CHAPTER 1

Introduction to A Wind Energy Generation System

1.1 INTRODUCTION

The aim of this chapter is to provide the basic concepts to understand a wind energy generation system and the way it must be operated to be connected to the utility grid.

It covers general background on wind turbine knowledge, not only related to the electrical system, but also to the mechanical and aerodynamics characteristics of wind turbines.

In Section 1.2 the components and basic concepts of a fixed speed wind turbine (FSWT) are explained, as an introduction to a modern wind turbine concept; also, energy extraction from the wind and power–torque coefficients are also introduced.

In Section 1.3 a simple model for the aerodynamic, mechanical, and pitch systems is developed together with a control system for a variable speed wind turbine (VSWT). This section explains the different configurations for the gearbox, generator, and power electronics converter, used in a VSWT.

Section 1.4 describes the main components of a wind energy generation system (WEGS), starting with a VSWT based on a doubly fed induction motor (DFIM); then a wind farm electrical layout is described and finally the overall control strategy for the wind farm and the wind turbine.

In Section 1.5, the grid integration concepts are presented since the rising integration of wind power in the utility grid demands more constraining connection requirements.

Since the low voltage ride through (LVRT) is the most demanding in terms of control strategy, Section 1.6 deals with the LVRT operation description. The origin, classification, and description of voltage dips are given in order to understand specifications for the LVRT. The section finishes by describing a grid model suitable to validate the LVRT response of wind turbines.

Section 1.7 provides a survey of solutions given by different wind turbine manufacturers. And finally a 2.4 MW VSWT is numerically analyzed.

To conclude, the next chapters are overviewed in Section 1.8.

Doubly Fed Induction Machine: Modeling and Control for Wind Energy Generation,
First Edition. By G. Abad, J. López, M. A. Rodríguez, L. Marroyo, and G. Iwanski.

1.2 BASIC CONCEPTS OF A FIXED SPEED WIND TURBINE (FSWT)

1.2.1 Basic Wind Turbine Description

The basic components of a wind turbine are described by means of a fixed speed wind turbine, based on a squirrel cage (asynchronous machine) and stall–pitch power control. This technology, developed in the late 1970s by pioneers in Denmark, was widely used during the 1980s and 1990s, and was the base of wind energy expansion in countries like Spain, Denmark, and Germany during the 1990s.

The main manufacturers developing this technology have been Vestas, Bonus (Siemens), Neg-Micon and Nordtank, in Denmark, Nordex and Repower in Germany, Ecotècnia (Alstom), Izar-Bonus and Made in Spain, and Zond (Enron-GE) in the United States. At present, many other small manufacturers and new players such as Sulzon in India or GoldWind in China are in the market.

The first fixed speed wind turbines were designed and constructed under the concept of reusing many electrical and mechanical components existing in the market (electrical generators, gearboxes, transformers) looking for lower prices and robustness (as the pioneers did when they manufactured the first 25 kW turbines in their garages in Denmark). Those models were very simple and robust (most of them are still working, and there is a very active secondhand market).

To achieve the utility scale of 600,750, and 1000 kW, development of wind turbines took only ten years, and around two-thirds of the world's wind turbines installed in the 1980s and 1990s were fixed speed models.

Before we describe the FSWT, let's have a look at the main concepts related to this technology:

- The fixed speed is related to the fact that an asynchronous machine coupled to a fixed frequency electrical network rotates at a quasifixed mechanical speed independent of the wind speed.
- The stall and pitch control will be explained later in the chapter, but is related to the way the wind turbine limits or controls the power extracted from the wind.

Figure 1.1 shows the main components of a fixed speed wind turbine.

The nacelle contains the key components of the wind turbine, including the gearbox and the electrical generator. Service personnel may enter the nacelle from the tower of the turbine.

To the left of the nacelle we have the wind turbine rotor, that is, the rotor blades and the hub. The rotor blades capture the wind and transfer its power to the rotor hub. On a 600 kW wind turbine, each rotor blade measures about 20 meters in length and is designed much like the wing of an aeroplane.

The movable blade tips on the outer 2–3 meters of the blades function as air brakes, usually called tip brakes. The blade tip is fixed on a carbon fiber shaft, mounted on a bearing inside the main body of the blade. On the end of the shaft inside the main blade, a construction is fixed, which rotates the blade tip when subjected to an outward movement. The shaft also has a fixture for a steel wire, running the length of the blade from the shaft to the hub, enclosed inside a hollow tube.

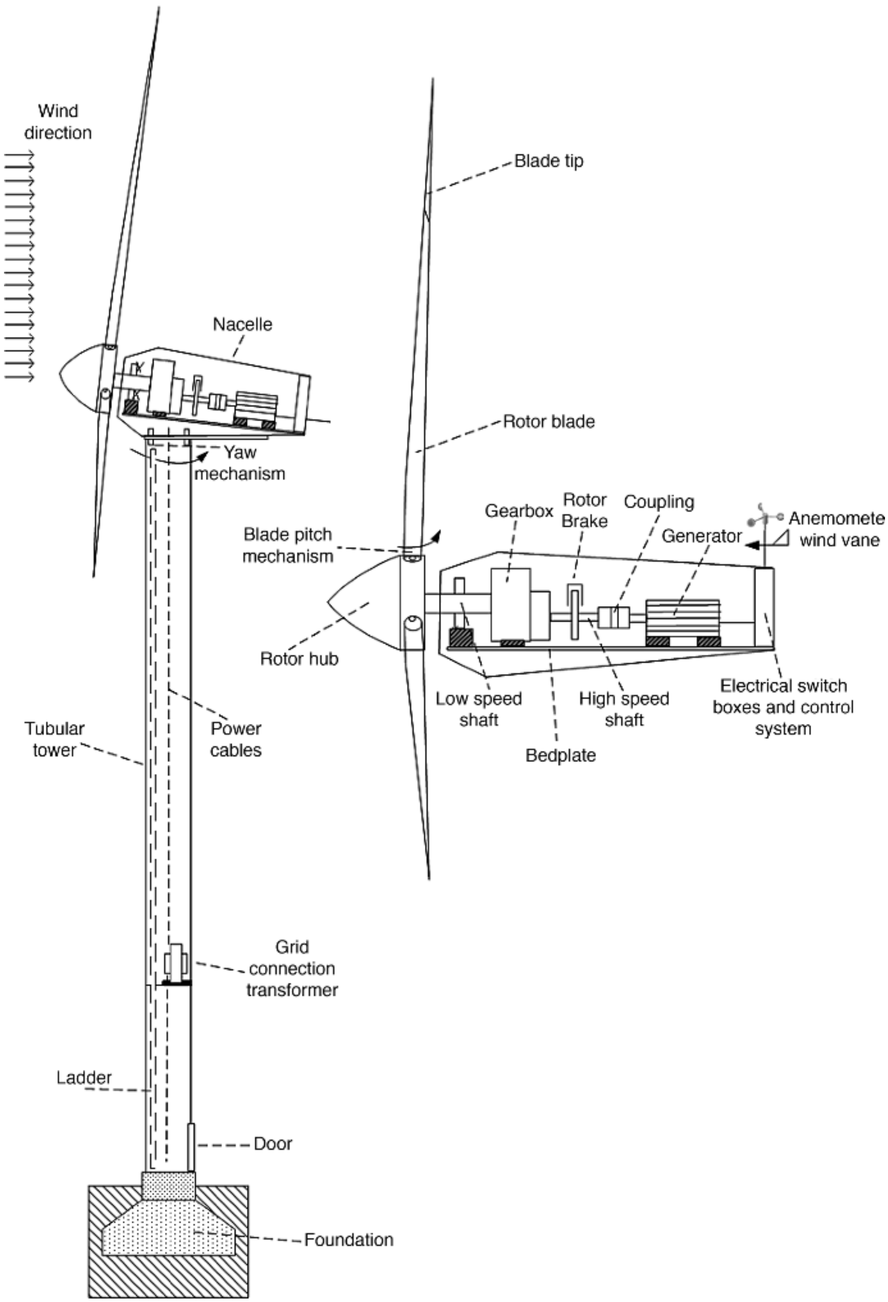


Figure 1.1 Main components of a fixed speed wind turbine.

During operation, the tip is held fast against the main blade by a hydraulic cylinder inside the hub, pulling with a force of about 1 ton on the steel wire running from the hub to the blade tip shaft.

When it becomes necessary to stop the wind turbine, the restraining power is cut off by the release of oil from the hydraulic cylinder, thereby permitting centrifugal force to pull the blade tip outwards. The mechanism on the tip shaft then rotates the blade tip through 90 degrees, into the braking position. The hydraulic oil outflow from the hydraulic cylinder escapes through a rather small hole, thus allowing the blade tip to turn slowly for a couple of seconds before it is fully in position. This thereby avoids excessive shock loads during braking.

The tip brakes effectively stop the driving force of the blades. They cannot, however, normally completely stop blade rotation, and therefore for every wind speed there is a corresponding freewheeling rotational speed. The freewheeling rotational speed is much lower than the normal operational rotational speed, so the wind turbine is in a secure condition, even if the mechanical brake should possibly fail.

The hub of the rotor is attached to the low speed shaft of the wind turbine. The low speed shaft of the wind turbine connects the rotor hub to the gearbox. On a 600 kW wind turbine, the rotor rotates relatively slowly, about 19–30 revolutions per minute (rpm).

The gearbox has a low speed shaft to the left. It makes the high speed shaft to the right turn approximately 50 times faster than the low speed shaft.

The high speed shaft rotates with approximately 1500 revolutions per minute (rpm) and drives the electrical generator. It is equipped with an emergency mechanical disk brake. The mechanical brake is used in case of failure of the aerodynamic brake (movable blade tips), or when the turbine is being serviced.

The electrical generator is usually a so-called induction generator or asynchronous generator. On a modern wind turbine, the maximum electric power is usually between 500 and 1500 kilowatts (kW).

The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate. The hydraulics system is used to reset the aerodynamic brakes of the wind turbine.

The electronic controller contains a computer that continuously monitors the condition of the wind turbine and controls the yaw mechanism. In case of any malfunction (e.g., overheating of the gearbox or the generator), it automatically stops the wind turbine and calls the turbine operator's computer via a telephone modem link.

The cooling unit contains an electric fan, which is used to cool the electrical generator. In addition, it contains an oil cooling unit, which is used to cool the oil in the gearbox. Some turbines have water-cooled generators.

The tower of the wind turbine carries the nacelle and the rotor. Generally, it is an advantage to have a high tower, since wind speeds increase farther away from the ground.

Towers may be either tubular towers (such as the one in Figure 1.1) or lattice towers. Tubular towers are safer for the personnel who have to maintain the turbines, as they may use an inside ladder to get to the top of the turbine. The advantage of lattice towers is primarily that they are cheaper. A typical 600 kW turbine will have a tower of 40–60 meters (the height of a 13–20 story building).

Wind turbines, by their nature, are very tall slender structures. The foundation is a conventional engineering structure that is designed mainly to transfer the vertical load (dead weight). However, in the case of wind turbines, due to the high wind and environmental loads experienced, there is a significant horizontal load that needs to be accounted for.

The yaw mechanism uses electrical motors to turn the nacelle with the rotor against the wind. The yaw mechanism is operated by the electronic controller, which senses the wind direction using the wind vane. Normally, the turbine will yaw only a few degrees at a time, when the wind changes its direction. The anemometer and the wind vane are used to measure the speed and the direction of the wind.

The electronic signals from the anemometer are used by the wind turbine's electronic controller to start the wind turbine when the wind speed reaches approximately 5 meters per second (m/s). The computer stops the wind turbine automatically if the wind speed exceeds 25 meters per second in order to protect the turbine and its surroundings.

The wind vane signals are used by the wind turbine's electronic controller to turn the wind turbine against the wind, using the yaw mechanism.

The wind turbine output voltages were in the low voltage range—380, 400, 440 V—for the first wind turbine models (20–500 kW) in order to be connected directly to the low voltage three-phase distribution grid, but the increasing power demand and the integration in wind farms has increased this voltage to 690 V. When the wind turbine must be connected to the medium voltage distribution grid, a transformer is included (inside the tower or in a shelter outside).

1.2.2 Power Control of Wind Turbines

Wind turbines are designed to produce electrical energy as cheaply as possible. Wind turbines are therefore generally designed so that they yield maximum output at wind speeds around 15 meters per second. Its does not pay to design turbines that maximize their output at stronger winds, because such strong winds are rare.

In the case of stronger winds, it is necessary to waste part of the excess energy of the wind in order to avoid damaging the wind turbine. All wind turbines are therefore designed with some sort of power control.

There are two different ways of doing this safely on modern wind turbines—pitch and stall control, and a mix of both active stall.

1.2.2.1 Pitch Controlled Wind Turbines On a pitch controlled wind turbine, the turbine's 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. Conversely, 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) as shown in Figure 1.1.

During normal operation, the blades will pitch a fraction of a degree at a time—and the rotor will be turning at the same time.

Designing a pitch controlled wind turbine requires some clever engineering to make sure that the rotor blades pitch exactly the amount required. On a pitch controlled wind turbine, the computer will generally pitch the blades a few degrees every time the wind changes in order to keep the rotor blades at the optimum angle and maximize output for all wind speeds.

The pitch mechanism is usually operated using hydraulics or electrical drives.

1.2.2.2 Stall Controlled Wind Turbines (Passive) stall controlled wind turbines have the rotor blades bolted onto the hub at a fixed angle.

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), but it increases the cross section of the blade face-on to the wind, and thus the ordinary drag. A fully stalled turbine blade, when stopped, has the flat side of the blade facing directly into the wind.

If you look closely at a rotor blade for a stall controlled wind turbine, you will notice that the blade is twisted slightly as you move along its longitudinal axis. This is partly done in order to ensure that the rotor blade stalls gradually rather than abruptly when the wind speed reaches its critical value.

The basic advantage of stall control is that one avoids moving parts in the rotor itself, and a complex control system. 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, for example, to avoid stall-induced vibrations.

1.2.2.3 Active Stall Controlled Wind Turbines An increasing number of larger wind turbines (1 MW and up) are being developed with an active stall power control mechanism.

Technically, the active stall machines resemble pitch controlled machines, since they have pitchable blades. In order to get a reasonably large torque (turning force) at low wind speeds, the machines will usually be programmed to pitch their blades much like a pitch controlled machine at low wind speeds. (Often they use only a few fixed steps depending on the wind speed.)

When the machine reaches its rated power, however, you will notice an important difference from the pitch controlled machines: If the generator is about to be overloaded, the machine will pitch its blades in the opposite direction from what a pitch controlled machine does. In other words, it will increase the angle of attack of the rotor blades in order to make the blades go into a deeper stall, thus wasting the excess energy in the wind.

One of the advantages of active stall is that one can control the power output more accurately than with passive stall, so as to avoid overshooting the rated power of the machine at the beginning of a gust of wind. Another advantage is that the machine can be run almost exactly at rated power at all high wind speeds. A normal passive stall controlled wind turbine will usually have a drop in the electrical power output for higher wind speeds, as the rotor blades go into deeper stall.

The pitch mechanism is usually operated using hydraulics or electric stepper motors.

As with pitch control, it is largely an economic question whether it is worthwhile to pay for the added complexity of the machine, when the blade pitch mechanism is added.

1.2.3 Wind Turbine Aerodynamics

The actuator disk theory explains in a very simply way the process of extracting the kinetic energy in the wind, based on energy balances and the application of Bernoulli's equation. The rotor wind capturing energy is viewed as a porous disk, which causes a decrease in momentum of the airflow, resulting in a pressure jump in the faces of the disk and a deflection of downstream flows (Figure 1.2).

The theory of momentum is used to study the behavior of the wind turbine and to make certain assumptions. The assumptions are that the air is incompressible, the fluid motion is steady, and the studied variables have the same value on a given section of the stream tube of air.

The power contained in the form of kinetic energy in the wind crossing at a speed V_v, surface A_1, is expressed by

$$P_v = \tfrac{1}{2}\rho A_1 V_v^3 \tag{1.1}$$

where ρ is the air density.

The wind turbine can recover only a part of that power:

$$P_t = \tfrac{1}{2}\rho\pi R^2 V_v^3 C_p \tag{1.2}$$

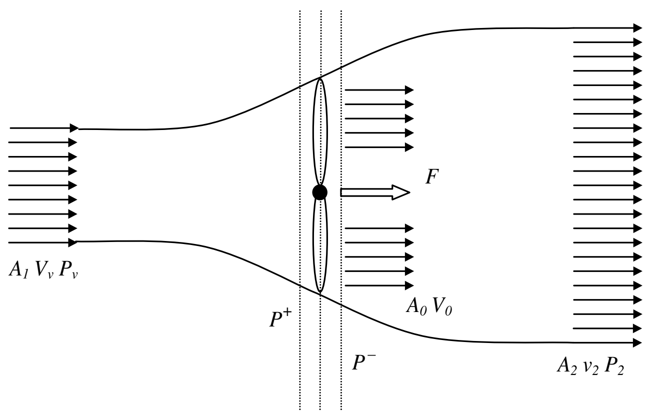


Figure 1.2 Schematic of fluid flow through a disk-shaped actuator.

where R is the radius of the wind turbine and C_p is the power coefficient, a dimensionless parameter that expresses the effectiveness of the wind turbine in the transformation of kinetic energy of the wind into mechanical energy.

For a given wind turbine, this coefficient is a function of wind speed, the speed of rotation of the wind turbine, and the pitch angle.

C_p is often given as a function of the tip speed ratio, λ, defined by

$$\lambda = \frac{R\Omega_t}{V_v} \tag{1.3}$$

where R is the length of the blades (radius of the turbine rotor) and Ω_t is the angular speed of the rotor.

The theoretical maximum value of C_p is given by the Betz limit:

$$C_{p\_theo\_max} = 0.593 = 59.3\%$$

The rotor torque is obtained from the power received and the speed of rotation of the turbine:

$$T_t = \frac{P_t}{\Omega_t} = \frac{\rho\pi R^2 V_v^3}{2\Omega_t} C_p = \frac{\rho\pi R^3 V_v^2}{2\lambda} C_p = \frac{\rho\pi R^3 V_v^2}{2} C_t \tag{1.4}$$

where C_t is the coefficient of torque. The coefficients of power and torque are related by the equation

$$C_p(\lambda) = \lambda \cdot C_t(\lambda) \tag{1.5}$$

Using the resulting model of the theory of momentum requires knowledge of the expressions for $C_p(\lambda)$ and $C_t(\lambda)$. These expressions depend mainly on the geometric characteristics of the blades. These are tailored to the particular site characteristics, the desired nominal power and control type (pitch or stall), and operation (variable or fixed speed) of the windmill.

The calculus of these curves can only be done by means of aeroelastic software such as Bladed or by experimental measurements.

From these curves, it is interesting to derive an analytical expression. This task is much easier than obtaining the curves themselves. Without analytical expression, it would save in table form a number of points on the curves and calculate the coefficient corresponding to a given λ (pitch angle) by means of a double interpolation.

The analytical expression for $C_p(\lambda)$ or $C_t(\lambda)$ may be obtained, for example, by polynomial regression. One typical expression that models these coefficients will be described in the next section.

Figure 1.3 shows an example of $C_p(\lambda)$ and $C_t(\lambda)$ curves for a 200 kW pitch regulated wind turbine.

The power and torque of the turbine are shown in Figure 1.4.

The wind speed V_v of precedent equations is not real; it is a fictitious homogeneous wind. It's a wind, expressed as a point of the area swept by the wind turbine, but the wind must be traceable torque T_t near the field that produced the true wind speed incident on the entire area swept by the rotor.

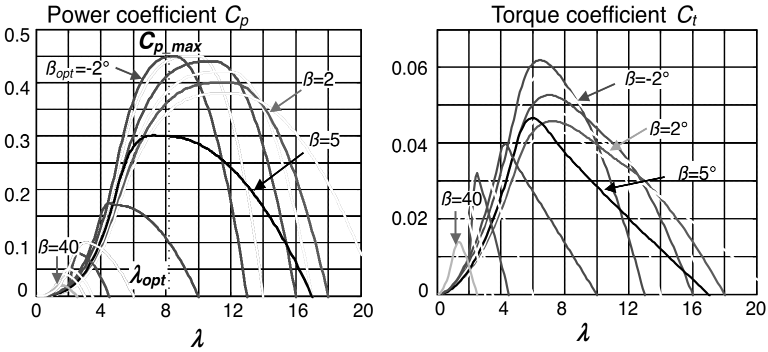


Figure 1.3 Curves of coefficients of power and torque of a 200 kW pitch regulated wind turbine, for different pitch angles β.

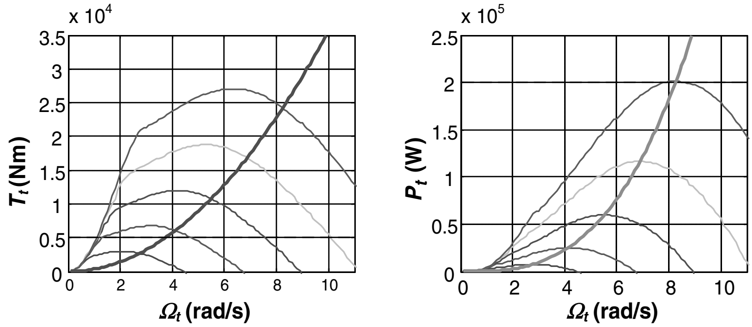


Figure 1.4 Curves of power and torque of a 200 kW pitch regulated wind turbine.

