operating areas (Eltra & Ekraft System, 2004). In this diagram, V_L is the lower voltage limit while V_{LF} is the lower voltage limit for full-load range for a nominal voltage V_N . In the same way, V_H is the upper voltage limit while V_{HF} is the upper voltage limit for full-load range. These voltage limits in a 132 kV (V_N) transmission grid may have values such as 119 kV for V_L , 125 kV for V_{LF} , 145 kV for V_H and 155 kV for V_{HF} for the case of the Danish system. The full-load range indicates the voltage range within which the wind farm can supply its nominal power without any restriction (continuous operation area).

5.3 Reactive power control and voltage regulation

Reactive power control is very significant for wind farms, because not all wind generation technologies have the same capabilities, while wind farms are often installed in remote areas and therefore reactive power has to be transported over long distances resulting in power losses. Some wind farms are required to have sufficient reactive power compensation to be neutral in reactive power at any operating point. Recent grid codes demand from wind farms to provide reactive output regulation, often in response to power system voltage variations, much as the conventional power plants.

The reactive power control requirements are related to the characteristics of each network and the voltage level considered, since the influence of the reactive power injection on the

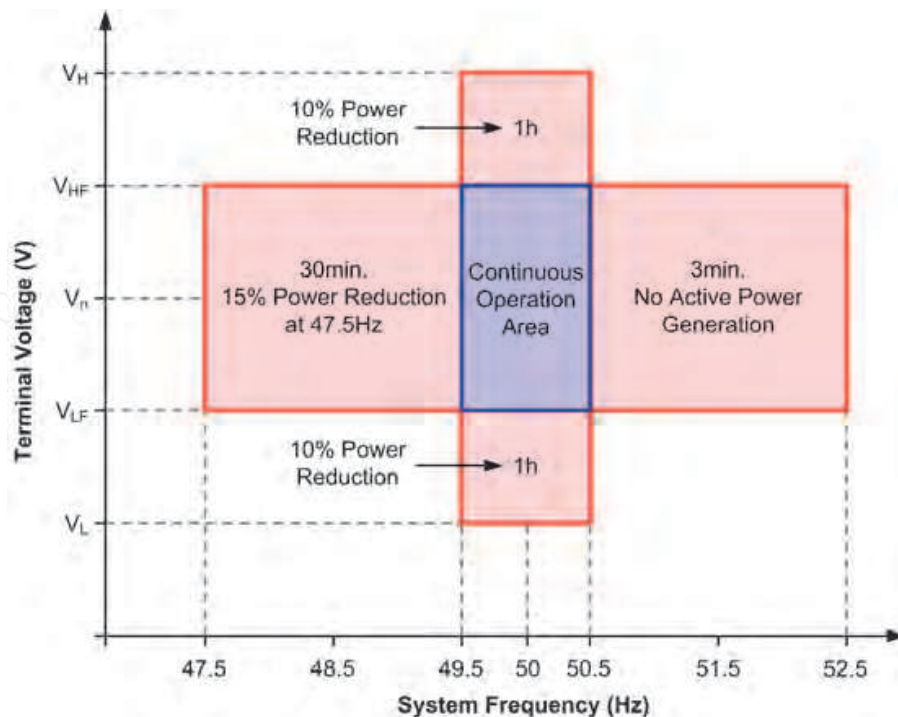


Fig. 5. Typical voltage and frequency dimensioning for wind generators

voltage profile is directly determined by the short-circuit capacity and impedance at the PCC of the wind farm. The short-circuit capacity at a given point in the electrical network represents the system strength or robustness. It is clear that the variations of the generated power result in variations of the voltage at PCC. If the impedance is small (the grid is strong) then the voltage variations are small. On the other hand, if the impedance is large (the grid is weak), then the voltage variations are large.

Voltage is closely related to the reactive power; consequently wind turbines with the ability of controlling reactive power can support and regulate the PCC local system voltage. Modern large wind farms are required to have the ability of controlling both active and reactive power. In the case of the fixed speed wind turbines with conventional induction generators, the reactive power can be controlled by thyristor-switched capacitor banks. Furthermore, a dynamic reactive power control unit based on power converters can additionally be installed at the PCC although at higher costs. In the case of power electronic converter-based variable speed wind turbines, such as those with DFIG systems or with full-scale power converters, the reactive power control can be performed by the converter itself. Consequently, significant active power fluctuations from the wind speed variations may not lead to corresponding fluctuations of the grid voltage at the connection point of the wind farm. Some codes recommend that the transmission system operators (TSOs) may define a set-point value for voltage or power factor or reactive power at the PCC of the wind farm.