The generation of this fictitious wind can be really complicated depending on the phenomenon to be analyzed, for example, for flicker studies.

1.2.4 Example of a Commercial Wind Turbine

The Nordex N60 (1.3 MW nominal power) is a typical example of a fixed speed wind turbine based on the concepts explained previously. The main characteristics of the turbine are:

- The diameter of the turbine is 60 meters and has a stall power regulation.
- The rotor rotates at 12.8 and 19.2 fixed speeds.
- The gearbox is a three-stage design with a ratio of 78.3 for a 50 Hz wind turbine, with the first stage as a high torque planetary stage and the second and third stages as spur stages.
- The generator is a water-cooled squirrel cage asynchronous type. It is connected to the gearbox by a flexible coupling and it can turn at two speeds

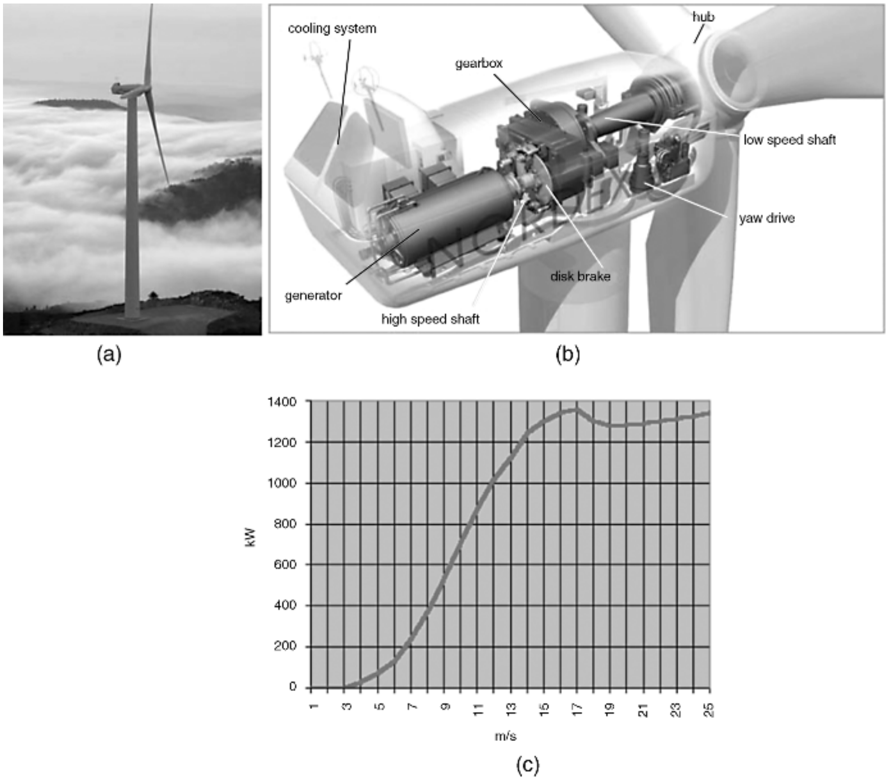


Figure 1.5 Nordex N60 fixed speed wind turbine: (a) picture of the complete wind turbine, (b) nacelle components, and (c) Power curve. (*Source:* Nordex).

(1000 and 1500 rpm), changing the number of pairs of poles of the machine (3 and 2).

- The generator is provided with a thyristor based soft-starter.
- The primary brake system is the aerodynamic blade tip brake. The secondary mechanical brake is a disk brake.

Figure 1.5 shows a picture of the Nordex N60, the main components located in the nacelle, and their power curve.

1.3 VARIABLE SPEED WIND TURBINES (VSWTs)

Figure 1.6 shows the nacelle layout of a Nordex N80 (2.5 MW nominal power), 2.5 MW variable speed wind turbine.

One must appreciate the big differences between the fixed speed and the variable speed wind turbines; it is a technological evolution from the first one. An increase

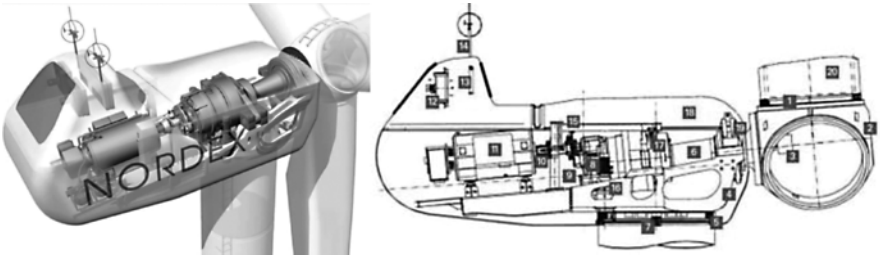


Figure 1.6 Nordex variable speed pitch regulated wind turbine. (*Source:* Nordex).

in size equals an increase in mechanical efforts, and the variable speed and the power control provide the tools to do this without risks. The major differences between them are:

- Power control is by means of pitchable blades.
- Doubly fed induction generator and power converters provide variable speed.

The main components of the nacelle and rotor are: (1) pitch bearing, (2) rotor hub, (3) pitch drive, (4) framework, (5) yaw adjustment bearing, (6) main rotor shaft, (7) yaw brakes, (8) gearbox, (9) holding brake, (10) coupling to generator, (11) generator, (12) cooler for the generator, (13) cooler for the gearbox, (14) wind sensors, (15) on-board crane, (16) yaw drive mechanism, (17) support of the gearbox, (18) nacelle fiberglass housing, (19) rotor bearing, and (20) stem of the rotor blade.

The following subsections will explain the basic models and control for the wind turbine. In Section 1.7 a more detailed description is given of commercial wind turbines.

1.3.1 Modeling of Variable Speed Wind Turbine

The proposed wind turbine model is composed of the following systems:

- Aerodynamic model, evaluates the turbine torque T_t as a function of wind speed V_v and the turbine angular speed Ω_t
- Pitch system, evaluates the pitch angle dynamics as a function of pitch reference β_{ref}
- Mechanical system, evaluates the generator and turbine angular speed (Ω_t and ω_m) as a function of turbine torque and generator torque T_{em}
- Electrical machine and power converters transform the generator torque into a grid current as a function of voltage grid
- Control system, evaluates the generator torque, pith angle and reactive power references as a function of wind speed and grid voltage

Figure 1.7 shows the interaction between the different subsystems.

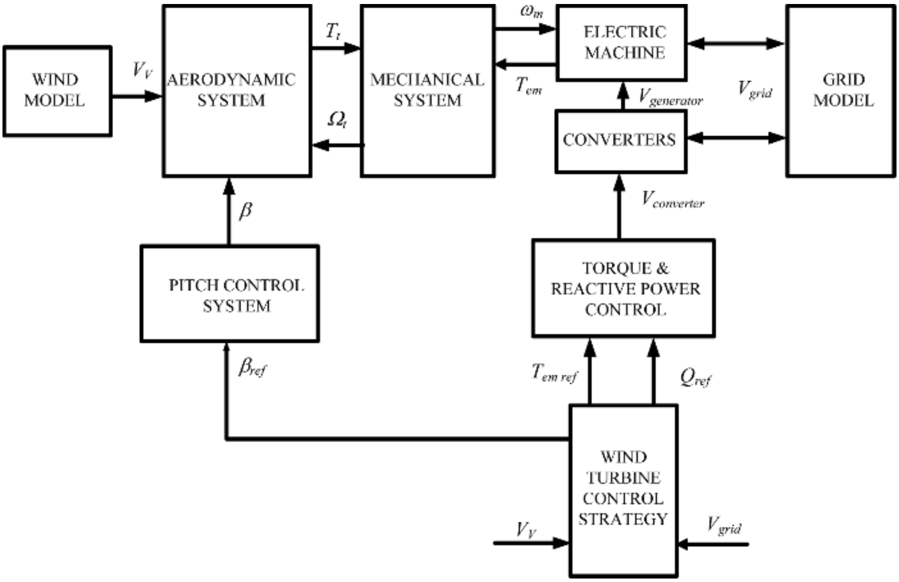


Figure 1.7 Block scheme of a variable speed wind turbine model.

1.3.1.1 Aerodynamic Model The aerodynamic model represents the power extraction of the rotor, calculating the mechanical torque as a function of the air flow on the blades. The wind speed can be considered as the averaged incident wind speed on the swept area by the blades with the aim of evaluating the average torque in the low speed axle.

The torque generated by the rotor has been defined by the following expression:

$$T_t = \tfrac{1}{2}\rho\pi R^3 V_v^2 C_t \tag{1.6}$$

As mentioned in a previous section, the most straightforward way to represent the torque and power coefficient C_p is by means of analytical expressions as a function of tip step ratio (λ) and the pitch angle (β). One expression commonly used, and easy to adapt to different turbines, is

$$C_p = k_1\left(\frac{k_2}{\lambda_i} - k_3\beta - k_4\beta^{k_5} - k_6\right)(e^{k_7/\lambda_i}) \tag{1.7}$$

$$\lambda_i = \frac{1}{\lambda + k_8} \tag{1.8}$$

with the tip step ratio,

$$\lambda = \frac{R\Omega_t}{V_v} \tag{1.9}$$

1.3.1.2 Mechanical System

The mechanical representation of the entire wind turbine is complex. The mechanical elements of a wind turbine and the forces suffered or transmitted through its components are very numerous.

It is therefore necessary to choose the dynamics to represent and the typical values of their characteristic parameters. The first is the resonant frequency of the power train. The power transmission train is constituted by the blades linked to the hub, coupled to the slow shaft, which is linked to the gearbox, which multiplies the rotational speed of the fast shaft connected to the generator.

For the purpose of this simulation model, representing the fundamental resonance frequency of the drive train is sufficient and a two mass model, as illustrated in Figure 1.8, can then model the drive train. The second resonance frequency is much higher and its magnitude is lower.

All the magnitudes are considered in the fast shaft. Inertia J_t concerns the turbine side masses, while J_m concerns those of the electrical machine. These inertias do not always represent exactly the turbine and the electrical machine. If the fundamental resonance frequency comes from the blades, part of the turbine inertia is then considered in J_m.

The stiffness and damping coefficients, K_{tm} and D_{tm}, define the flexible coupling between the two inertias. As for the inertias, these coefficients are not always directly linked to the fast shaft but to the fundamental resonance, which may be located somewhere else.

D_t and D_m are the friction coefficients and they represent the mechanical losses by friction in the rotational movement.

The turbine rotational speed and driving torque are expressed in the fast shaft by

$$\Omega_{t\_ar} = N\Omega_t \tag{1.10}$$

$$T_{t\_ar} = \frac{T_t}{N} \tag{1.11}$$

where N is the gearbox ratio.

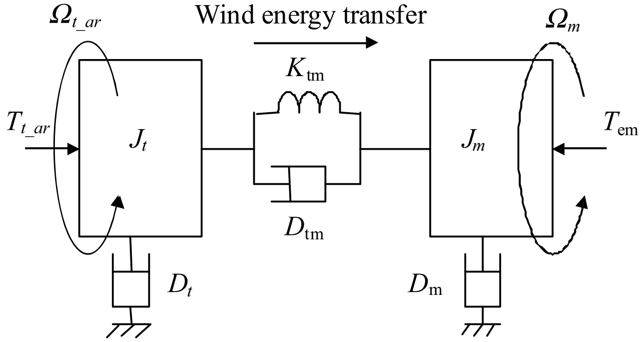


Figure 1.8 Two mass mechanical model.

Next,

$$
\begin{aligned}
J_t \frac{d\Omega_{t\_ar}}{dt} &= T_{t\_ar} - D_t\Omega_{t\_ar} - T_{em} \\
J_m \frac{d\Omega_m}{dt} &= T_{em} - D_m\Omega_m + T_{em} \\
\frac{dT_{em}}{dt} &= K_{tm}(\Omega_{t\_ar} - \Omega_m) + D_{tm}\left(\frac{d\Omega_{t\_ar}}{dt} - \frac{d\Omega_m}{dt}\right)
\end{aligned}
\tag{1.12}
$$

The model can be simplified by neglecting the damping coefficients (D_t, D_m, and D_{tm}), resulting in a model with two inertias (J_t and J_m) and the stiffness (K_{tm}). The resulting transfer function relating the generator torque and speed presents a pole at ω_{01} pulsation and a zero ω_{02} pulsation:

$$\omega_{01} = \sqrt{K_{tm}\frac{J_t + J_m}{J_t J_m}} \tag{1.13}$$

$$\omega_{02} = \sqrt{\frac{K_{tm}}{J_t}} \tag{1.14}$$

The pole has a frequency in the range between 1 and 2 hertz for a multimegawatt wind turbine.

1.3.1.3 Pitch System The controller is designed for rotating all the blades at the same angle or each of them independently. This independent regulation gives more degrees of freedom to the control system. This particular operation would reduce the stresses in the blades. The independent regulation of blades is an important innovation that will bring more intelligence into the control system of wind turbines.

In studying a dynamic control system, a blade pitch involves many torques and forces. The representation of this torques requires modeling the structural dynamics of the blade, the behavior of the air around the blades, or the inclusion of friction in the bearings. Moreover, regulation of the speed of rotation around the longitudinal axis of the blades has a bandwidth much greater than that of the control of the angle itself.

Given these last two observations, the most standard approach is to represent the loop control, the rate of change of pitch angle, and a linear system of first order containing the main dynamics of the actuator (hydraulic or electric).

In fact, when modeling the pitch control, it is very important to model the rate of change of this angle. Indeed, given the effort sustained by the blades, the variation of the pitch must be limited. It is limited to about 10°/s during normal operation and 20°/s for emergencies.

Regulation of the blade angle is modeled as shown in Figure 1.9, by a PI controller that generates a reference rate of change of pitch; this reference is limited and a first-order system gives the dynamic behavior of speed control of pitch variation. The pitch angle itself is then obtained by integrating the variation of the angle.

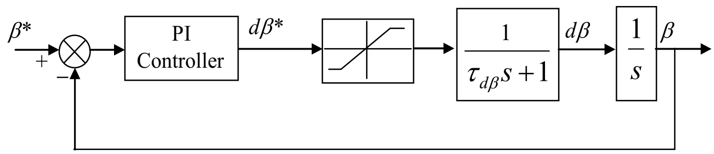


Figure 1.9 Pitch system and control model.

1.3.2 Control of a Variable Speed Wind Turbine

Control of a variable speed wind turbine is needed to calculate the generator torque and pitch angle references in order to fulfill several requirements:

- Extract the maximum energy from the wind.
- Keep the turbine in safe operating mode (power, speed, and torque under limits).
- Minimize mechanical loads in the drive train.

Design of this strategy is a very complicated task strongly related with the aerodynamic and mechanical design of the turbine, and indeed only known by the manufacturers. In this section only the aspects related to the energy extraction and speed–power control will be treated.

Figure 1.10 shows a general control scheme for the VSWT, where the two degrees of freedom are the generator torque and the pitch angle.

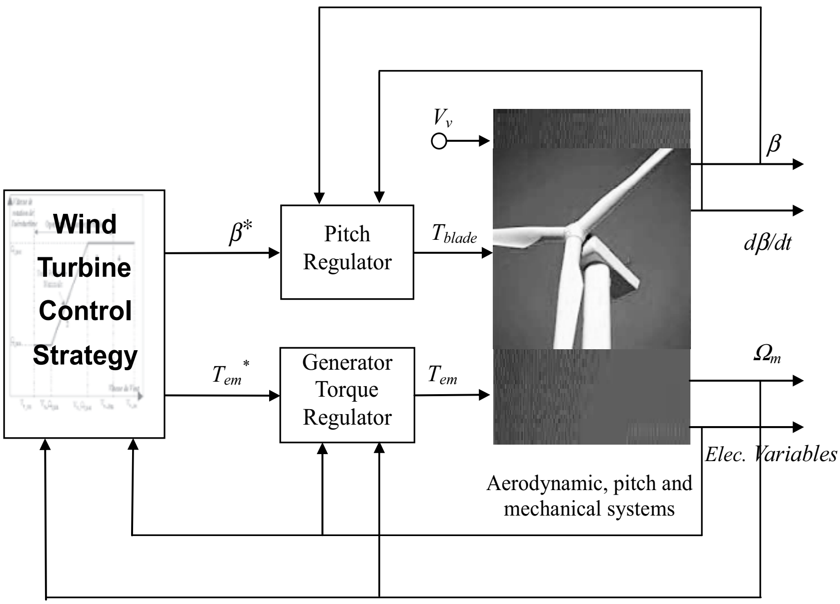


Figure 1.10 Pitch regulated variable speed wind turbine control schema.

This control is independent of the generator technology and can be simulated without modeling the electrical machine, power converters, and their associated controls just including the torque dynamics as a first-order system.

Moreover, for DFIG based wind turbines this limitation also serves to limit the slip of the electrical machine and therefore the voltage must provide the rotor converter.

The following subsections describe the wind turbine control strategy and the control objectives.

1.3.2.1 Turbine Speed Control Regions The wind turbine control strategy most commonly used is illustrated in Figure 1.11 and consists of four operation zones:

1. Limit the minimum speed of operation.
2. Follow the curve of maximum power extraction from variable speed operation with partial load.
3. Limit the maximum speed at partial load operation.
4. Limit the maximum operating speed at rated power output.

Figure 1.11 shows the wind turbine speed as a function of the wind speed.

The minimum speed limit is explained by the fact that we must prevent the turbine from rotating at speeds corresponding to the resonant frequency of the tower. This resonance frequency is about 0.5 Hz and a rotational speed too small can excite it.

Moreover, for DFIM based turbines this limitation also serves to limit the sliding of the electrical machine, and hence the rotor voltage, and therefore the voltage that must provide the drive rotor.

The imposition of a maximum speed can also be explained by the limitation of sustained efforts by the blades. Indeed, a rotation speed too high can cause inertial

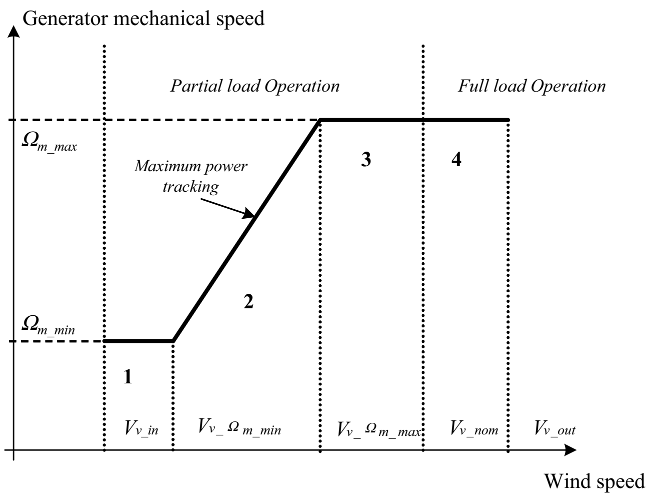


Figure 1.11 Wind turbine control strategy based on four speed regions.

loads unbearable by the blades and the turbine shaft. Also, the linear speed of the tip of the blade must be limited.

For DFIM based turbines, this limitation responds to the desire to limit the slip but also the maximum power that passes through the rotor and therefore by the rotor converter and network. With this strategy, the power to operate the converters will be around 25% of the rated power of the electric generator.

Therefore, the wind generator starts to run at the wind speed connection (cut-in wind speed) with a rotating speed Ω_{t_min}.

When the wind speed becomes more important, it reaches the maximum aerodynamic performance operating in Zone 2. As wind speed increases, the rotation speed also increases until the maximum rotation speed Ω_{t_max}. The wind generator then operates in Zone 3. When wind speed reaches its nominal value, the generator works at the rated mechanical power and the energy captured for higher wind speeds should be regulated at this nominal value.

Zone 4 corresponds to operation at full load. Here, the mechanical power can be limited either by varying the pitch or by torque control. Typically, the electromagnetic torque is maintained at nominal value and adjusts the pitch angle to keep the turbine at maximum speed and rated power.

Figure 1.12 shows the torque and power in different operation modes.

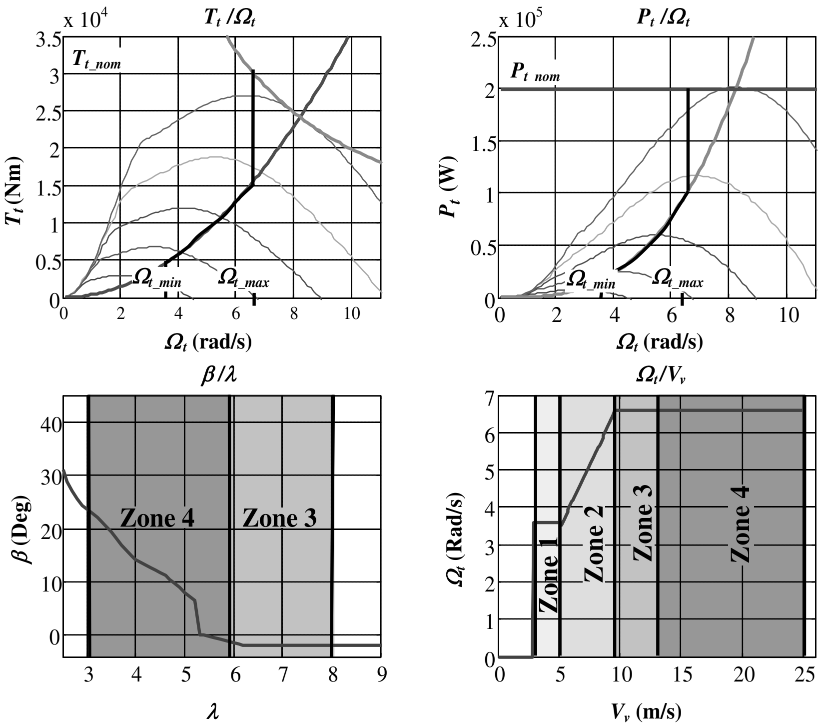


Figure 1.12 Curves of power and torque of a 200 kW pitch regulated wind turbine.

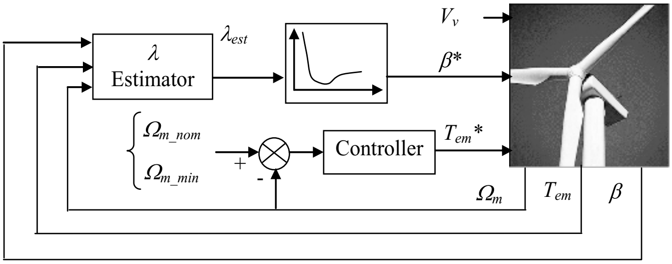


Figure 1.13 Control schemes for regions 1 and 3.

1.3.2.2 Regions 1 and 3: Minimum and Maximum Speed Control The main objective is to maintain a constant speed of rotation of the turbine at its minimum value in Zone 1 and its nominal value in Zone 3.

Regarding energy efficiency, maximization is not as high a priority as in Zone 2, where the speed of the turbine may evolve to maintain a specific speed λ_{opt} corresponding to the maximum power coefficient C_{p_max}. Here, the generator operates at constant speed.

The specific speed λ varies with wind speed. Depending on the shape of the curves of power coefficient parameterized by the pitch angle, it might be interesting to vary this angle to optimize aerodynamic performance.

It is therefore interesting to plot the curve representing the optimum blade angle, giving it a maximum power coefficient for a given λ. The reference pitch of maximum energy efficiency is λ, a given specific speed obtained from this curve. See Figure 1.13.

1.3.2.3 Region 2: Maximum Power Tracking In this operation region, the objective of the speed control is to follow the path of maximum power extraction. In the literature, different methods are proposed to regulate the wind turbine at partial load following the maximum power extraction trajectory.

Two different types of controllers have been considered; one consists of taking as the electromagnetic torque reference the electromagnetic torque related to the maximum power curve of Figure 1.12 for each turbine rotational speed value and using the dynamically stable nature of the VSWT around this curve. This controller is called the indirect speed controller (ISC).

The second controller generates the optimal turbine rotational speed (this is linked to the optimal tip speed ratio) for each wind speed value, and uses this as the turbine rotational speed reference. Then, it controls the turbine rotational speed with a regulator. It is called the direct speed controller (DSC).

Indirect Speed Controller It can easily be shown that the WT is dynamically stable around any point of the maximum power curve of Zone 2 of Figure 1.12. This means that for any rotational speed variation around a point in the maximum power curve, the VSWT naturally goes back to its operating point.

Imagine that the VSWT is operating at point *a* of the curve in Figure 1.14a, the wind speed and the electromagnetic torque being fixed. If the turbine rotational speed is

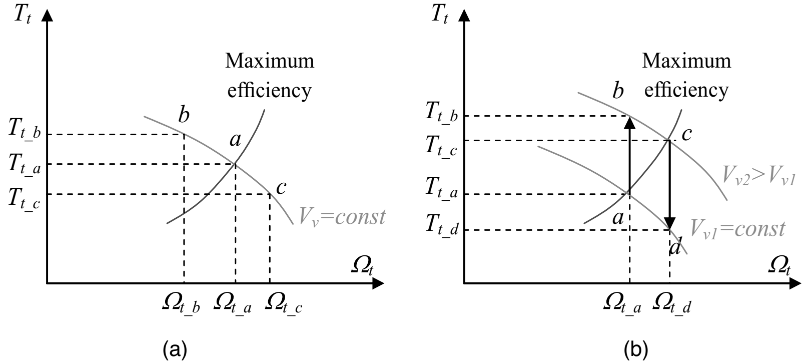


Figure 1.14 Stability study around a point of the maximum power curve.

reduced to Ω_{t_b}, the operating point passes to point b, and the turbine torque is then T_{t_b}. The electromagnetic torque is fixed to its preceding value corresponding to T_{t_a}, so T_{t_b} is higher than T_{em}, and the turbine rotational speed increases until it is again stabilized around the Ω_{t_a} value.

Considering this stability property, the aerodynamic torque T_t can be kept in the maximum power curve in response to wind variations, if the electromagnetic torque T_{em} is controlled in a way to follow this curve. Actually, imagine that the VSWT is operating at point a of the curve in Figure 1.14b.

When the wind speed value increases from V_{v1} to V_{v2}, the operating point becomes b, and the turbine torque becomes T_{t_b}. The controller provides the electromagnetic torque corresponding to the maximum power curve (point c), which is smaller than T_{t_b}. This makes the turbine rotational speed increase until it reaches the equilibrium point c.

When the turbine is working on the maximum power point,

$$\lambda_{opt} = \frac{R\Omega_t}{V_v}, \quad C_p = C_{p\_max}, \quad \text{and} \quad C_t = C_{t\_opt}$$

The aerodynamic torque extracted by the turbine is then given by

$$T_t = \frac{1}{2}\rho\pi R^3 \frac{R^2\Omega_t^2}{\lambda_{opt}^2}\frac{C_{p,\max}}{\lambda_{opt}} \tag{1.15}$$

That is,

$$T_t = \frac{1}{2}\rho\pi \frac{R^5}{\lambda_{opt}^3} C_{p,max}\Omega_t^2 = k_{opt\_t}\Omega_t^2 \tag{1.16}$$

where

$$k_{opt\_t} = \frac{1}{2}\rho\pi \frac{R^5}{\lambda_{opt}^3} C_{p,max}$$

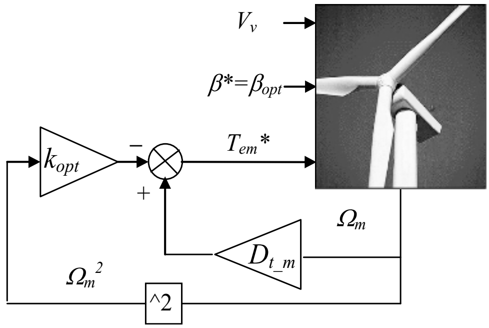


Figure 1.15 Indirect speed control ($D_{tm} = D_t + D_m$).

It results in an optimal torque evolving as a quadratic function of the wind turbine speed.

Moreover, from Equation (1.12) written in steady state,

$$\begin{aligned} 0 &= \frac{T_t}{N} - D_t\Omega_t N - K_{tm}(\Omega_{t\_ar} - \Omega_m) \\ 0 &= T_{em} - D_m\Omega_m - K_{tm}(\Omega_m - \Omega_{t\_ar}) \end{aligned} \tag{1.17}$$

where $\Omega_m = N\Omega_t$.

$$T_{em} = -\frac{T_t}{N} + (D_t + D_m)\Omega_m \tag{1.18}$$

Replacing T_t in Equation (1.18) by the expression (1.16), we have

$$T_{em} = -k_{opt}\Omega_m^2 + (D_t + D_m)\Omega_m \tag{1.19}$$

where

$$k_{opt} = \frac{1}{2}\rho\pi\frac{R^5}{\lambda_{opt}^3 N^3}C_{p\_max} \tag{1.20}$$

This last expression leads to the controller illustrated in Figure 1.15.

As seen in Equation (1.19), the behavior of the rotational speed Ω_t depends on the dynamics of the mechanical coupling.

With the ISC method, the behavior of the electromagnetic torque T_{em} and that of Ω_t is the same, since the relation between Ω_t and T_{em} has no dynamics. The electromagnetic torque is not used to increase the Ω_t dynamics as it could be if it were the output of a regulator. Thus, the main disadvantage of the ISC is that the mechanical coupling dynamics is not cancelled out, leading to a fixed soft response of the system.

Direct Speed Controller The DSC tracks the maximum power curve more closely with faster dynamics.

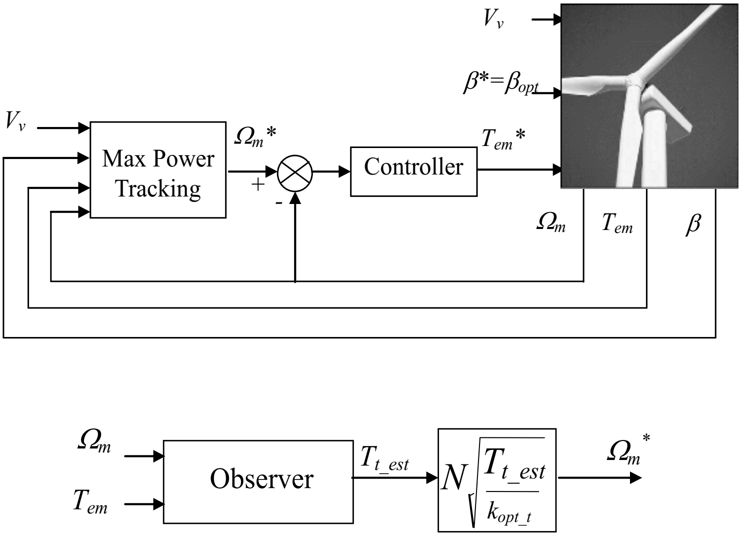


Figure 1.16 Direct speed control.

Knowing the definition of the tip speed ratio λ, the optimal VSWT rotational speed Ω_{t_opt} could be found from the wind speed (V_v). Unfortunately, V_v cannot be measured because it is a fictitious wind speed; it does not exist.

The rotational speed optimal value can nevertheless be obtained from an estimation of the aerodynamic torque. An observer based on Equation (1.12) and using magnitudes such as the electromagnetic torque T_{em} and the turbine rotational speed Ω_t, directly linked to measured signals, can easily be designed to estimate the turbine aerodynamic torque T_{t_est}.

Thus, from Equation (1.16), in the optimal operating point,

$$\Omega_m^* = N\sqrt{\frac{T_{t\_est}}{k_{opt\_t}}} \tag{1.21}$$

Once the rotational speed reference is generated, a regulator controls Ω_t using the electromagnetic torque value T_{em}. The diagram of the DSC is illustrated in Figure 1.16.

1.3.2.4 Region 4: Power Control The most common control structure for controlling the wind turbine in this region is illustrated in Figure 1.17. Here the electromagnetic torque is held constant at its nominal value. Most of the electrical power generated is that of the stator, that is, the electromagnetic torque produced by the electrical stator pulsation ω_s; this structure leads to proper regulation of electric power. The flicker emission is therefore low with this configuration. The electromagnetic torque does not, however, contribute to regulation of the speed of

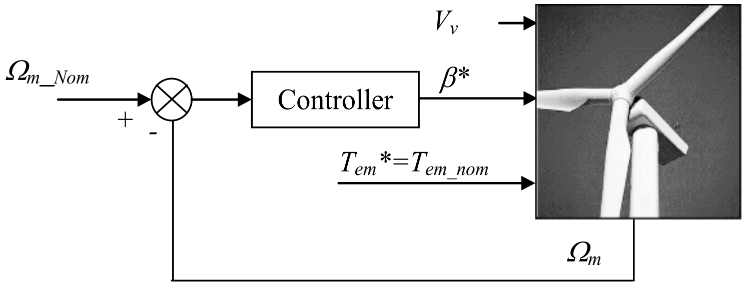


Figure 1.17 Power control in region 4: β controls Ω_m with T_{em} constant at nominal value T_{em_nom}.

rotation. Another disadvantage is that, since T_{em} is constant, the mechanical coupling at low fundamental resonance and flexibility of this coupling cannot be dumped.

1.3.3 Electrical System of a Variable Speed Wind Turbine

Until the mid-1990s, most of the installed wind turbines were fixed speed ones, based on squirrel cage induction machines directly connected to the grid, and the generation was always done at constant speed.

Today, most of the installed wind turbines are variable speed ones, based on a doubly fed induction generator (DFIG), sharing the market with the wound rotor synchronous generators (WRSGs) and the new arrivals, based on the permanent magnet synchronous generators (PMSGs). All of these generator choices allow variable speed generation.

In this section, the evolution of the variable speed generation systems is briefly described. Looking at the generator used in the generation system of the wind turbine, the variable speed wind turbine basic topologies can be classified into three different categories.

1.3.3.1 Doubly Fed Induction Generator Solutions The doubly fed induction generator has been used for years for variable speed drives. The stator is connected directly to the grid and the rotor is fed by a bidirectional converter that is also connected to the grid (Figure 1.18).

Using vector control techniques, the bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed. The converter's main aim is to compensate for the difference between the speed of the rotor and the synchronous speed with the slip control.

The main characteristics may be summarized as follows:

- Limited operating speed range (-30% to $+20\%$)
- Small scale power electronic converter (reduced power losses and price)
- Complete control of active power and reactive power exchanged with the grid

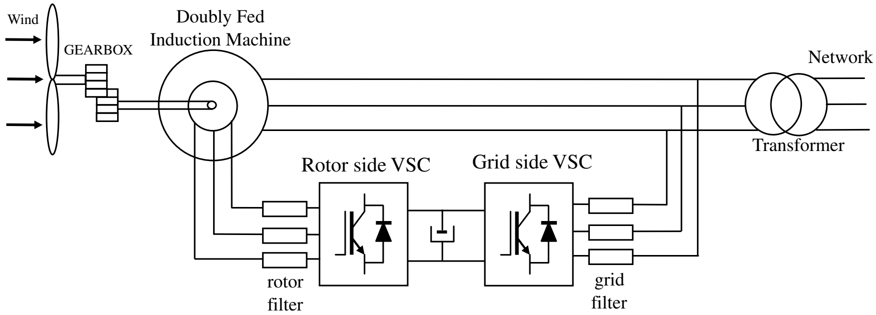


Figure 1.18 Doubly fed induction machine based wind turbine.

- Need for slip-rings
- Need for gearbox (normally a three-stage one)

1.3.3.2 Full Converter Geared Solutions The full converter with gearbox configuration is used with a permanent magnet synchronous generator (PMSG) and squirrel cage induction generator (SCIG). Using vector control techniques again, a bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed.

The SCIG uses a three-stage gearbox to connect the low speed shaft to the high speed shaft. Although today the PMSG machine also uses a two-stage gearbox, the objective is to decrease the gearbox from two stages to one, since the nominal speed of the machine is medium.

The induction generator–squirrel cage rotor has the following main characteristics (Figure 1.19):

- Full operating speed range
- No brushes on the generator (reduced maintenance)
- Full scale power electronic converter
- Complete control of active power and reactive power exchanged with the grid
- Need for gear (normally three-stage gear)

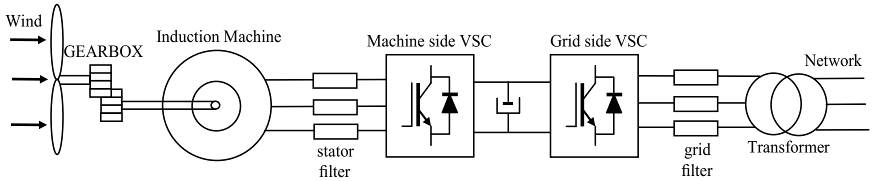


Figure 1.19 Induction machine (SCIG) based wind turbine.

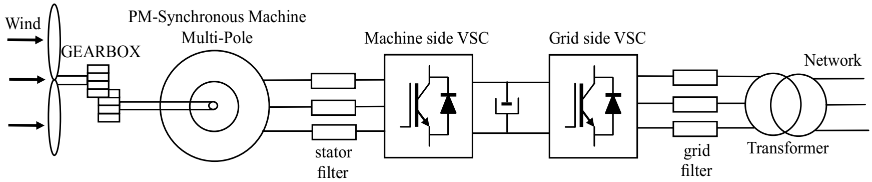


Figure 1.20 Synchronous machine (PMSG) based wind turbine.

The synchronous generator–permanent magnet has the following main characteristics (Figure 1.20):

- Full operating speed range
- No brushes on the generator (reduced maintenance)
- Full scale power electronic converter
- Complete control of active power and reactive power exchanged with the grid
- Possibility to avoid gear
- Multipole generator
- Permanent magnets needed in large quantities
- Need for gear (normally one- or two-stage gear)

1.3.3.3 Full Converter Direct Drive Solutions Two solutions are proposed in the market:

- Multipole permanent magnet generator (MPMG)
- Multipole wound rotor synchronous generator (WRSG)

The multipole permanent magnet generator allows connecting the axis of the machine directly to the rotor of the wind turbine. Using vector control techniques, a bidirectional converter assures energy generation at nominal grid frequency and nominal grid voltage independently of the rotor speed.

The biggest disadvantage of this technique is the size of the bidirectional converter, which must be of the same power level as the alternator. Also, the harmonic distortion generated by the converter must be eliminated by a nominal power filter system. The advantage of this technique is the elimination of the mechanical converter (gearbox

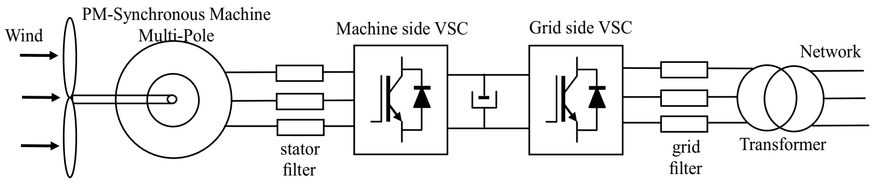


Figure 1.21 Synchronous machine direct drive based wind turbine.

coupling) because the machine can operate at low speed. Another disadvantage is that the multipole machine requires an elevated number of poles, with the size of the machine being bigger than the generators with the gearbox coupling. See Figure 1.21.

1.4 WIND ENERGY GENERATION SYSTEM BASED ON DFIM VSWT

1.4.1 Electrical Configuration of a VSWT Based on the DFIM

The configuration adopted in this book (Figure 1.22) connects the stator directly to the grid, and the rotor is fed by a reversible voltage source converter, as first proposed Peña and co-workers.

The stator windings are supplied at constant frequency and constant three-phase amplitude, since it is directly connected to the grid.

The rotor windings are supplied by a power electronics converter able to feed the DFIM with a variable voltage and frequency three-phase voltages.

This configuration is especially attractive as it allows the power electronic converter to deal with approximately 30% of the generated power, reducing considerably the cost and the efficiency compared with full converter based topologies.

The following subsections briefly describe the main components of the electrical system.

1.4.1.1 Generator The doubly fed induction machine (DFIM), doubly fed induction generator (DFIG), or wound rotor induction generator (WRIG) are common terms used to describe an electrical machine with the following characteristics:

- A cylindrical stator that has in the internal face a set of slots (typically 36–48), in which are located the three phase windings, creating a magnetic field in the air gap with two or three pairs of poles.

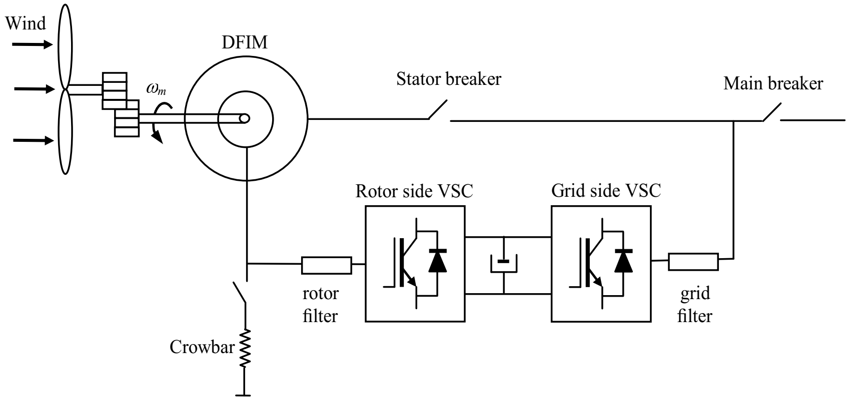


Figure 1.22 General DFIM supply system.

- A cylindrical rotor that has in the external face a set of slots, in which are located the three phase windings, creating a magnetic field in the air gap of the same pair of poles as the stator.
- The magnetic field created by both the stator and rotor windings must turn at the same speed but phase shift to some degrees as a function of the torque created by the machine.
- As the rotor is a rotating part of the machine, to feed it, it's necessary to have three slip rings. The slip ring assembly requires maintenance and compromises the system reliability, cost, and efficiency.

Figure 1.23 shows the different components of the machine.