A Voltage Regulator (VR) is included in modern wind generator in order to determine its terminal voltage magnitude to supply (or absorb) to the transmission system the desired amount of reactive power. A mismatch between the supply and demand of reactive power results in a change in the system voltage: if the supply of lagging reactive power is less than the demand, a decrease in the system voltage results; conversely, if the supply of lagging reactive power exceeds the demand, an increase in system voltage results. There are rigorous requirements on the extent to which the system voltage can be allowed to deviate

from its nominal values ($\pm 10\%$ for low voltage networks and $\pm 5\%$ for medium or high voltage networks). Voltage or reactive power requirements in the grid codes are usually specified with a limiting curve such as that shown in Fig. 6 (Martínez de Alegría et al. 2007). The mean value of the reactive power over several seconds should stay within the limits of the curve. When the generating unit is providing low active power the power factor may deviate from unity because it can support additional leading or lagging currents due to the reactive power demanded by the utility. When the generating unit is working under nominal conditions, the power factor must be kept close to unity so that it avoids excessive currents. Another advantage of local reactive power generation is the reduction of losses in the system. As the reactive power is locally generated and locally consumed, the current through all upstream devices and the power losses in the network are reduced. Thus, the wind farm should have the capability to control the voltage and/or the reactive power at the PCC. This is essential in order to ensure secure operation of the system. The wind farm operator has the opportunity to gain additional payments for providing reactive power.

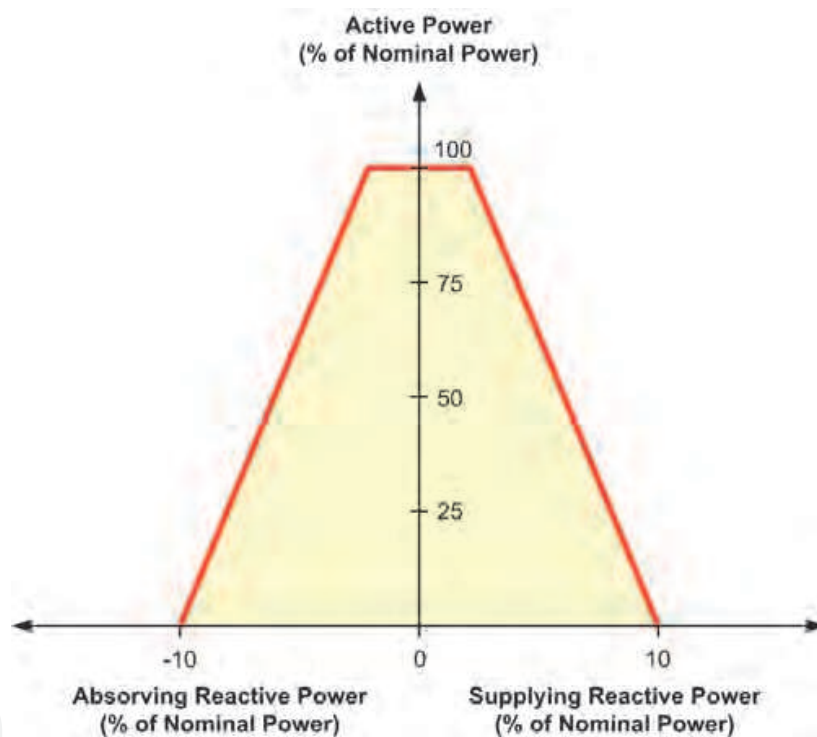


Fig. 6. Typical reactive power limiting curve for wind generators

5.4 Active power control and frequency control

One of the most important and limiting factors in wind power integration into the electric grid is the spinning reserve needed due to the unpredictability of wind and the possible sudden loss of wind generation. Usually, a good prediction of the wind can be achieved 1–4 h in advance; although better prediction methods are still needed. In order to avoid a collapse in the power system, adequate spinning reserve or very strong connections with neighbour countries are necessary.