From the point of view of a variable speed wind turbine (VSWT), several characteristics are required:

- The stator windings are designed for low voltage levels (400, 690, 900 V) in the majority of manufacturers with the exception of Acciona, which uses a medium voltage winding (12 kV) with the aim of reducing the size of the input transformer.
- The rotor windings are designed for medium voltage windings in order to fit the nominal voltage of the converter with the rotor voltage at maximum speed (slip). For example, for a machine with nominal stator and rotor line-to-line voltage of 690 V, with a maximum slip of 33%, the maximum rotor voltage will be 0.33 of the rotor nominal voltage, that is, 228 V. If the rotor winding is sized to 2090.9 volts (690/0.33), the maximum voltage will be 690 V, that is, the maximum available voltage for a back-to-back converter connected to a 690 grid. Note that in older machines the rotor voltage was 420 V in order to reduce the voltage level of the power converter.
- The number of pole pairs is currently selected as two. This implies synchronous speeds of 1500 rpm for a 50 Hz grid frequency, and a typical speed range from 1000 to 2000 rpm approximately. Several manufacturers select three pole pairs in order to minimize mechanical efforts or to use a cheaper converter. This implies synchronous speeds of 1000 rpm, and a typical speed range from 750 to 1250 rpm approximately for a four-quadrant converter.
- Operational speed range is 900 to 2000 rpm, with a maximum overspeed up to 2200 rpm for two pole pair machines.
- The machine is forced air or water cooled and a water–air heat exchanger is necessary in the nacelle.

1.4.1.2 Reversible Power Electronic Converter The generator torque active power and reactive power through the rotor and the stator are controlled by adjusting the amplitude, phase, and frequency of the voltage introduced in the rotor.

Most manufacturers adjust the synchronous speed to be centered in the middle of the variable speed operation range (1500 rpm for two pole generators in wind turbines with a variable speed range from 1000 to 2000 rpm), which means that the machine,

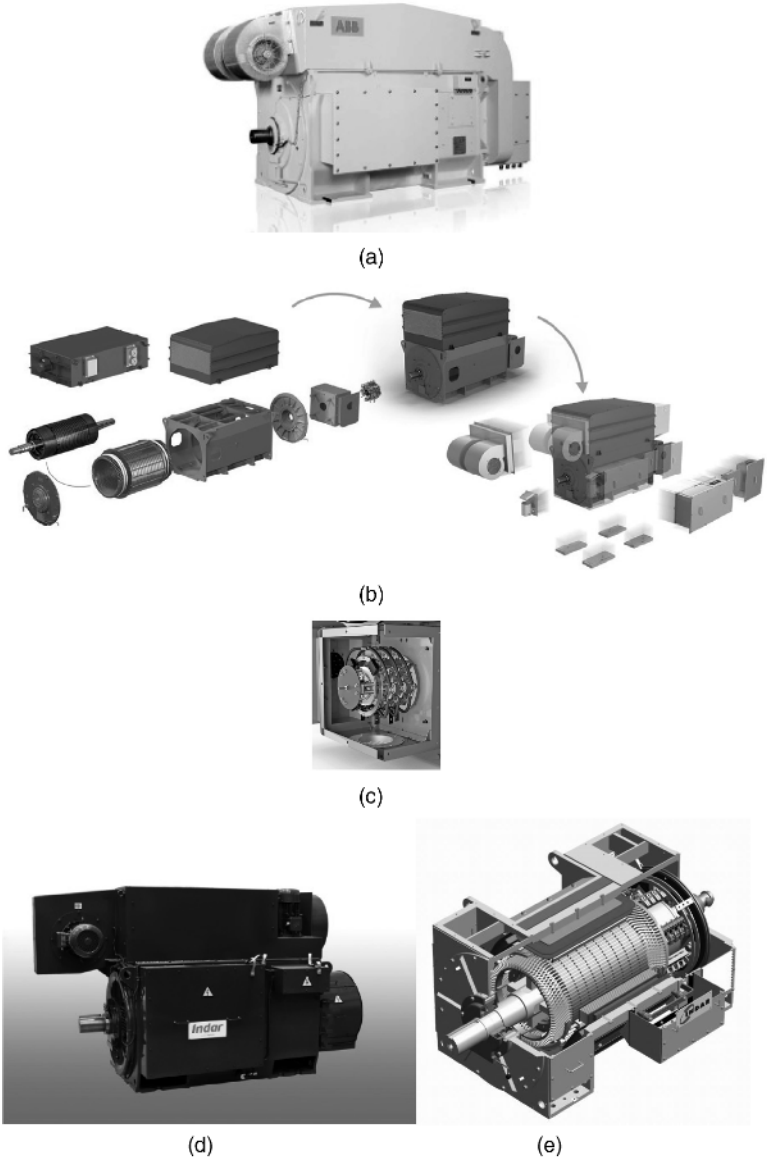


Figure 1.23 (a) Picture of the machine; (b) CAD representation of DFIG components; (c) slip rings (source ABB); (d) picture of the machine; and (e) CAD representation. (*Source*: Indar-Ingeteam.)

working at subsynchronous and hypersynchronous speeds with positive and negative torques, needs to be fed by a four-quadrant power electronic converter.

The standard power electronic converter used in this application is a back-to-back converter composed of two three-phase inverters sharing the DC bus. At present, most manufacturers uses two-level converters with standard IGBTs in order to reduce the cost for the 1.5 to 3 MW wind turbines; but for the most powerful offshore ones (3 to 6 MW), three-level converters are expected to be the best option. Both options will be studied in Chapter 2.

The two converters have two degrees of freedom that can be used in different ways:

- The rotor side converter (RSC) and filter generates a three-phase voltage with variable amplitude and frequency in order to control the generator torque and the reactive power exchanged between the stator and the grid. The rotor converter control strategy will be explained in the next few chapters, but two main concepts should be kept in mind:
  - The rotor voltage frequency will be the difference between the stator frequency and the mechanical speed in electrical radians.
  - The rotor voltage amplitude (for a machine with a turns ratio equal to 1, identical nominal voltage for stator and rotor) will be the nominal voltage multiplied by the slip.
- The grid side converter (GSC) and filter exchanges with the grid the active power extracted or injected by the rotor side converter from the rotor. The output frequency will be constant but the output voltage will change in order to modify the exchanged active and reactive power. The active power is indirectly controlled by means of the DC bus controller and the reactive power.

The sizing (rated current) of both converters is different depending on the strategy selected for magnetizing the machine:

1. If the machine is magnetized from the rotor, the RSC must be sized for delivering the quadrature torque component and the direct magnetizing current (around 30% of the nominal current of the machine). The GSC only must deliver the active power current component.
2. If the machine is magnetized from the stator, the RSC must be sized for delivering the quadrature torque component. The GSC only must deliver the active power current component and the reactive power current component.

The typical characteristics of these converters are the following:

- Vector control or direct torque control (DTC) for generator and grid converter control; active and reactive power control; and grid code support
- Two-level, three-phase converter with IGTBs, at switching frequency of 2.5–5 kHz
- LCL filter for the GSC, and *dv*/*dt* filter for the RSC
- Nominal power: 500 to 2500 kVAs
- Nominal voltage 690 V, $+10\%$ to -15%.

(a)

(b)

Figure 1.24 Back-to-back IGBT based 2L-VSC for 690 V DFIM based wind turbines. (*Source*: Ingeteam (a) and ABB (b).)

- Nominal DC bus voltage 1000 V
- Very low total harmonic distortion (THD < 3%)
- Air or water cooled, in order to reduce the size of the cabinets

Figure 1.24 shows two examples of converters.

1.4.1.3 Crowbar Protections When a voltage dip occurs in the network, current transients in the stator windings (due to the stator's direct connection to the grid) and grid side converter are produced. Hence, these two behaviors are completely different:

- The grid side converter doesn't lose current control in most cases.
- Stator disturbance is transmitted to the rotor, causing uncontrollable currents that can produce damage to the rotor converter due to the overcurrents and the

overvoltage of the DC link. Frequently, there is a high transformation ratio between the stator and rotor windings; thus, the rotor converter has restricted control over the generator.

A circuit called crowbar is connected to the rotor to protect the RSC. The crowbar avoids voltage bus exceed his maximum value once the RSC loses current control providing a path for the rotor currents. The crowbar short-circuit the rotor and the machine operates as a squirrel cage machine, see Figure 1.22.

The crowbar power converter may be implemented with several power structures. In this section we will analyze two configurations that allow a passive and an active crowbar. Both schemas rectify the rotor current and short-circuit the rotor by means of a resistance. The passive crowbar is constructed with a thyristor and allows closing the circuit but does not allow it to open until the crowbar current is extinguished. The active crowbar is constructed with an IGBT and allows opening the circuit in forced commutation.

The control system of the crowbar may be materialized in many ways depending on the power converter structure and the desired performances. After a voltage dip, the rotor current regulators lose control and an energy flow from the stator to the rotor charges the bus capacitor. To avoid the bus voltage from reaching the converter limits, it is necessary to break this energy flow, and the simplest method is to short-circuit the rotor when the bus voltage reaches a limiting value.

With a passive control, the crowbar act as a protection system; the time necessary to open the stator breaker is approximately 100 milliseconds, causing at the end the disconnection of the wind turbine. When the control objective is to keep the wind turbine connected to the grid during fault, it is necessary to control the bus voltage. The simplest technique consists of comparing the bus voltage with its maximum and normal operation reference values and, depending on that comparison, keeping the crowbar circuit open or closed. This technique is called active crowbar control. The bus capacitor load dynamics is determined by the rotor–bus energy flow, and the discharge is determined by the capacity of the grid side inverter (bus to grid energy flow).

1.4.1.4 Transformer Generally, the output voltage of the wind turbine is not designed to fit with low voltage or medium voltage networks, and a transformer is necessary to adapt the turbine voltage to the coupling point.

There are several ways to connect the stator and the back-to-back converter to the grid (Figure 1.25):

- If the stator voltage and the back-to-back converter are the same (commonly 690 V AC), one transformer rated at full power, with a medium voltage primary of several kilovolts (10–30 kV) and a low voltage secondary, is used.
- If the stator voltage is in the range of medium voltage, one transformer rated at the rotor power is used. In this case, the stator voltage is directly connected to a medium voltage distribution grid or to the medium voltage grid of a wind farm.

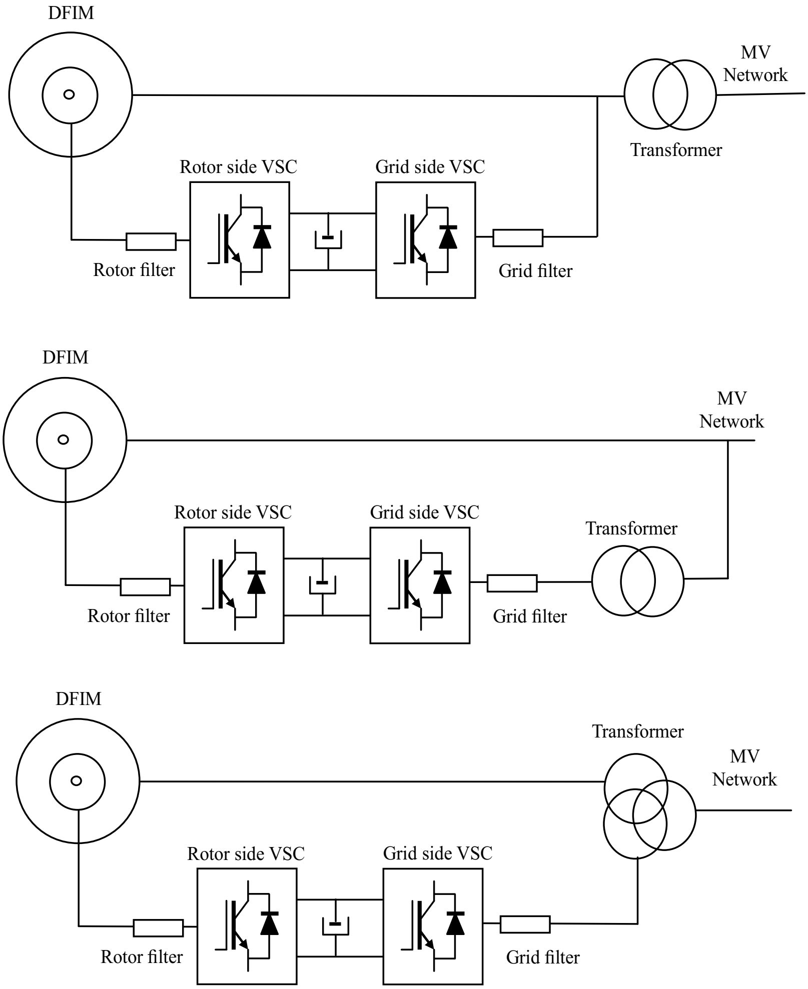


Figure 1.25 Different transformer connections.

- If the stator and back-to-back converter voltages are both in the low voltage range, but different, two secondary windings are used.

All three ransformer configurations have advantages, and the main advantages and disadvantages are summarized in Table 1.1.

The most common technologies used for these transformers are cast resin when they are located in the wind turbine: the nacelle or tower.

Figure 1.26 shows two examples of transformers in liquid filled and resin encapsulated technological solutions.

TABLE 1.1 Transformer Topology Comparison

Option	Advantages	Disadvantages
a	• One single secondary winding • The primary MV winding can be adapted to different MV grids	• Full power transformer
b	• The transformer is rated at 30% of the wind turbine power	• The transformer leakage impedance limits the short-circuit current
	• Less transformer loses	• The MV grid must fit the stator MV voltage
	• Stator electrical design	• Security concerns, as the MV range means more capacitating courses for maintenance employees
c	• The stator voltage and the power electronics can be designed with different voltage levels	• The transformer is more expensive

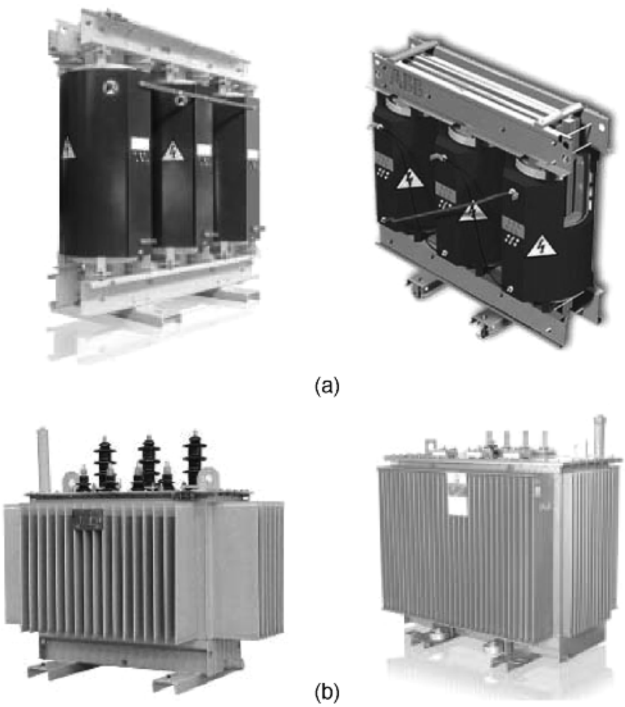


Figure 1.26 Picture of (a) a dry transformer (cast resin) and (b) a liquid filled (oil) transformer. (*Source:* ABB.)

1.4.2 Electrical Configuration of a Wind Farm

The first commercial wind turbines were installed as single units on farms or in small villages in Denmark and Germany and were connected directly to the low voltage distribution grid. Due to the financial support of the government, Danish farmers find in wind energy a new income that improves the always complicated economic situation of agriculture.

The increased power of turbines, and their connection to the medium voltage distribution grids, made it necessary to include a transformer in the turbine to connect it to the medium voltage distribution grids (rated 10–33 kV). In the first wind turbines, this transformer and the breaker and protection system were located in shelters near the wind turbine and were shared by several wind turbines. Once the size of the towers became adequate, the transformers were located in the tower. At present, the transformer is located in the nacelle in the biggest wind turbines.

Once wind technology acquires the necessary maturity and governments adopt a green policy for renewable energy generators, utility scale wind energy generation systems will appear. At present, most of the wind turbines are installed in groups currently called "wind farms" or "wind parks"; for example, in Spain the maximum power of a farm is 50 MW, while in the United States you can find wind farms of 200 MW.

These kinds of wind farms are directly connected to the transmission or subtransmission grids by means of an electrical substation especially constructed for the wind farm.

Electrical collection from each of the wind turbines at the point of interconnection with the wind farm can be done in many different ways but the most standard one is shown in Figure 1.27.

A wind farm has the following components:

- The substation:
  - The input breaker in the high voltage side of the transformer.
  - The coupling transformer to the transmission grid. The primary voltage will vary with each country's standards from 66 to 220 kV. The secondary voltage will vary from 10 to 33 kV.
  - One output breaker on the medium voltage side of the transformer.
  - Static VAR compensation (capacitor banks and inductors), connected by means of medium voltage breakers.
  - Dynamic VAR compensation based on SVC or STATCOM, this last connected by means of a coupling transformer.
  - Inductor or transformer to limit fault currents.
- Medium voltage feeders and circuits for each turbine cluster.
- Wind turbines. In each wind turbine there is a medium voltage breaker, a transformer, and two sectionalizers to open the input and output circuits.

Inside the substation building are located the electrical cabinets for the protective relays and the measuring, communication, and Scada system.

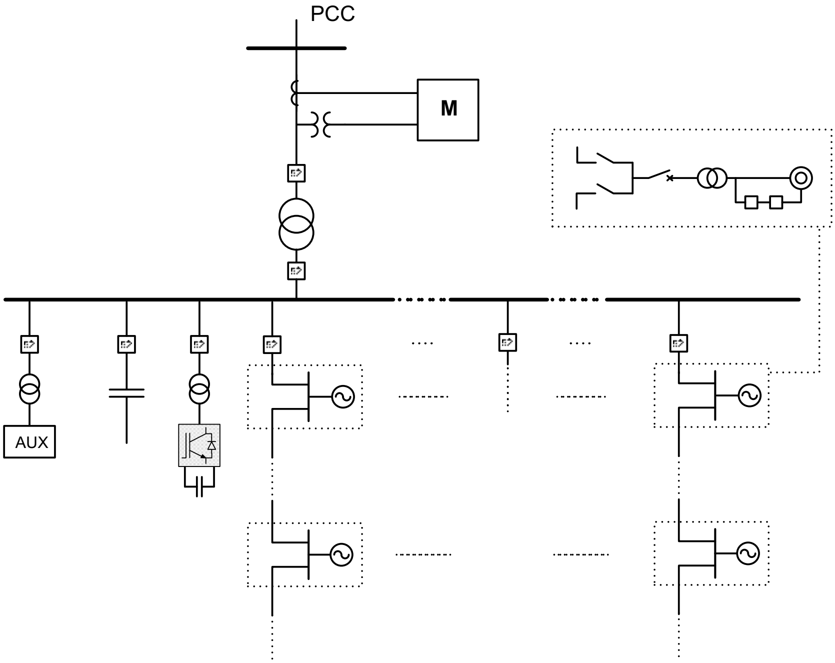


Figure 1.27 Electrical layout of a wind farm connected to the transmission grid.

From the point of view of wind turbine grid integration, the electrical layout of the wind farm is important because of the way the grid outages affect the turbine behavior.

In the following subsections we analyze how the transformer connection types can influence the types of dips that can affect the wind turbine.

1.4.3 WEGS Control Structure

Modern wind farms must be operated as conventional power plants due to the political and institutional agreement for clean energy following the Kyoto Protocol.

As will be explained in the next section, grid codes—the rules that transmission system operators (TSOs) and distribution system operators (DSOs) impose, are more and more restricted, mainly due to the increased penetration of this technology in the generation mix.

One good example of this is Spain. With 19.5 GW of wind power installed in 2009 and a valley consumption of 22 GW, countermeasures must be taken in order to guarantee the stability of the power system when wind power is a 30–40% of the generation mix.

In the last few years, operation and control of wind farms has been one of the most important tasks for the Spanish TSOs, due to the high increment of the wind energy capacity connected to the grid and, specifically, to the high voltage transmission network. This new scenario has modified the traditional criteria for operating the

Spanish power system with the same confidence levels of reliability and security that existed in the past, when this high amount of variable energy did not exist in the generation mix.

This situation has led to the recent publication of technical documents (grid codes) for regulating all aspects of the integration of wind farms in the power systems. At present, in Spain, it is mandatory for all wind farms with a power capacity higher than 10 MW to be connected to a dispatching center with some specific requirements for communication and measurements that must be fulfilled.

Likewise, Spanish TSOs have proposed that when several wind farms evacuate energy to a common point of the transmission network, only one mediating body (usually the owner with the most power connected) must be between the TSO and the rest of the wind farm owners.

The functions of this new figure, named the connection point manager (CPM), are mainly to be in charge of the operation and management of all the power evacuated at that point and to be the only speaker (intermediary) with the TSO.

At present, modern variable speed wind turbines (VSWTs) are capable of exchanging reactive power with the grid and reducing active power by using pitch control systems and dynamic torque control on the electrical generator.

This scenario is where the wind farm controller plays an important role in controlling the active and reactive power injected by the wind farm into the grid according to the references and control mode signals received from the TSO or the CPM. This provides wind farms with the possibility to participate actively in the control tasks of the grid in the same way as conventional power plants do.

Figure 1.28 shows a proposal of the overall control strategy necessary to operate, in a secure way, a grid with increased penetration of renewable energy systems.

At the top, the control center of the TSO or the DSO communicates with the wind farm controller and receives information about the generation state and reactive power capacity of the generators, and sends the references of active–reactive power

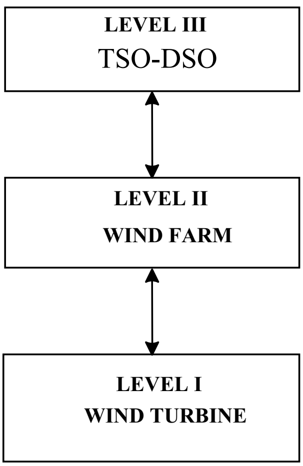


Figure 1.28 Hierarchic control structure for a WEGS.

requirements to operate the grid in an efficient way and maintain the necessary security level. The WEGS must have the same behavior as conventional power plants.

1.4.3.1 Wind Farm Control System

The references from the TSO-DSO arrive at the wind farm control and define the requirements for each wind turbine and for the substation reactive power static compensation (capacitor banks or inductors); this is sent by a communication channel in real time.

An overall diagram of this control level is illustrated in Figure 1.29. The centralized control objective must be that the wind farm behaves as a single unit (like a conventional power plant).

The inputs will be the system operator references, measurements from the point of common coupling (PCC), and the state and available power of each wind turbine.

In order to implement a centralized control it is necessary to have an effective communication between the wind farm centralized control (WFCC) and each of the wind turbines. Thus, while each of the wind turbines report to the WFCC the active power and reactive power that they can deliver at any moment, the WFCC should provide each of the wind turbines with references of active and reactive power.

The control objective of the WFCC is the regulation of active and reactive powers injected at the point of common coupling. Figure 1.30 shows a commonly used control structure and flow of signals between different subsystems.

The control system must perform the following tasks for active power:

1. Evaluate the operation mode for active power control: receive a reference or deliver all available power, automatic frequency control, delta or balance control.
2. Limit the generation deviation if necessary (power gradient limiter).
3. Regulate the active power in the PCC.
4. Dispatch the wind turbine active power reference ($P_{ref}^{WT_i}$) as a function of the wind farm power reference (P_{ref}^{WF}). The dispatch function can be done in many different ways, for example, as a function of the available power ($P_{disp}^{WT_i}$) of each

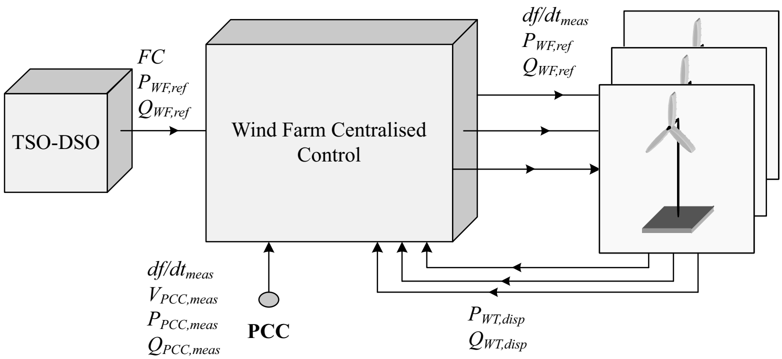


Figure 1.29 Signal flow between grid operator, wind farm control, and wind turbine.

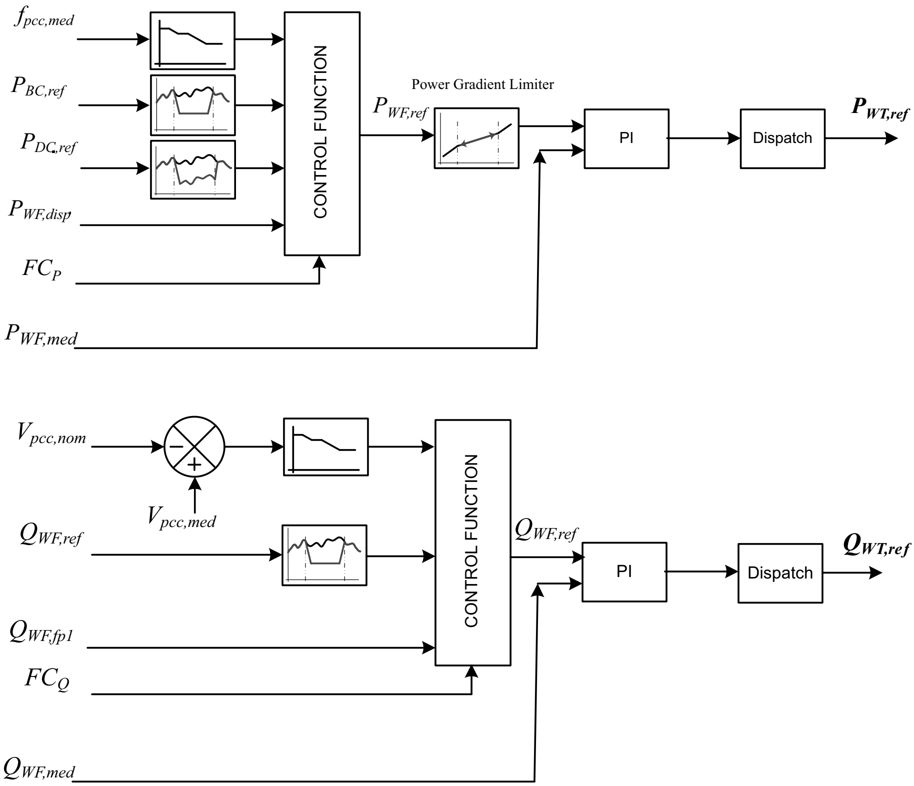


Figure 1.30 Wind farm control: (a) active power control and (b) reactive power control.

wind turbine:

$$P_{ref}^{WT_i} = \frac{P_{disp}^{WT_i}}{P_{disp}^{WF}} P_{ref}^{WF}, \quad \text{where} \quad P_{disp}^{WF} = \sum_{i=1}^{n} P_{disp}^{WT_i}$$

An other option is to send the wind farm reference (per unit) to all the wind turbines and each one will translate the reference to the available wind turbine power.

The control system must perform the following tasks for reactive power:

1. Evaluate the operation mode for reactive power control: receive a reference or deliver all available power, automatic voltage control, reactive control.
2. Regulate the reactive power in the PCC.
3. Dispatch the wind turbine power reference ($Q_{ref}^{WT_i}$) as a function of the wind farm power reference (Q_{ref}^{WF}). The dispatch function can be done in many

different ways, for example, as a function of the available power ($Q_{disp}^{WT_i}$) of each wind turbine:

$$Q_{ref}^{WT_i} = \frac{Q_{disp}^{WT_i}}{Q_{disp}^{WF}} P_{ref}^{WF}, \quad \text{where} \quad Q_{disp}^{WF} = \sum_{i=1}^{n} Q_{disp}^{WT_i}$$

The active and reactive operation modes will be detailed in following subsections.

1.4.3.2 Wind Turbine Control System The general control strategy of a variable speed wind turbine can be divided into three different control levels, as depicted in Figure 1.31.

Control level I regulates the power flow between the grid and the electrical generator.

The rotor side converter is controlled in such a way that it provides independent control of the electromechanical torque of the generator (sometimes the stator active power is used, both are related directly by means of the stator frequency, as will be studied in subsequent chapters) and the stator reactive power.

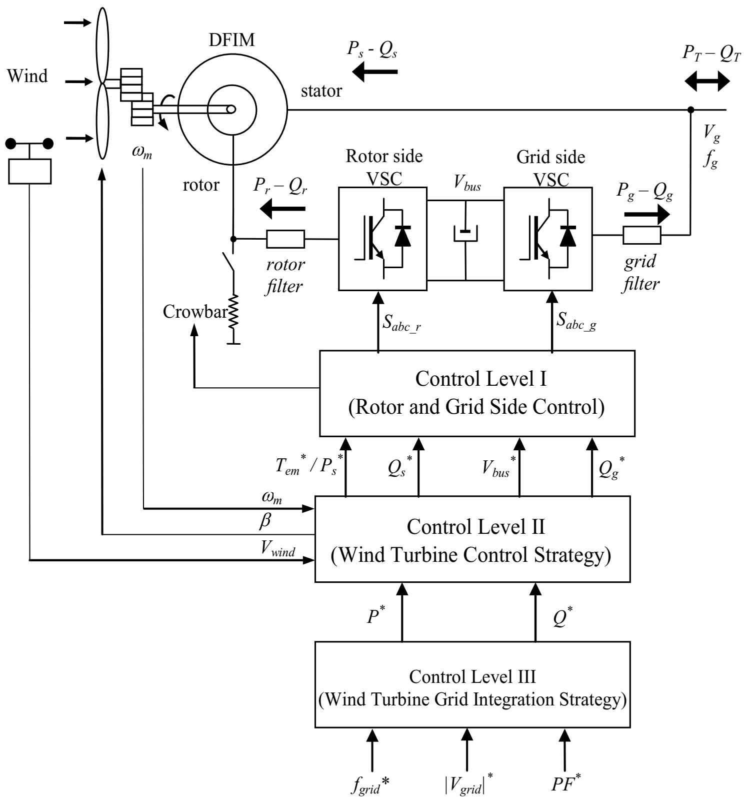


Figure 1.31 General wind turbine control strategy based on DFIM.

In Chapter 7 the vector control techniques for the DFIG will be studied in detail, and in Chapter 8 direct power control techniques will be analyzed.

The grid side converter provides decoupled control of active and reactive power flowing between the converter and the grid. The active power is exchanged between the rotor and the DC bus and the control calculates the active power exchanged with the grid to keep the DC bus voltage constant. In Chapter 2, vector control and direct power control techniques for this converter will be detailed.

The crowbar converter protects the rotor side converter when a voltage dip occurs. In Chapter 9 the most significant hardware solution will be explained.

Control level II is responsible for controlling wind energy conversion into mechanical energy, that is, the amount of energy extracted from the wind by the wind turbine rotor. This control level calculates the references for control level I. Two main operating modes are commonly used:

- Extract the maximum power from the wind, coordinating torque (stator active power) and pitch angle (β) references, always keeping the wind turbine under the speed limits, as explained in preceding subsections. This is the normal operation mode, in order to maximize the return on investment.
- Respond to active and reactive power references from the higher control level. This is necessary to have reserve power in the wind turbine. This is a future operation mode, necessary in grid scenarios with large dependence on wind power.

Control level III is dedicated to the wind turbine–grid integration. This control level performs the same functionalities as the wind farm control:

- Provide ancillary services: voltage (V_{grid}) and frequency (f_{grid}) control (droop characteristics), or inertial response.
- Respond to active and reactive power references from the grid operator or wind farm centralized control.

1.5 GRID CODE REQUIREMENTS

The grid codes of most countries generally aim to achieve the same thing. Electricity networks are constructed and operated to serve a huge and diverse customer demographic.

Electricity transmission and distribution systems serve, by way of example, the following types of user:

- Large high-consumption industrial factories
- High-sensitivity loads requiring high quality and reliable uninterrupted supplies
- Communications systems (e.g., national)
- Farms
- Shops and offices

- Domestic dwellings
- Large power stations

In simple terms, it is vital that electricity supplies remain "on." To do this, the system operator not only balances the system with suitable levels of generation to meet demand, but also requires larger capacity users of the system, including both generation and load, to actively participate in ensuring system security.

To achieve this, the following technical requirements are possibly the most crucial and appear common across most European countries:

- Frequency and voltage tolerance
- Fault ride through
- Reactive power and voltage control capability
- Operating margin and frequency regulation
- Power ramping

And future technical requirements may include:

- Inertial response
- Power system stabilizer
- Wind farm control

1.5.1 Frequency and Voltage Operating Range

The electrical behavior of the network, in terms of frequency and voltage, due to its dynamic nature is continuously changing. Generally, these changes occur in very small quantities. It is a requirement that users of the transmission system are able to continue operating in a normal manner over a specified range of frequency and voltage conditions. With respect to frequency and for a 50 Hz system, this would be in the range of 49 to 51 Hz. With respect to voltage, this range could be ±10% of the nominal voltage.

However, at times the ranges could be wider, although it would normally be expected that the user would continue operating under an extreme condition for a defined period of time, for example, 47 Hz for 15 seconds or +20% of the nominal voltage for 1 hour. Beyond these extremes, the user would normally be required to disconnect from the system.

Table 1.2 shows a common range of conditions within which a user would be required to operate.

TABLE 1.2 Example of Possible Frequency and Voltage Tolerance Requirements

	Normal Continuous Operation	Required	Very Short Term
Frequency	49–51 Hz	47.5–49 Hz and 51–52 Hz	47–47.5 Hz
Voltage	±5%	±10%	

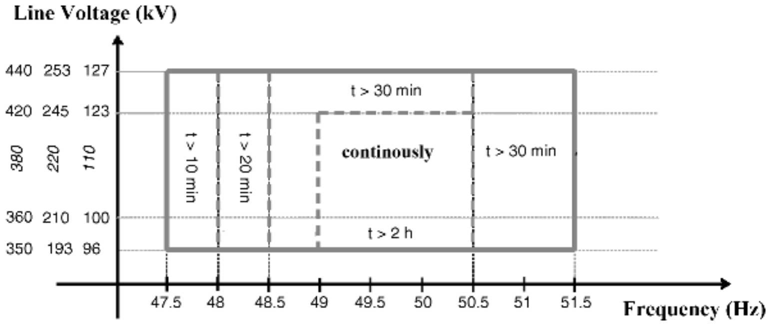


Figure 1.32 EON Netz GMBH grid code related to frequency.

As an example, the EON grid code related to the operating times as a function of frequency is illustrated in Figure 1.32.

1.5.2 Reactive Power and Voltage Control Capability

1.5.2.1 Power Factor Control To minimize losses and thus maintain high levels of efficiency, it is preferable that networks operate with voltage and current in-phase—that is, the power factor is unity.

However, users of electrical systems often tend to have inductive loads or generation facilities that operate such that voltage and current are out-of-phase. In addition, power system components including lines and transformers, for example, produce or consume large levels of reactive power. From the network user's perspective (looking from the installation toward the network) an inductive load/generation facility is said to have a leading power factor because the current leads the voltage. Put another way, the user is consuming reactive power.

As the behavior of the network is continuously changing, users are required to have the ability to adjust their reactive power production or consumption, in order that reactive power production and consumption are balanced over the entire network. In most cases, it is the generators who provide this control ability. The range, for example, could be from 0.95 leading to 0.95 lagging.

An example is the proposed curve of power factor as a function of grid voltage in the EON grid code (see Figure 1.33).

1.5.2.2 Voltage Support A generating station may be required to operate over a range of power factors to provide or consume reactive power as discussed and shown above. Alternatively, the installation may be required to operate in voltage control mode, that is, to adjust its reactive power production or consumption in order to control voltage on the local network.

If the network voltage decreases to a level below a predefined range, an installation may be required to supply reactive power to the network to raise the voltage. Conversely, if the network voltage increases to a level above a predefined upper

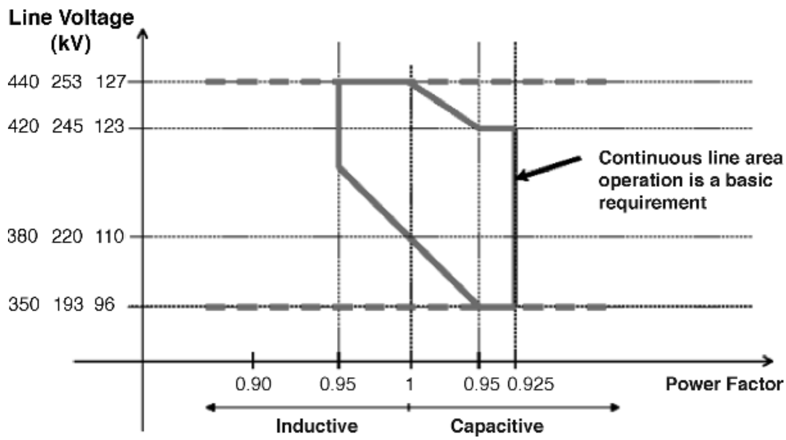


Figure 1.33 Reactive power control as a function of grid voltage (EON Netz GmbH).

limit, then the installation would be required to consume reactive power to bring the voltage back within acceptable limits.

1.5.2.3 Reactive Power Wind Turbine Operation Modes In order to accomplish the functionalities mentioned, the following operation modes (Figure 1.34) for the reactive power control of the wind turbine are typically defined:

- Reactive power control—the wind turbine is required to produce or absorb a constant specific amount of reactive power.
- Automatic voltage control—the voltage in the wind turbine point of common coupling (PCC) is controlled. This implies that the wind farm can be ordered to produce or absorb an amount of reactive power.

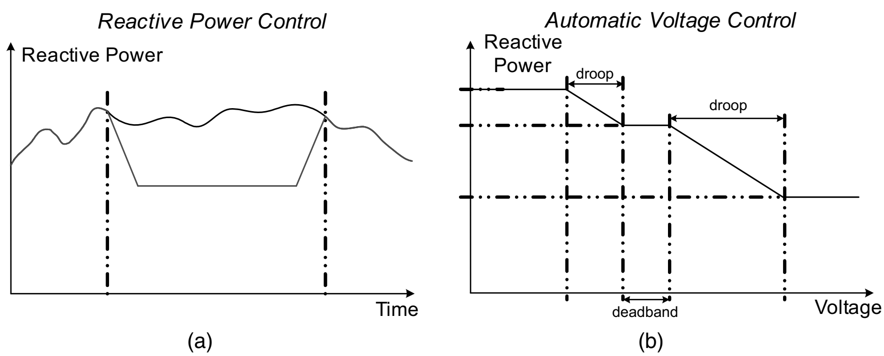


Figure 1.34 Reactive power operation modes: (a) reactive power Control and (b) automatic voltage control.

1.5.3 Power Control

Some network operators impose limits on power output. This could be during normal continuous operation and/or during ramping up to an increased output or ramping down to a decreased output.

This requirement might be necessary in the first case to limit output because of limitations in the capabilities of other generators or the transmission or distribution networks. In the latter case, this might be necessary so that network control systems and other generators have time to respond to a new operating state.

When a generator comes on-line it is providing the network with an increased amount of power which not only affects frequency, but also requires existing operating installations to adjust their operational characteristics to adapt to the “new” operating state.

With respect to wind power, for decreasing wind speed conditions there are limitations in the capabilities of wind turbines. If the wind speed is falling, a wind turbine may not be able to maintain its output or fully control the rate of decrease of output. However, wind speed profiles can be predicted and so if a controlled ramp down or clearly defined power reduction rate is required, a wind turbine’s output can be reduced early, thus reducing the maximum rate of change of output power.

An example is the proposed curve of power (as a percentage of the momentary possible power production) as a function of grid frequency in the ESB National Grid code (see Figure 1.35).

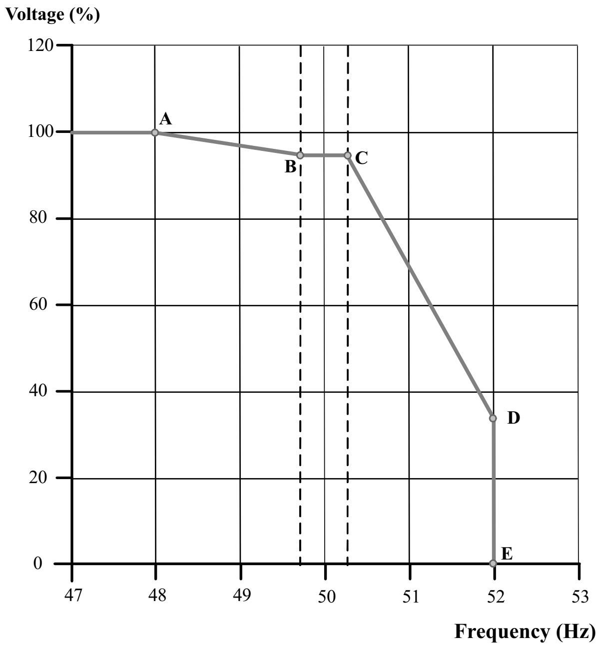


Figure 1.35 Power versus frequency in ESB National Grid

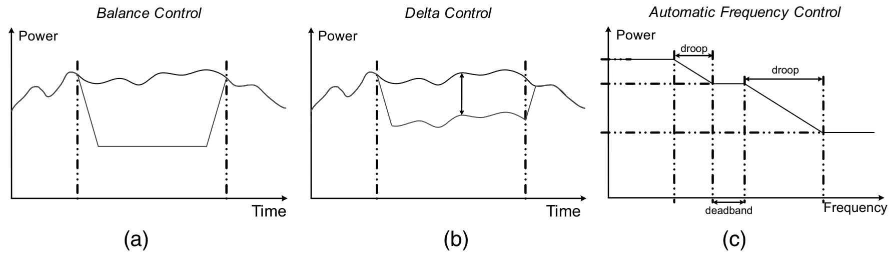


Figure 1.36 Active power operation modes: (a) balance control, (b) delta control, and (c) automatic frequency control.