Active power control requirements for supporting and stabilizing the system frequency refer to the ability of wind farms to regulate (usually, but not exclusively, reducing) their power output to a defined level (active power restriction), either by disconnecting turbines

or by pitch control action for the case of variable speed wind turbines. In addition, wind farms are required to provide frequency response, that is, to regulate their active output power according to the frequency deviations (Lalor et al., 2005). In some countries, generation based on intermittent sources of energy (i.e. wind and solar power) are exempted from the obligation to supply primary reserves. Neither do they, neither have to offer any capacity as reserve power or regulating power to the TSO. In some other countries, such as Germany, Ireland and Denmark, their grid codes demand that wind farms have the ability of active power restriction. Some other like the British code requires that wind farms have a frequency control device capable of supplying primary and secondary frequency control, as well as over-frequency control. As a general remark, it is clear that most grid codes require wind farms (especially those of high capacity) to provide frequency response, i.e. to contribute to the regulation of system frequency. It should be emphasized that the active power ramp rates must comply with the respective rates applicable to conventional power units.

Fig. 7 shows a typical grid code-limiting curve for frequency controlled regulation of the active power (Martínez de Alegría et al. 2007). High-frequency response can be provided from full output to a reduced output when the frequency exceeds 50 Hz and the new grid codes require that when the frequency increases above the rated value generating plants should decrease their output at a given rate. On the other hand, at nominal frequency, the wind farms would be required to limit their power output below the maximum achievable power level. By doing so, if the frequency starts to drop, the wind farm would increase the power output to the maximum achievable power, trying to sustain the frequency.

The provision of frequency response will be purchased based on the prices placed in the market. High-frequency response from wind powered generation is a service already of interest, especially at minimum demand conditions and it could become an additional source of income for wind farm owners. Low-frequency response capability would be interesting if the pay for such response would compensate the loss of generated power.

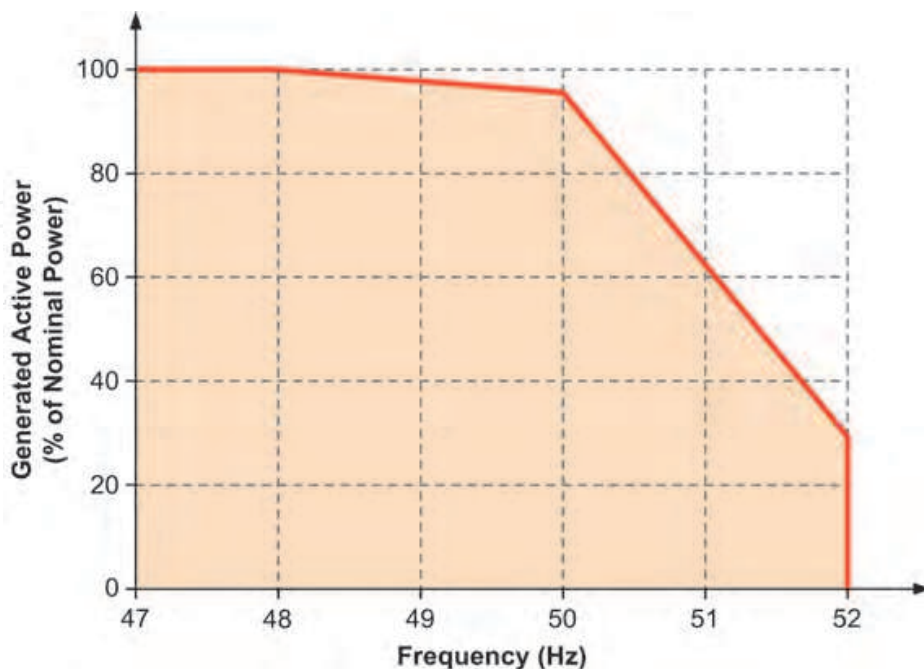


Fig. 7. Typical frequency controlled regulation of active power

5.5 Voltage flicker emission

Flicker is another voltage quality issue on wind power generation associated with the electric grid. Flicker is defined as a measure of annoyance of flickering light bulbs on human, caused by active and reactive power fluctuation as a result of the rapid change in wind speed. Fluctuations in the system voltage (more specifically in its RMS value) can cause perceptible light flicker depending on the magnitude and frequency of the fluctuation. This type of disturbance is called voltage flicker, or shortened as flicker (Bollen, 2000).