1.5.3.1 Active Power Wind Turbine Operation Modes In order to accomplish the functionalities mentioned, the following operation modes (Figure 1.36) for the power control of the wind turbine are typically defined:

- Balance control—whereby wind turbine production can be adjusted downward or upward, in steps, at constant levels.
- Delta control—whereby the wind turbine is ordered to operate with a certain constant reserve capacity in relation to its momentary possible power production capacity. This operation mode allows an installation to operate at a margin below its rated power output–maximum power extraction so that it may respond to significant changes in frequency by increasing or decreasing its output.
- Power gradient limiter—which sets how fast the wind turbine power production can be adjusted upward and downward. Such a limiter helps to keep production balance between wind farms and conventional power plants.
- Automatic frequency control—the frequency measured in the wind farm point of common coupling (PCC) is controlled. The wind turbine must be able to produce more or less active power in order to compensate for a deviant behavior in the frequency.

1.5.3.2 Inertial Response Most wind turbine concepts utilize variable rotor speed, as this has major advantages for reduction of drive train and structural loads. All conventional generators are fixed speed; that is, the entire drive train rotates at synchronous speed and therefore provides a substantial synchronously rotating inertia. Rotating loads also provide such inertia, although the generators dominate. This inertia provides substantial short-term energy storage, so that small deviations in system frequency result in all the spinning inertias accelerating or decelerating slightly and thereby absorbing excess energy from the system or providing additional energy as required.

This happens without any control system, effectively instantaneously. Without this, modern power systems could not operate.

In addition to this "smoothing" effect in normal operation, the spinning inertia also provides large amounts of energy in the event of a sudden loss of generation: the rate of decrease of system frequency in the first second or so after such an event is entirely governed by the amount of spinning inertia in the system.

Variable speed wind turbines have less synchronously connected inertia, and in the case of the FC concept, none at all. As wind turbines displace conventional generation, there will be less spinning inertia, and therefore the system will become harder to control and more vulnerable to sudden loss of generation.

It is feasible that future grid codes will require all or some generators to provide an inertia effect.

This can in principle be provided by variable speed wind turbines, but this requires a control function and cannot occur without intervention. The control function will sense frequency changes and use this to adjust generator torque demand, in order to increase or decrease output power.

The effect is similar to the frequency-regulation function discussed earlier, but is implemented by generator torque control rather than pitch control. A more complex implementation could also include pitch control.

It is possible that wind turbines would not need to provide this function for small-scale frequency deviations, as conventional generation capacity may still be sufficient. Instead, the requirement could be limited to responses to large-scale deviations associated with a sudden loss of generation.

Initial studies show that, in principle, variable speed wind turbines can provide a greater inertia effect than conventional synchronous machines, because generator torque can be increased at will, extracting relatively large amounts of energy from the spinning wind turbine rotor. This decelerates the wind turbine rotor rapidly, and so may not be sustained for very long before aerodynamic torque is reduced. High generator torque also results in high loads on the drive train, which may add significant cost.

It is concluded that an inertia effect is available, in principle, but may have implications for wind turbine design and cost. It is not clear if some of the FSWT concepts may provide the necessary control.

1.5.4 Power System Stabilizer Function

Power system stabilizer (PSS) functions can be provided by conventional generators. In essence, the output power of the generator is modulated in response to frequency deviations, in order to damp out resonances between generators. These resonances are most likely to occur between two groups of large generators separated by a relatively weak interconnection.

Again, because of the tight control of generator torque provided by the DFIG concept, and possibly also FSWT, this function should also be able to be provided if required.

However, it should be pointed out that because variable speed wind turbines have very little synchronously connected inertia, the risk of such resonances actually reduces as wind penetration increases. Thus, there is an argument that PSS functions should be provided only by conventional generation.

1.5.5 Low Voltage Ride Through (LVRT)

The LVRT fulfillment for wind turbines has become a major requirement from the TSO-DSOs all around the world.

The first wind turbines based on squirrel cage asynchronous generators were very sensitive to grid outages. The protections were tuned in such a way that the wind turbine disconnected with even minor disturbances.

This caused two major problems for the TSO-DSO:

1. The protections were unable to detect faults in lines near wind farms, due to loss of short-circuit current from the wind farms.
2. The loss of wind power generation (reconnection of a fixed speed wind farm takes several minutes) necessitates fast response generation plants (such as hydro) or an increase in the fast reserve power.

So, as mentioned earlier, the first requirement of the TSO is to “keep connected.”

But wind turbine behavior during a grid fault is very different depending on the technology (fixed speed or variable speed, and full converter technologies or doubly fed) and also different from conventional power plants based on synchronous generators.

Thus, the TSOs decided to standardize the pattern of current versus voltage during faults, that is, the current that the generator consumes during the fault.

In Chapter 9, the crowbar control strategy and design will be studied in detail. The control strategy must allow the wind turbine:

- To remain connected to the power system and not consume active power during the fault
- To be provided with reactive power during the fault to assist voltage recovery
- To return to normal operation conditions after the fault

Voltage recovery is a complementary requirement; wind generators try to minimize the impact of wind parks in the power system during a short circuit and fault clearing. Voltage recovery is performed by reactive current injection of the wind generator.

1.6 VOLTAGE DIPS AND LVRT

If a defined fault occurs on the transmission system, it is a normal requirement of the transmission system operator that a generating station remain in operation and connected to the system—thus, it “rides through” the fault.

The definition of the fault is derived from the response time of the network protection systems to clear the fault. A normal duration to clear a fault is in the range of hundreds of milliseconds; hence, the requirement of the user will be to ride through a fault that has a significant drop in voltage of some hundreds of milliseconds in duration.

Because this issue is very important for the grid integration of wind energy systems, the following subsections will be oriented to describe the basic concepts:

- The electric power system (EPS) and the origin of the dips in the EPS
- The definition, classification, and transmission in the EPS of dips
- The procedure to validate the simulated LVRT requirements for wind turbines in Spain.

1.6.1 Electric Power System

1.6.1.1 Description The electric power system (EPS) is the set of infrastructures responsible for the generation, transport, and distribution of electrical energy and can be considered as some of the biggest infrastructures in the world.

Electric power transmission is the bulk transfer of electrical energy from generating power plants to substations located near population centers. This is distinct from the local wiring between high voltage substations and customers, which is typically referred to as electricity distribution. Transmission lines, when interconnected with each other, become high voltage transmission networks.

Figure 1.37 shows a schematic diagram of an EPS, with traditional distribution from generation to a residential user.

Historically, transmission and distribution lines were owned by the same company, but over the last decade or so many countries have introduced market reforms that have led to the separation of the electricity transmission business from the distribution business. Thus, in many countries, there are one or two transmission system operators (TSOs), several distribution system operators (DSOs), and trading companies.

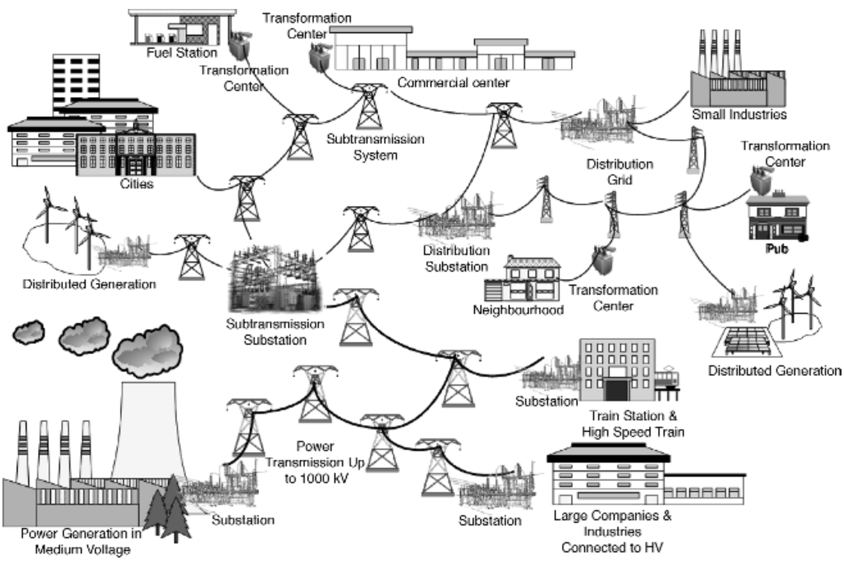


Figure 1.37 Schematic diagram of an EPS.

Wind power generators are commonly connected at all the voltage levels of the EPS, from the most powerful wind farms (from 25 to 250 MW) that are connected to transmission or subtransmission lines (from 66 to 745 kV) to the lower power wind turbines (50 to 500 kW) connected directly to the low voltage (380, 400, 440 V) distribution lines.

Therefore, the connection rules (grid codes) for each voltage level are elaborated by the different companies that operate the networks.

Another important point is the connection of different transformers and ground (related to the protective systems for lines) at different levels; for example, Figure 1.38 shows a diagram of the Spanish transmission and distribution network.

The transmission system operator is responsible for operating the high voltage transmission system. In Spain the TSO operates the 220 and 400 kV transmission system. The 220 and 400 kV systems are connected by means of autotransformers. Big power generation plants such as nuclear, coal, and hydro are connected at this level.

The distribution system operators are responsible for operating the distribution lines and also the subtransmission system necessary to connect the consumer centers to the transmission system. Typical voltages in this subtransmission system are 69 and 132 kV in Spain. The subtransmission system and the transmission system are connected by means of star–star transformers with neutral connected to earth.

Once the lines arrive at the consumer centers, it's necessary to step down the voltage to the proper level for domestic customers. This is done in two steps:

- A high voltage line arrives at the distribution substations where the DSO decreases the voltage levels to 10, 20, 30 kilovolts and distributes the power in different feeders. These transformers have a Delta-Star connection with neutral to ground.
- From each feeder several transformation centers reduce the voltage from medium voltage to low voltage (400 V) and distribute the single-phase lines to domestic customers. These transformers have a Delta connection.

1.6.1.2 Origin of Voltage Dips Voltage dips are primarily caused by short-duration overcurrents flowing through the power system. The principal contributions to overcurrents are power system faults, motor starting, and transformer energizing.

Power system faults are the most frequent cause of voltage dips, particularly single-phase short circuits. In the event of a short circuit, for a large area of the adjacent network, the voltage in the faulted phase drops to a value between 0 and 1 p.u., depending on the impedance between the point of fault and the point of measurement.

Voltage dips are caused by faults on the utility network or within the wind farm. A network fault indicates either a short-circuit condition or an abnormal open-circuit condition. The nature of voltage dips can be influenced by the symmetry of a network fault.

Two types of voltage dips are depicted: asymmetrical dip and symmetrical dip.

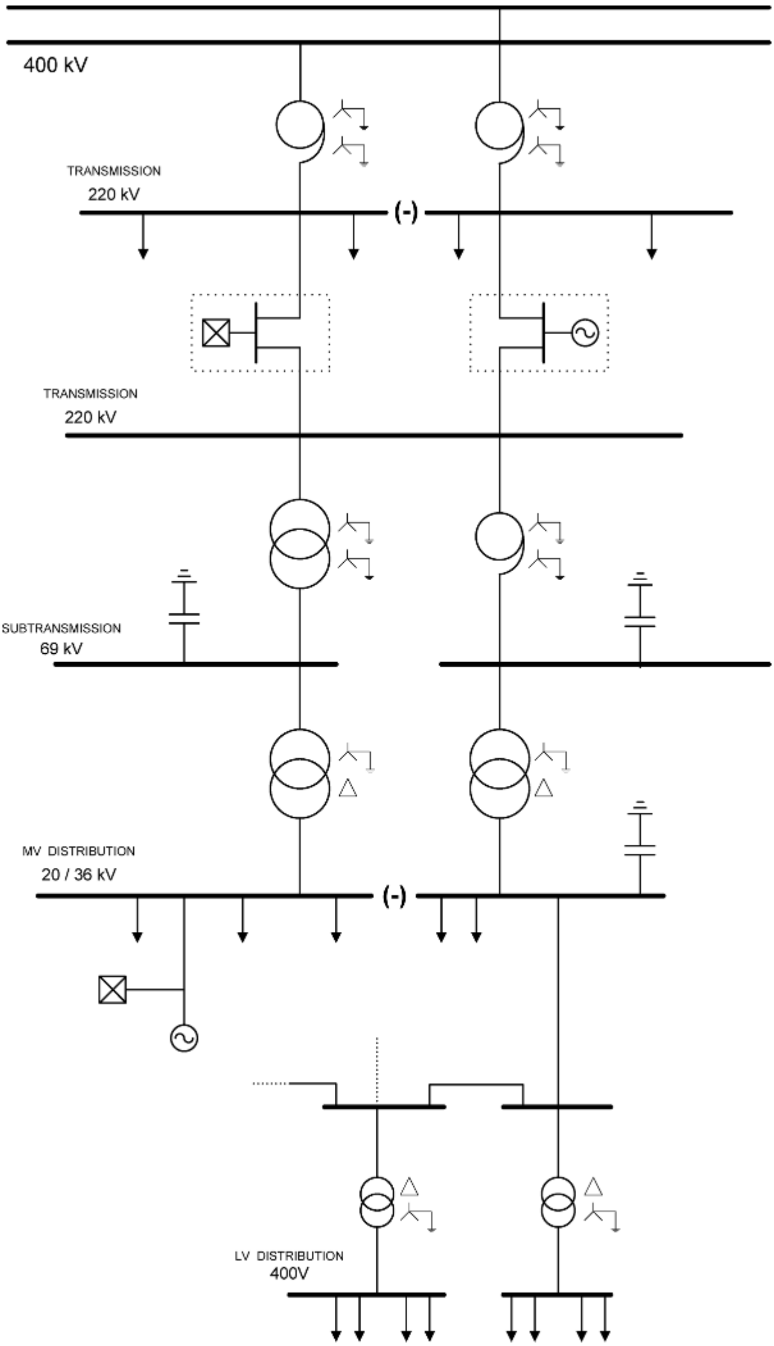


Figure 1.38 Spanish transmission and distribution network.

The supply network is very complex. The extent of a voltage dip at one site due to a fault in another part of the network depends on the topology of the network and the relative source impedances of the fault, load, and generators at their common point of coupling.

The drop in voltage is a function of the characteristics of fault current and the position of the fault in relation to the point of measurement. The duration of the dip event is a function of the characteristics of system protection and recovery time of the connected loads.

1.6.2 Voltage Dips

1.6.2.1 Definition Voltage dips—or sags, which are the same thing—are brief reductions in voltage, typically lasting from a cycle to a second or so, or tens of milliseconds to hundreds of milliseconds. (Longer periods of low or high voltage are referred to as “undervoltage” or overvoltage.”)

Voltage dips are the most common power disturbance. At a typical industrial site, it is not unusual to see several dips per year at the service entrance, and far more at equipment terminals. The frequency is even higher in the interior of the site or in developing countries that have not achieved the same levels of power quality as more developed nations.

Dips do not generally disturb incandescent or fluorescent lighting, motors, or heaters. However, some electronic equipment lacks sufficient internal energy storage and therefore cannot ride through dips in the supply voltage. Equipment may be able to ride through very brief, deep dips, or it may be able to ride through longer but shallower dips.

Normally, the grid voltage fluctuates around its nominal value with variations within a maximum range of $\pm 10\%$ of that value. A dip is the sudden drop in voltage from one or more phases followed by a rapid restoration to its nominal value after a short space of time between half a period (10 ms at 50 Hz) and 1 minute.

For the voltage fall to be considered a dip, the voltage value must be between 1% and 90% of its nominal value (IEC 61000-2-1, EN 50160). A drop below 1% is usually called a short interruption. Above 90% it is considered that the voltage is within the normal range of operation.

In three-phase grids, dips can be divided into two broad categories:

- Three-phase dips, when the voltages of the three phases fall into the same proportion.
- Asymmetric dips, where all three phase drops are not equal and the voltage is unbalanced: for example,
  - Single-phase dips that affect only one phase.
  - Biphasic dips that involve two phases.

The voltage dips are normally characterized by the depth and duration, as can be seen in Figure 1.39.

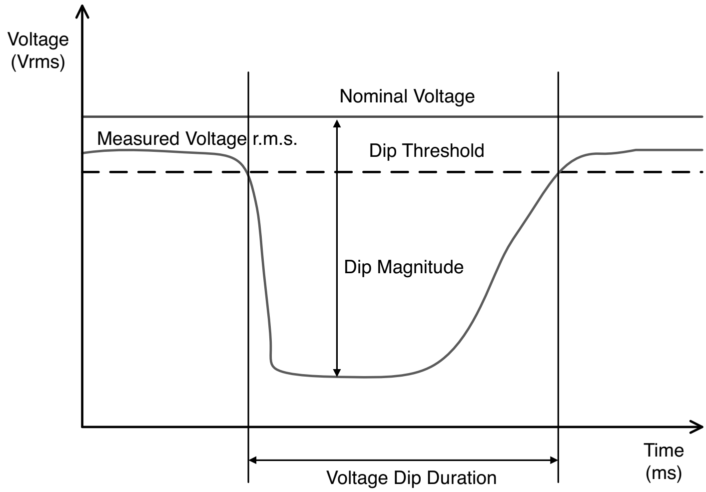


Figure 1.39 Parameters of a dip.

The depth measures the voltage drop in relative terms. It is measured at the deepest point of the valley. The voltage is usually measured by the rms value calculated for each half-period ($RMS_{1/2}$); hence, the minimum duration for a voltage dip is set for half a period. The duration is defined as the length of time that voltage is less than 90% of the nominal value.

1.6.2.2 Classification Bollen and co-workers propose a more intuitive approach to the characterization of three-phase voltage dips. The ABC classification method distinguishes between seven dip types (A to G) by analyzing the possible types of short circuits and the dip propagation through transformers.

Table 1.3 summarizes these dip classes as a function of fault type, location and connection of measuring instruments in the AC grid.

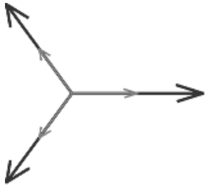
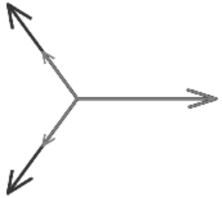
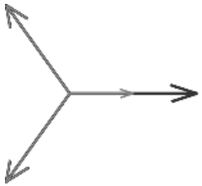
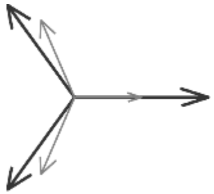
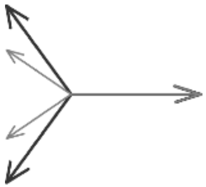
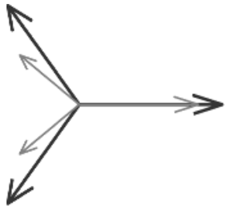
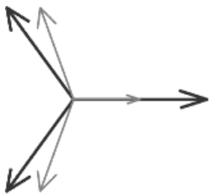
Table 1.4 shows voltage phasors for different dip classes, in which the positive-sequence, negative-sequence, and zero-sequence impedances are considered to be equal.

If the amplitude depth is defined with the variable p, the fault voltages are defined in the equations for each fault type.

TABLE 1.3 Dip Classes of Several Faults Measured at Different Locations

Fault Type	Dip Class (measured between phase and neutral)	Dip Class (measured between phase and neutral after a Δy or YΔ transformer)	Dip Class (measured between phases)	Dip Class (measured between phases after a Δy or YΔ transformer)
Three-phase	A	A	A	A
Single-phase	B	C	D	C
Phase-to-phase	C	D	C	D
Two-phase-to-ground	E	F	F	G

TABLE 1.4 Voltage Dip Types

Type	Phasor Diagram	Phasor Amplitudes	Type	Phasor Diagram	Phasor amplitudes
A		$\underline{V_a} = 1 - p$ $\underline{V_b} = 1 - p$ $\underline{V_c} = 1 - p$	**E**		$\underline{V_a} = 1$ $\underline{V_b} = a^2 \cdot (1 - p)$ $\underline{V_c} = a \cdot (1 - p)$
B		$\underline{V_a} = 1 - p$ $\underline{V_b} = a^2$ $\underline{V_c} = a$	**F**		$\underline{V_a} = 1 - p$ $\underline{V_b} = \frac{p-1}{2} - j \cdot \frac{3-p}{\sqrt{12}}$ $\underline{V_c} = \frac{p-1}{2} + j \cdot \frac{3-p}{\sqrt{12}}$
C		$\underline{V_a} = 1$ $\underline{V_b} = a^2 + j \cdot \frac{\sqrt{3}}{2} \cdot p$ $\underline{V_c} = a - j \cdot \frac{\sqrt{3}}{2} \cdot p$	**G**		$\underline{V_a} = 1 - \frac{p}{3}$ $\underline{V_b} = \frac{p-3}{6} - j \cdot \frac{\sqrt{3}}{2} \cdot (1 - p)$ $\underline{V_c} = \frac{p-3}{6} + j \cdot \frac{\sqrt{3}}{2} \cdot (1 - p)$
D		$\underline{V_a} = 1 - p$ $\underline{V_b} = a^2 + \frac{1}{2}p$ $\underline{V_c} = a + \frac{1}{2}p$			

1.6.2.3 Transformer Effect The ABC classification method was introduced to describe the propagation of voltage dips through transformers. This method of voltage dip classification is the oldest and the most commonly used, possibly due to its simplicity.