There are two types of flicker emissions associated with wind turbines, i.e. during continuous operation and switching operation due to the generator and capacitor switchings. The switching operation is the condition of cut-in and cut-out by the wind turbine. The standard IEC 61400-21 (2008) requires flicker to be monitored in these two operation modes. Frequently, one or the other is the predominant. The acceptable flicker limits are generally established by individual utilities. Rapid variations in the power output from a wind turbine, such as generator switching and capacitor switching, can also result in variations in the RMS value of the voltage. At certain rate and magnitude, the variations cause flickering of the electric light. In order to prevent flicker emission from impairing the voltage quality, the operation of the generation units should not cause excessive voltage flickers. It is reported that flicker is relatively less critical issue in variable speed wind turbine generation systems; however, it needs to be improved for higher power quality.

The flicker emissions from a wind turbine installation should be limited to comply with the flicker emission limits. It is recommended that the long term flicker severity factor P_{lt} , calculated with a “flicker algorithm” defined for 2 h periods, lesser or equal than 0.50 in 10–20 kV networks and $P_{lt} \leq 0.35$ in 50–60 kV networks are considered acceptable. However, different utilities may have different flicker emission limits.

5.6 Harmonics emission

Harmonic disturbances are a phenomenon associated with the distortion of the fundamental sine wave and are produced by nonlinearity of electrical equipment. Harmonic emission is another crucial issue for grid connected wind turbines because it can result in voltage distortion and torque pulsations, which consequently causes possible destructive overheating in the generator and in other equipment, and other problems such as increased currents and additional power losses (Bollen, 2000). Harmonics can also raise problems in communication and control systems. Although wind turbines emit low-order harmonics by nature, self-commutated power electronic converters used in modern variable speed wind turbines can filter out this low-order harmonics. In addition, the pulse width modulation (PWM) switching strategy employed to control these converters, with a typical switching frequency of a few thousand Hz, shifts the harmonics to higher frequencies where the harmonics can be easily removed by smaller filters (Acha et al., 2002). However, the self-commutated converters introduce high-order harmonics instead. In addition, inter-harmonics, which is non-integer harmonics, is another type of harmonic emission by these technologies. It contributes to the level of the flicker and has an interference with control and protection signals in power lines, which are regarded as the most harmful effects on the power system.

Harmonic standards are specified to set up the limits on the Total Harmonic Distortion (THD) as well as on the individual harmonics. Wind turbine power quality standard IEC 61400-21 (2008), along with harmonic measurement standard IEC 61000-4-7 (2008), provides

the requirements for on current harmonics, current inter-harmonics and higher current components to be measured and reported in modern wind power systems.

6. Regulatory exigencies for grid connection of wind generation in selected countries

This section briefly describes major technical regulations for grid connection of wind generation in selected countries such as Germany, Denmark and Argentina (Alboyaci & Dursun, 2008).

6.1 Germany

The German interconnected transmission system operates at voltage levels 220 kV and 380 kV (Lines of less than 150 kV are considered distribution lines in Germany) and is divided into four control areas, each in responsibility of one TSO: RWE Transportnetz Strom GmbH, E.ON Netz GmbH, Vattenfall Europe Transmission (VE-T) GmbH and EnBW Transportnetze AG. Together, the four control areas form the German control block, which makes part of the UCTE (Union for the Co-ordination of Transmission of Electricity) synchronous zone in continental Europe (Erlich & Bachmann, 2005). These TSOs issued grid requirements on wind turbine connection and operation on the electric grid (E.ON Netz, 2006). Simultaneously, the association of German transmission grid operators, VDN, summarized special requirements concerning renewable energy sources operating on the high voltage network in a document as an appendix to the existing general grid codes (Alboyaci & Dursun, 2008).

According to the German code, the requirements of transient fault behaviour of wind generators are divided mainly in two categories: one for generators with large contribution to the fault current at the grid connection requirement (GCR) i.e. the fault current is at least two times the nominal current for at least 150 ms, and one for generators where the fault current contribution is less than that.

Onshore wind farms require connection to the 380 kV high voltage system and must be treated like conventional power plants. However, new technical solutions are required for connecting large wind farms at a distance of 100-200 km offshore to the mainland. The German code related to the FRT (or LVRT) requirements of wind farms stipulate that they must remain connected during voltage dips down to 0%. However, it must be noted that these requirements apply to the PCC to the network, generally at high voltage level. This indicates that the corresponding voltage dip at lower voltage levels, i.e. near the wind turbine terminals, are likely to be rather above 15%.