Three groups of transformer connections must be analyzed:

- Wye–wye with neutral point connected
- Delta–delta and wye–wye without connecting neutral point
- Wye–delta and delta–wye

The first group of transformers allow circulating common mode currents. The second group of transformers do not allow circulating common mode currents. This means that the common mode component is eliminated.

The third group of transformers, apart from common mode component elimination, introduce a phase angle between primary and secondary voltages. Note that positive and negative sequences are phase shifted by the opposite signed angle.

Due to these reasons, the type of voltage dip in the primary side can be changed in the secondary side. A Type A voltage dip does not change with a transformer because it only has a positive sequence.

Figure 1.40 represents the transformation of different types of voltage dip according to the ABC classification method.

1.6.2.4 Transformer Effect in a Wind Farm The wind turbine can suffer grid outages at the point where it's connected to the high, medium, or low voltage network. In low voltage networks the turbine is directly connected to the low voltage distribution grid without a transformer. In medium voltage grids (distribution), the turbine is connected by means of the turbine step-up transformer.

Turbines connected to high voltage grids (transmission and subtransmission) are usually found in wind farms with the electrical layout explained in Section 1.4.2. In this case a typical example of the electrical circuit between the point of common coupling of the wind farm to the wind turbine is represented in Figure 1.41.

In order to study the effect of transmission network short circuits on the wind turbine, the following elements are modeled:

- The high voltage equivalent grid, represented by the equivalent Thèvenin circuit
- The substation transformer with a short-circuit impedance
- The impedance of the feeder from the substation to the wind turbine
- The coupling transformer with a short-circuit impedance
- The internal electrical circuit of the turbine

The short circuits can be located in high voltage (HV) or medium voltage (MV) grids and will affect the wind turbine in different ways but due to the transformer

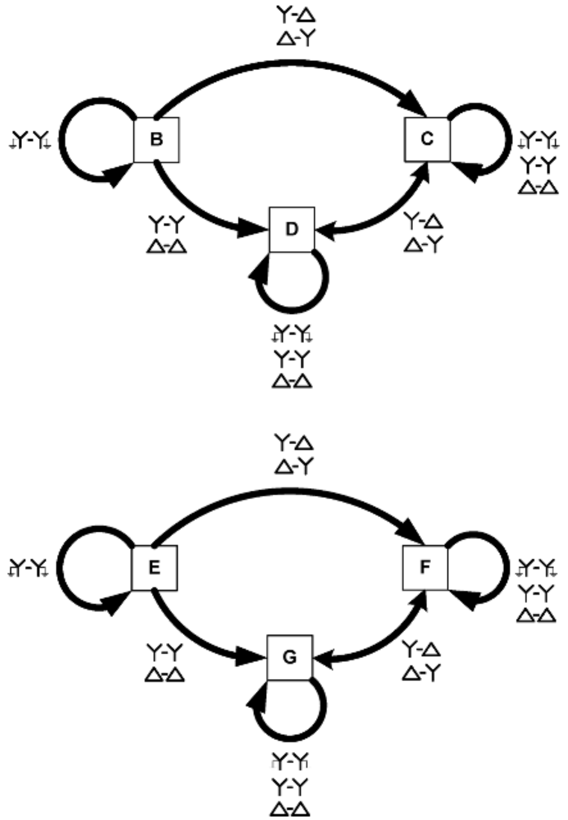


Figure 1.40 Transformer effect in the type of voltage dip.

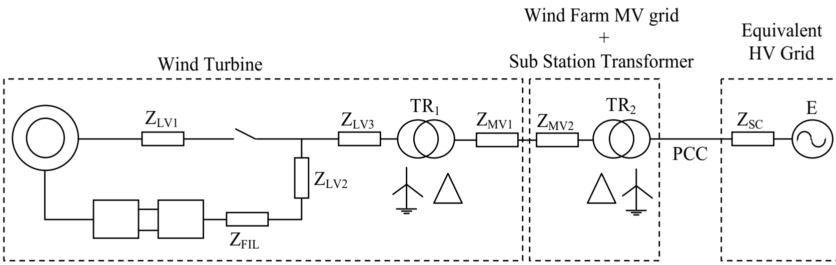


Figure 1.41 Transformer effect in the type of voltage dip for high voltage grid.

configuration only three-phase and two-phase voltage dips will occur at the low voltage connection point of the turbine.

The electrical configuration of wind farms is different in each country and the same goes for how the transmission and distribution systems are operated; each example must be considered separately.

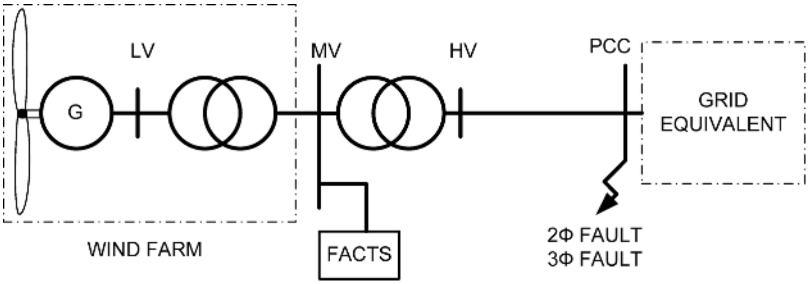


Figure 1.42 Single-line schematic of the electrical system layout.

1.6.3 Spanish Verification Procedure

The purpose of the procedure is to measure and assess the response of wind farms in the event of voltage dips. This procedure ensures uniformity of tests and simulations, precision of measurements, and assessment of the response of wind farms in the event of voltage dips. The requirements for the response to dips are specified in the electrical system Operational Procedure 12.3.

The following subsections will describe the most relevant points of the procedure related to the simulation of the behavior of the wind turbine to verify a response to voltage dips.

1.6.3.1 Topology of Electrical System In order to carry out wind farm simulations, an electrical configuration as described in Figure 1.42 will be used, which must contain at least the following elements:

- Wind farm devices and their specifications.
- Medium to high voltage step-up transformer
- Evacuation line (AT - PCR)
- Grid equivalent

All groups of the WTGs connected through the electrical power circuits will be connected at the medium voltage (MV) point. If additional loads or other wind farms are connected between the high voltage (HV) point and Evacuation line (HV - PCC) the grid connection point (GCP), also called point of common coupling (PCC), those additional loads or wind farms will be taken out of the simulation, in order to avoid any modification of the equipment that connects to the GCP (transformers and lines).

1.6.3.2 Equivalent Electrical Grid The rest of the electrical grid that does not belong to the wind farm being studied must be modeled so that the fault clearance at the grid connection point reproduces the usual voltage profile in the Spanish electrical system—a sudden increase upon clearing of the fault and a slower recovery afterwards. This profile will be considered fixed and independent of the geographic location of the wind farm to be studied.

In order to simulate the equivalent electrical grid, a dynamic system has been chosen consisting of one node in which the equivalent dynamic model of the UCTE (UCTE node) is modeled, along with another node in which an equivalent model reflects the dynamic characteristics due to the hypothetical closest electrical grid (RED node) and a third that represents the GCP (GCP node). These nodes are separated by impedances of predetermined values in such a way as to reproduce the typical voltage profile of the Spanish electrical system. In this way, it is guaranteed that all of the wind farms are tested, by simulation, for short circuits with equal characteristics.

The UCTE equivalent includes a synchronous generator (Generator 1) of an apparent power that reflects a realistic value for the interconnected apparent power and therefore the inertia of the UCTE system. This generator is modeled in 20 kV bars with a step-up transformer. The demand of the UCTE system is modeled as a load in the equivalent node of the system.

In order to consider the dynamic side of the equivalent of the closest grid, a synchronous generator has been included (Generator 2) and a demand. Generator 2 is modeled in 20 kV bars with a step-up transformer and the demand is modelled as a load in 20 kV bars connected to the RED node through a transformer.

The properties of the equivalent electrical grid must include at least the elements represented in Figure 1.43.

1.6.3.3 Evaluation of Response to Voltage Dips The final part of the simulation procedure consists of the strict evaluation of the wind farm's response to voltage dips. Once the electrical system, its associated dynamic elements, and the starting conditions before simulation have been defined, a fault can be applied to the grid connection point.

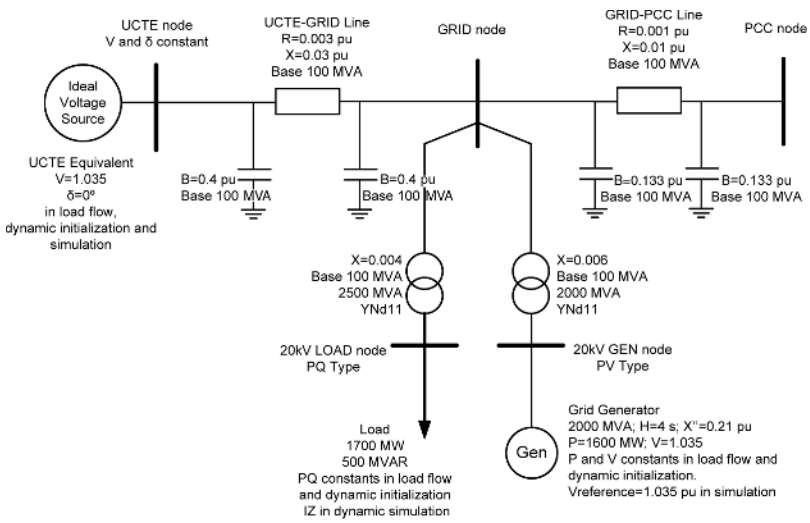


Figure 1.43 Model of the equivalent electrical grid (single-line scheme).

Once the initial conditions are adjusted at the WTG terminals, the active generated power corresponding to the full or partial load and zero reactive power will be considered the initial conditions prior to the simulation. Once the simulations have been carried out, the following requirements must be achieved for each test category:

1. *Continuity of Supply*. During the simulation, it must be shown that the wind farm withstands the specified dips in the test procedure without disconnection. To carry out these simulations, it is necessary that the simulation model includes internal protections, which determine the triggering of the WTG in case of voltage dips and return the resulting disconnection signal.

If the entire wind farm (without aggregation) is simulated, the simulated installation guarantees a continuity of supply if the number of machines remaining connected during the dip is such that the loss of generated active power does not exceed 5% of the power previous to the fault. If an equivalent wind farm (with aggregation) is used, the triggering of the WTG will determine the continuity of supply for the complete wind farm.

2. *Voltage and Current Levels at the WTG Terminals*. After checking the voltage level during the no load test, the voltage and current values in each phase for the four categories described above must be measured and recorded during the load tests (WTG connected during the short circuit).

3. *Exchanges of Active and Reactive Power as Described in OP 12.3*. In the wind farm simulation, it must be shown that neither a specific beginning or clearance point for the voltage dip nor a power factor for the WTGs, which are especially favorable for compliance with the requirements set in OP 12.3, has been chosen.

1.7 VSWT BASED ON DFIM MANUFACTURERS

This section discusses manufacturers that propose wind turbines based on the DFIM, and then develops a complete model for a 2.4 MW wind turbine along with the basic analysis of the aerodynamic, mechanical, and electrical magnitudes.

1.7.1 Industrial Solutions: Wind Turbine Manufacturers

The main players in the market have product solutions based on the DFIM. Table 1.5 shows some of their characteristics for the 50 Hz model wind turbines. The aim of this table is to give readers an idea of the main parameters of the turbines.

In order to understand the table, it's necessary to explain some concepts.

- Turbine speed: minimal–nominal–maximum: The turbine operates in the maximum power tracking region between the minimal and the nominal speed. The maximum speed limit is due to the difficulty in regulating the nominal speed during gusts and lessening the mechanical stress on the turbine when the turbine is operating at nominal power.

TABLE 1.5 Main Characteristics of Commercial Wind Turbines

Company	Model/Power	Turbine Speed Minimal–Nominal–Maximal	Rotor Diameter	Gearbox Ratio Type	Generator Voltage Stator/Rotor	Generator Speed Pole Number Minimal–Nominal–Maximal
Vestas	V80–2 MW	10.8–16.7 rpm 19.1 rpm	80	100.33 Three-stage planetary/helical	690 V – 480 V/—	2 1083/1672 1916
Repower	MM82–2.0 MW	8.5 – 17.1 rpm 17.1 rpm (+12.5%)	82	Approximately 105.4 Planetary/spur wheel	690 V/—	2 900–1800 rpm
	5M–5.075 kW	7.7 – 12.1 rpm 12.1 rpm (+15.0 %)	126	Approximately 97 Two helical planetary/one spur wheel	950 V/660 V	3 750–1170 rpm 1170 rpm (+15.0 %)
Gamesa	G52–850 kW	14.6 – 30.8 rpm —	52	1:61.74 One planetary/Two parallel axis	690 V/—	2 1000–1950 —
	G87–2.0 MW	9.0 – 19.0 rpm —	87	1:100.5 One planetary/Two parallel axis	690 V/—	2 900–1680 rpm 1900 rpm
Acciona	AW 1500 1.5 MW	20.2 rpm	70	1:59 Four-stage planetary	12 kV/—	3 770–1320 rpm 1200
	AW 3000 3 MW	14.2 rpm	100	1:77	12 kV/—	3 770–1320 rpm 1.100 rpm

Ecotecnia	ECO 80	—	80	1:100.6	690 V	2
	2 MW	9.7–19.89 rpm				1000–1950 rpm
						1800 rpm
	ECO 100	—	100	1:126.319	1.000 V/—	2
	3 MW	7.5–14.25 rpm.				1000–1950 rpm
						1800 rpm
Nordex	S70	—	70	1:74	690 V	1000–1800 rpm
	1.5 MW	10.6–19 rpm				1800 rpm (+10.0%)
	N80	9.6–18 rpm	80	1:68.7	660 V	3
	2.5 MW					740–1300 rpm
Mitsubishi	MWT92	9–15 rpm	92	1:76.9	690 V	3
	2.4 MW	16.9 rpm		Three-stage, one planetary and two parallel		690–1153.5
						1300 rpm

- The rotor diameter is always a little bigger than the length of the blades, due to the hub diameter and because sometimes the blades have extensions. The tip maximum speed in meters per second is the turbine maximum speed in radians per second; multiplied for the rotor ratio, this speed is around 300 kilometers per hour in most turbines.
- Generator speed: minimal–nominal–maximal: The generator speed must be calculated by multiplying the turbine speed by the gearbox ratio. The minimal, nominal, and maximal values must correspond with the turbine ones.
- Generator pole number: The generator synchronous speed is 1500 rpm for a two pole pair generator, and 1000 rpm for a three pole pair generator connected to a 50 Hz grid.
- The typical stator voltage is 690 V or less than 1000 V, due to the fact that security rules for low voltage implies AC voltages upto 1000 volts and DC voltages upto 1500 V. Medium voltage equipments, for example, in power electronics, will require more strict security rules and ratified formation.
- The typical ratio between the rotor and stator voltages is in the range of 2.6 to 2.8, resulting in open rotor voltages of 1794–1932 V. As explained earlier, the rotor voltage is a function of the slip, which is limited to 500/1500 rpm in most wind turbines, resulting in a maximum rotor voltage in the range of 598–644 V rms line to line.

Before starting the next section, it's necessary to mention that all the information shown in this section comes from the manufacturer's web pages and wind turbines brochures.

1.7.1.1 Alstom-Ecotècnia Alstom-Ecotècnia was a manufacturer of FSWTs until the 1990s when it started to develop model ECO 74, the first VSWT based on the DFIG that the company commercialized. At present the company's product range is based on two platforms—the 2 and the 3 MW.

Figure 1.44 shows a picture, a three-dimensional CAD drawing, and the brochure description of the main components of an ECO 100 wind turbine nacelle.

The main characteristics of the nacelle design are:

- A modular design that permits on-site testing and assembly of components (rotor hub, frame, housing).
- Housing that is made of three independent elements. Lateral housings provide extra space to install the power transformer, the inverter, and control cabinets. Placing the power transformer in the nacelle reduces the power lost during transmission from the generator to the transformer.

Alstom wind turbines are based on a unique mechanical design concept: the ALSTOM PURE TORQUE™ concept. The hub is supported directly by a cast frame on two bearings, whereas the gearbox is fully separated from the supporting

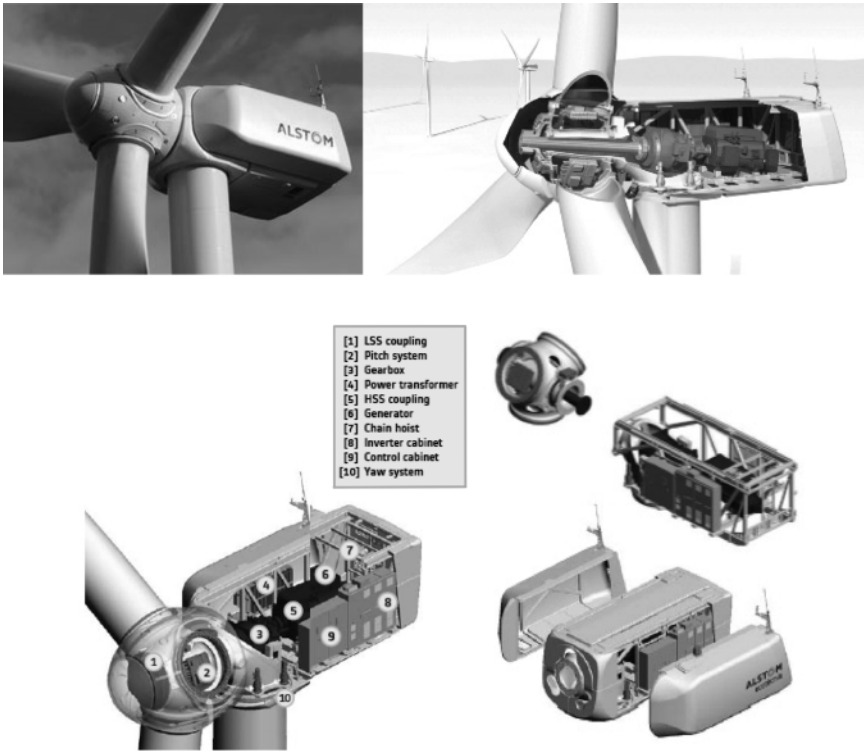


Figure 1.44 Picture and main components of the nacelle for an ECO 100 wind turbine. (*Source*: Alstom.)

structure, as shown Figure 1.45. As a consequence the deflection loads (red arrows) are transmitted directly to the tower whereas only torque is transmitted through the shaft to the gearbox.

Figure 1.46 shows the power curve.

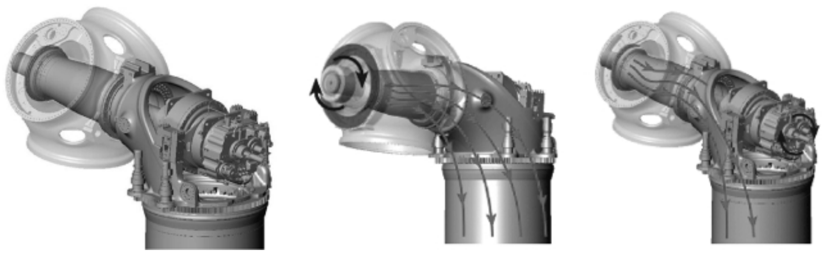


Figure 1.45 Pure torque system to transmit the mechanical efforts between the rotor and the tower. (*Source*: Alstom.)

Velocity [m/s]	Power [kW]
3	19
4	102
5	237
6	434
7	721
8	1080
9	1550
10	2091
11	2600
12	2843
13	2950
14	2989
15	3000
16	3000
17	3000
18	3000
19	3000
20	3000
21	3000
22	3000
23	3000
24	3000
25	3000

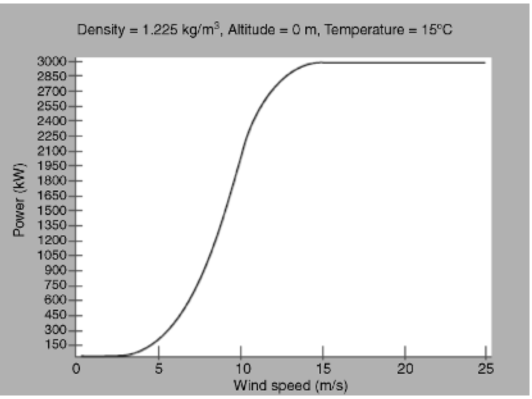


Figure 1.46 Power curve of the ECO 100 wind turbine. (*Source*: Ecotècnia.)

1.7.1.2 Gamesa Gamesa is a Spanish manufacturer with a wide range of products, and one of the first to propose a VSWT based on DFIG. At present it offers three platforms—G5X, G8X, and G9X based on DFIG.

Figure 1.47 shows a picture, the brochure description of the main components in the nacelle, and the power curve for a G87 2 MW wind turbine.