The frequency range that wind turbines have to tolerate is about 47.5–51.5 Hz. It must be possible to limit the active power output from every operating point as a percentage of the nominal power. For power reduction a ramp rate of at least 10% of nominal power per minute must be possible.

It has to be possible to operate wind farms with nominal power of less than 100 MW with power factor between 0.95 lagging and 0.95 leading. The required power factor values are always applied at the grid connection point. Wind farms rated 100 MW or more have to be able to operate at power factor between 0.925 lagging and 0.95 leading. The power factor range is however limited depending on the grid voltage to avoid leading power factor at grid voltages below nominal values. Generators with small fault current contribution are

required to support grid voltage in case of faults by supplying reactive power proportional to the voltage drop. Between 10% and 50% voltage drop the generators have to supply reactive current between 10% and 100% rated current, linearly proportional to the voltage. Generators with big fault current contribution, on the other hand, are not required to contribute to voltage support during transient faults.

6.2 Denmark

The Danish transmission system operates at voltage levels 132 kV, 150 kV and 400 kV and has historically been administered by two independent TSOs: Eltra in the West, and Elkraft System in the East. In 2005, these merged to form the new state-owned operator, Energinet Denmark which also oversees operation of the gas network. The two separate TSOs arose because their respective networks were geographically and electrically separate from each other (Eltra & Ekraft System, 2004).

While not directly connected, both are interconnected to neighbouring countries. Western Denmark is synchronized by the UCTE system with Germany and has 1670 MW of DC links with Norway and Sweden. Eastern Denmark is part of the NordPool market and is connected synchronously to Sweden and asynchronously to Germany. While the physical transfer capability is significant, there are operational limits of 800 MW to the North and 1300 MW to the South because of congestion on their neighbours' grid (Eltra & Ekraft System, 2004; Alboyaci & Dursun, 2008).

According to the Danish code, no specific voltage operating ranges and respective trip times in transient fault situations are specified in these grid connection requirements. Wind farms have to stay connected and stable under permanent 3-phase faults on any arbitrary line or transformer and under transient 2-phase fault (unsuccessful auto-reclosure) on any arbitrary line. In the case of a fault incidence, the voltage can be down to 70% of the initial voltage for duration of up to 10 seconds, which must not lead to instability of the wind farm. The controllability of the wind farm must be sustained for up to 3 faults within 2 minutes, or for up to 6 faults if the delay between the faults is 5 minutes; each fault happening during steady state operation. This requirement makes sure that the turbines are fitted with sufficient auxiliary power supplies. When the voltage falls after a fault below 60–80% for longer than 2–10 seconds, it is likely that the turbines have accelerated so much, that the grid cannot get them back to normal speed. The Danish code related to the FRT requirements of wind farms stipulate about the same requirements than the German counterpart, i.e. wind generators must remain connected during voltage dips down to 0% at the PCC to the high voltage network (above 15% at the lower voltage wind turbine terminals). However, these specifications may vary according to the voltage level or the wind farm power: e.g. wind farms connected to the Danish grid at voltages below 100 kV are required to withstand less severe voltage dips than the ones connected at higher voltages, in terms of voltage dip magnitude and duration.

The frequency range that wind turbines have to tolerate is about 47–53 Hz. Controlled limitation of active power is demanded to limit the reactive power demand of wind farms after a fault. In addition, power limitation is demanded to ensure supply and demand balance if a part of Denmark becomes an island due to a fault. It must be possible to reduce power to less than 20% of nominal power within less than 2 seconds. This corresponds to a ramp rate of 40% of rated power per second.

Wind farms are required to have sufficient reactive power compensation to be neutral in reactive power at any operating point. This requirement has to be fulfilled at the grid connection point. In the 150 kV system, steady state operation has to be possible under full load in the voltage range between 0.95 p.u. and 1.13 p.u. In the 400 kV system the voltage range is narrower, hence less onerous for generators to cope with. If the voltage reaches 1.2 p.u. at the grid connection point (irrespective of the voltage level) the wind farm has to start performing voltage reduction within 100ms of detection. Voltage reduction can be achieved by switching reactors to increase the reactive power demand of the wind farm.

6.3 Argentina

Argentina has one of the best regions of wind characteristics of the world, which is The Patagonia. For many experts, the Patagonian wind is the world's best quality continental resource. The meteorological average wind speed in this region is from 5 to 10 m/s approximately at 10 m height. The meteorological wind power at 10 m height of Patagonia is about 200 GW. However, the wind energy market in Argentina has not yet taken off because of lack of effective government policy stimulus.

The Argentinean interconnected transmission system operates at voltage levels 132 kV, 220 kV and 500 kV and is in responsibility of just one TSO: CAMMESA (Wholesale Electricity Market Administration Company). This TSO has issued preliminary grid requirements concerning wind turbine connection and operation on the high voltage network in a document as an appendix No. 40 (CAMMESA, 2010) to the existing general grid codes (aka the procedures).

According to the Argentinean code, the requirements of transient fault behaviour of wind generators are separated in two groups: wind farms type A with big contribution to the fault current at the grid connection requirement and wind farms type B with the fault current contribution lesser than the previous category.

Wind farms must be treated as conventional run-of-river hydraulic power plants. However, those issues of exclusive nature to wind generation are defined in the appendix No. 40. This last document briefly considers four aspects: (a) requirements of insertion to the grid, (b) voltage control and reactive dispatch, (c) operation and restrictions and (d) power quality.

The main condition for a wind farm to be accepted to be included into the wholesale electricity market is its size, which must be larger than 1 MW.

The wind farm must perform the obligations of supply and absorption of reactive power so that exhibits a power factor ($\cos \phi$) of 0.95 either inductive or capacitive at the PCC to the network. For the case of wind farms type A, the maximum admissible voltage disturbance at the PCC to the grid as a consequence of the larger rapid variation of generation and the greater variation of frequent generation is 1% for network voltage levels between 132 kV and 500 kV, 2% for levels between 35 kV and 132 kV and 3% for voltage levels lower than 35 kV. In this case, the wind farm must operate controlling the voltage at the PCC or at an internal bus, and must include a cooperative control so as to share the reactive power among each wind generator. For the case of wind farms type B, since the larger rapid variation of generation and the greater variation of frequent generation produce voltage changes lesser than the previously indicated, then it is not required that the wind farm operates controlling the terminal voltage level and may operate at the fixed power factor required by the TSO. The Argentinean code related to the FRT requirements of wind farms stipulate that they must remain connected during voltage dips down to 0 at the PCC to the

high voltage network (above 15% at the lower voltage wind turbine terminals). The frequency range that wind turbines have to tolerate is about 47.5–52.5 Hz. Wind turbines must meet, in regard to injection of harmonics, flicker, etc. with standard IEC 61400–21.

7. Conclusion

This chapter has provided an overall perspective of modern wind power systems, including a discussion of major wind turbine concepts and technologies. More specifically, of the various wind turbine designs, pitch-controlled variable speed wind turbines controlled by means of power electronic converters have been considered. A revision of modern structures of wind turbines has also been carried out, including towers and foundations, rotor, nacelle with drive train and other equipment, and control system, among others. In the survey, the technical exigencies encountered in the majority of grid codes concerning wind generation interconnection have been deeply reviewed. These include fault ride-through capability, system voltage and frequency operating range, reactive power and voltage regulation, active power regulation and frequency control as well as voltage flicker emission and harmonics emission. Moreover, an analysis of the different grid codes emitted by the organizations entrusted to regulate the electrical sector in selected countries such as Germany and Denmark has been carried out and compared to Argentina.

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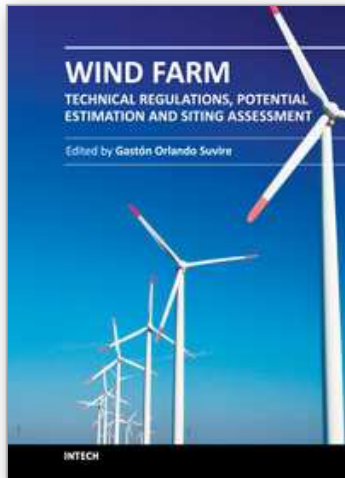
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The evolution of wind power generation is being produced with a very high growth rate at world level (around 30%). This growth, together with the foreseeable installation of many wind farms in a near future, forces the utilities to evaluate diverse aspects of the integration of wind power generation in the power systems. This book addresses a wide variety of issues regarding the integration of wind farms in power systems. It contains 10 chapters divided into three parts. The first part outlines aspects related to technical regulations and costs of wind farms. In the second part, the potential estimation and the impact on the environment of wind energy project are presented. Finally, the third part covers issues of the siting assessment of wind farms.

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