The main characteristics of the nacelle design are:

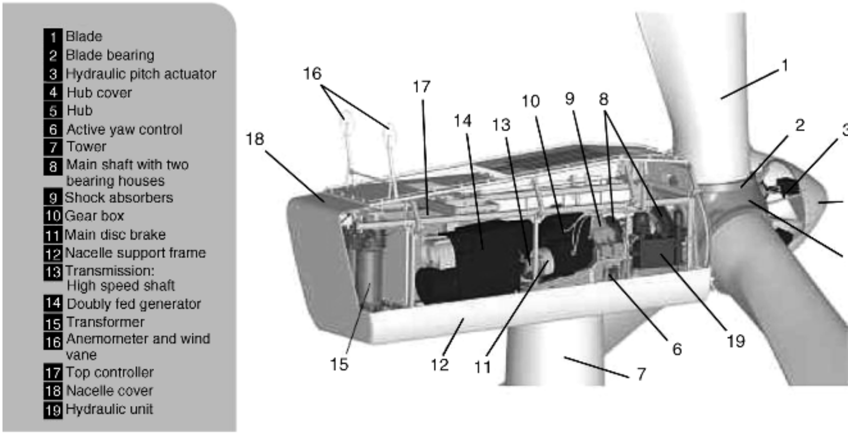
- Drive train with the main shaft supported by two spherical bearings that transmit the side loads directly to the frame by means of the bearing housing. This prevents the gearbox from receiving additional loads, thus reducing malfunctions and facilitating its service.
- All the components of the drive train (low speed axel, gearbox, disk brake, and generator) are located in series with the transformer after them to equilibrate the weight.

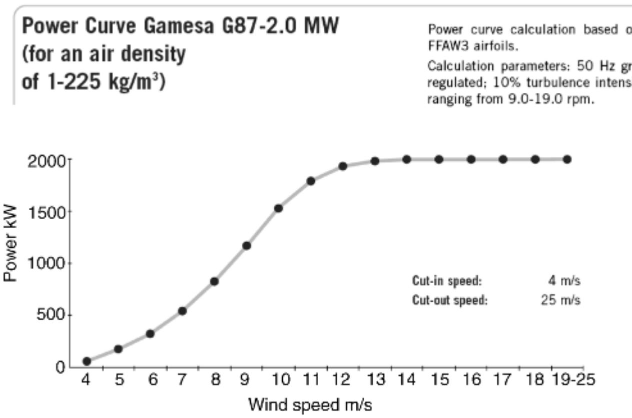
Figure 1.48 shows the nacelle assembly procedure in the Gamesa facilities. The nacelle is transported assembled in one single truck without the hub and cone.

1.7.1.3 Acciona The AW 3000 is the most powerful wind turbine manufactured by Acciona. Figure 1.49 shows a wind turbine picture and a drawing with the main components of the nacelle.

Some interesting characteristics of the nacelle mechanical design are:

- Robust double frame that reduces the stress on the drive train.
- Yaw system that uses a gear ring integrated into the tower and six geared motors integrated into the nacelle.





Speed (m/s)	Power (kW)
4	78.6
5	181.2
6	335.4
7	549.8
8	831.5
9	1174.8
10	1528.3
11	1794.7
12	1931.1
13	1981.0
14	1995.3
15	1998.9
16	1999.8
17	2000.0
18	2000.0
19-25	2000.0

Figure 1.47 Picture, main components of the nacelle for a G87 wind turbine, and power curve. (*Source*: Gamesa.)

From the electrical point of view:

- The doubly fed generator generates at medium voltage (12 kV of stator voltage), which reduces losses and avoids the need for a transformer in many cases. The transformer is rated for the rotor power.

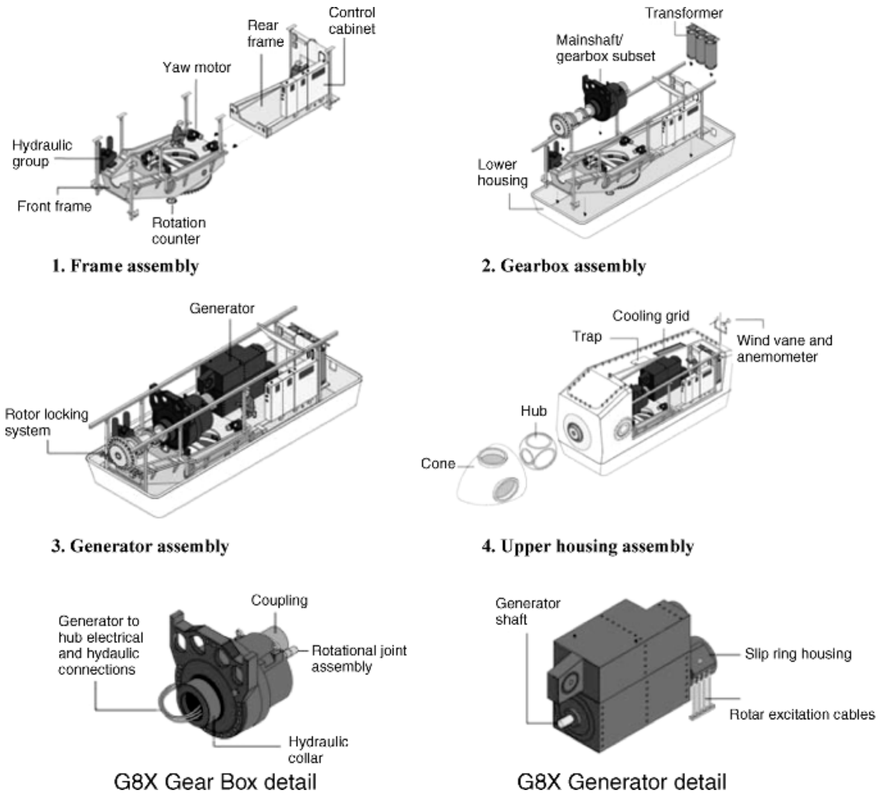


Figure 1.48 Assembly procedure of main components in a G87 nacelle. (*Source*: Gamesa.)

- The generator has three pole pairs.
- All the electric and electronic components are located in the tower.

1.7.1.4 General Electric The entity was created as a developer (not manufacturer), Zond, in 1980. Enron acquired Zond in January 1997. In 2002 GE acquired the wind power assets of Enron during its bankruptcy proceedings. Enron Wind was the only surviving U.S. manufacturer of large wind turbines at the time, and GE increased engineering and supplies for the Wind Division and doubled the annual sales to $1.2B in 2003. It acquired ScanWind in 2009.

The GE 1.5 MW is the most widely used wind turbine in its class. Developed by Zond in collaboration with the U.S. DOE (Department of Energy), it was initially commercialized by Enron in 1996 and improved by GE from 2002 on. Some interesting data as of March 2009 are the following:

- 12,000 + turbines are in operation worldwide.
- 19 countries employ them.
- 170 + million operating hours have been logged.
- 100,000 + GWh have been produced.

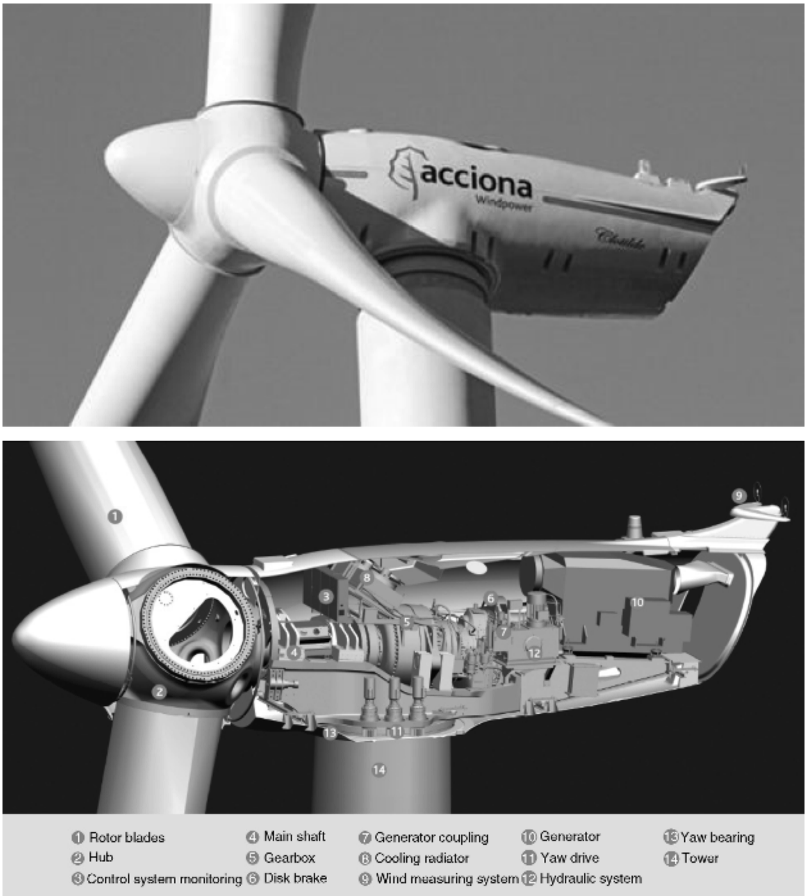


Figure 1.49 Main components of an AW 3000 nacelle. (*Source*: Acciona.)

Figure 1.50 shows a picture and the brochure description of the main components of the nacelle.

Some of the performance characteristics of the turbine are:

- Variable speed control: GE technology features unique variable speed control technology to maximize energy capture from the wind and minimize turbine drive-train loads.
- Unique wind volt-amp-reactive ("WindVAR") technology: This control provides support to and control of local grid voltage, improving transmission efficiencies and providing the utility grid with reactive power (VARs), increasing grid stability.
- Low voltage ride-through technology: For the first time, wind turbines can remain online and feed reactive power to the electric grid right through major system disturbances.

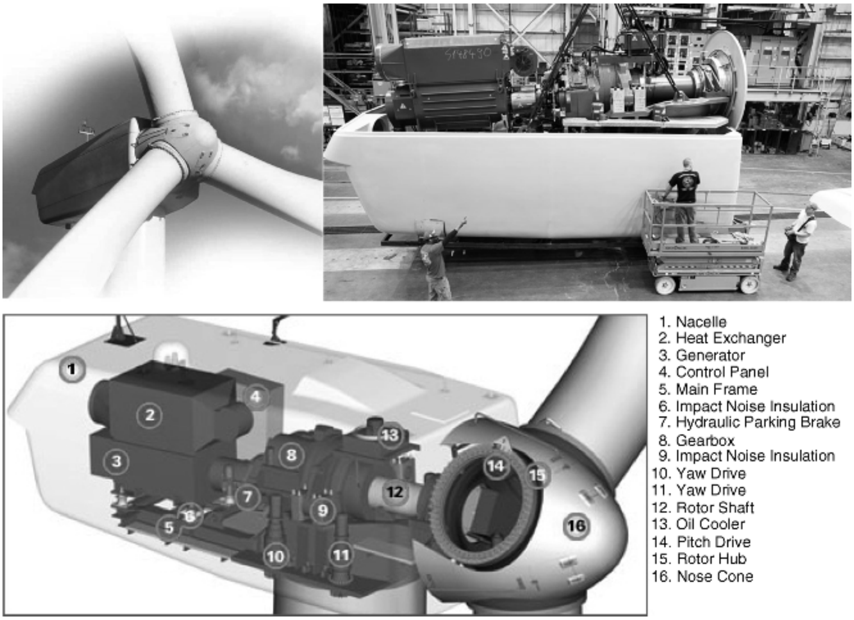


Figure 1.50 Pictures and main components of a 1.5 MW nacelle. (*Source:* GE.)

- Advanced electronics: The wind turbine's control system continually adjusts the wind turbine's blade pitch angle to enable it to achieve optimum rotational speed and maximum lift-to-drag at each wind speed. This "variable speed" operation maximizes the turbine's ability to remain at the highest level of efficiency.
- Variable speed operation enables the loads from the gust to be absorbed and converted to electric power. Generator torque is controlled through the frequency converter. This control strategy allows the turbine rotor to over-speed operation in strong, gusty winds, thereby reducing torque loads in the drive train.
- Active damping: The variable speed system also provides active damping of the entire wind turbine system, resulting in considerably less tower oscillation when compared to constant speed wind turbines. Active damping of the machine also limits peak torque, providing greater drive-train reliability, reduced maintenance cost, and longer turbine life.

Figure 1.51 shows the power curve for a 1.5 MW wind turbine.

1.7.1.5 Vestas Traditionally, Vestas has been using two technologies in most of its models with power ranges between 600 and 2000 kW: the Opti Slip (speed control by rotor resistance control) and the Active Stall (power control combining pitch

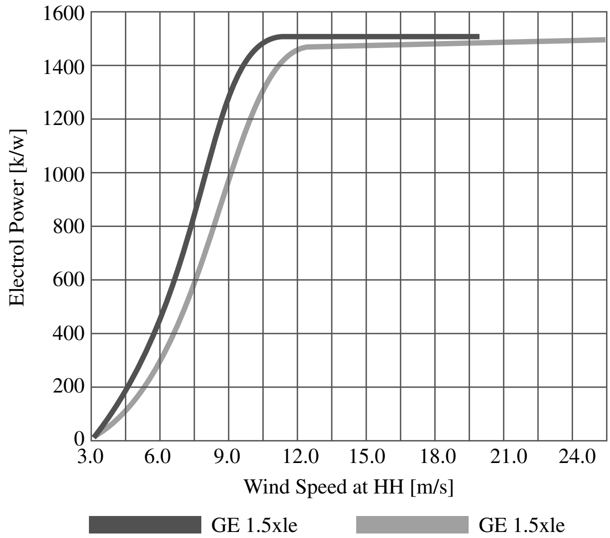


Figure 1.51 Power curve for a 1.5 MW wind turbine. (*Source:* GE.)

control and stall). These technologies provide a speed variation of 10%, enhancing power quality and reducing mechanical stress during wind gusts.

The V80, V90, and V120 wind turbines have a wide range of variable speed and are based on DFIG. Figure 1.52 shows a wind turbine picture and a drawing with the main components of the nacelle.

An interesting characteristic of the mechanical design is the OptiTip® pitch regulation system. This system features microprocessors that rotate the blades around their longitudinal axes, thus ensuring continuous adjustment to maintain optimal blade angles in relation to the prevailing wind. At the same time, sound levels are maintained within the limits stipulated by local regulations.

From the electrical point of view, the OptiSpeed® system:

- Allows the turbine rotor speed to vary between 9 and 19 rpm, depending on conditions.
- Reduces wear and tear on the gearbox, blades, and tower on account of the lower peak loading. Moreover, as turbine sound is a function of wind speed, the lower rotation speeds made it possible to reduce sound levels.
- Helps the turbine deliver better quality power to the grid, with rapid synchronization, reduced harmonic distortion, and less flicker.

Figure 1.53 shows the power curve for different noise levels.

1.7.1.6 Repower Repower is a German manufacturer, at present the property of Sulzon, that specializes in multimegawatt wind turbines, such as the MM82–2 MW and the 5M, with 6M development just about complete.

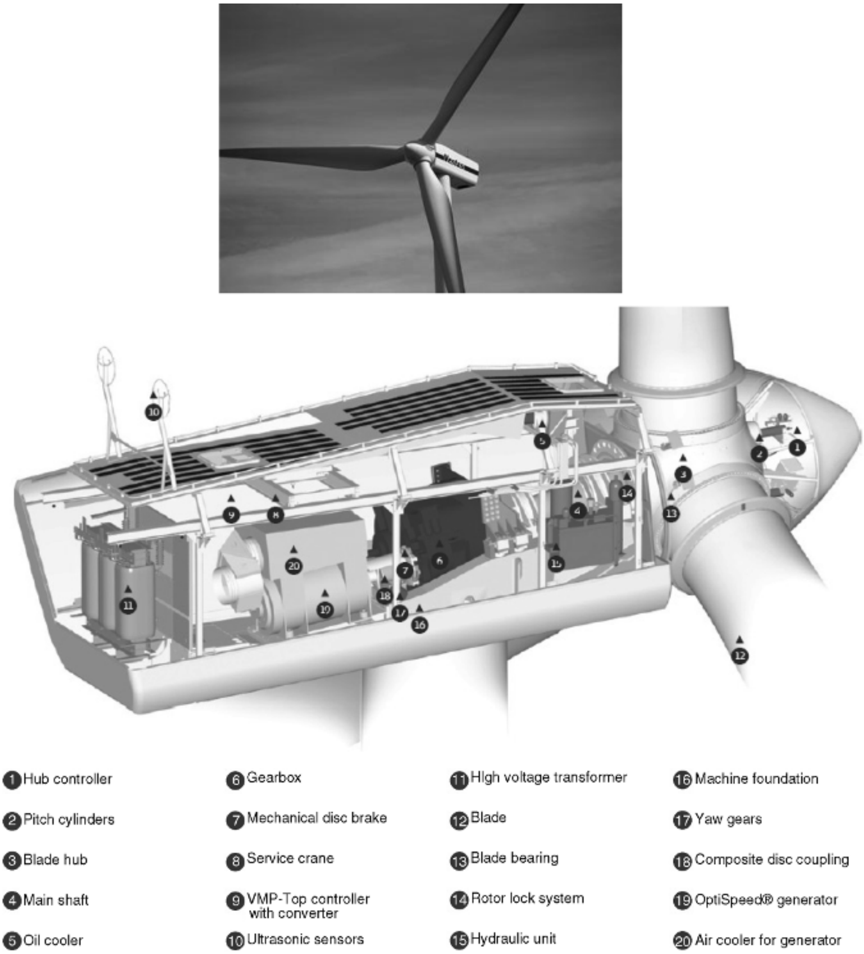


Figure 1.52 Picture and main components of a V80 2 MW nacelle. (*Source:* Vestas.)

Figure 1.54 shows a picture, the brochure description of the main components of the nacelle, and the power curve for a Repower MM82–2 MW wind turbine.

The main characteristics of the design are:

- Rotor bearing and shaft: High performance spherical roller bearing with adjusted bearing housing and permanent lubrication for prolonged service life. Rotor shaft forged from heat-treated steel and optimized for power flow.
- Holding brake: Secure holding of rotor due to generously dimensioned disk brake. Soft-brake function reduces stress on the gearbox.
- Generator and converter: Yield-optimized variable speed range. Low conversion loss and high total efficiency as converter output is limited to a maximum of 20%

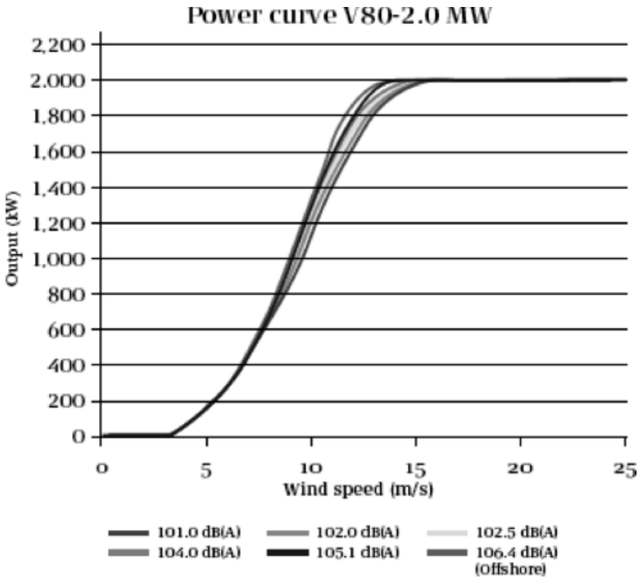


Figure 1.53 Power curve of the wind turbine. (*Source:* Vestas.)

of the overall output. Fully enclosed generator with air/air heat exchanger. Optimized temperature level in generator, even at high outside temperatures.

- All the components of the drive train (low speed axle, gearbox, disk brake, and generator) are located in series over the main frame.

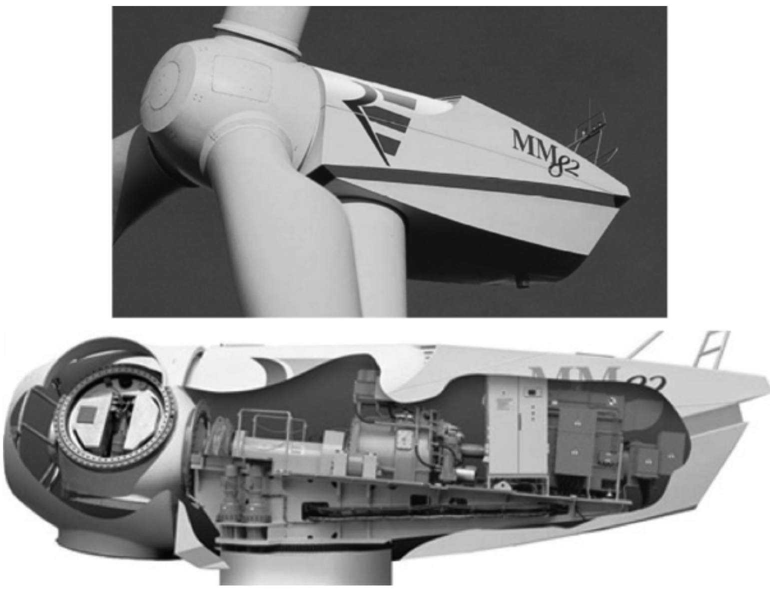


Figure 1.54 Picture and main components of a MM82 nacelle. (*Source:* Repower.)

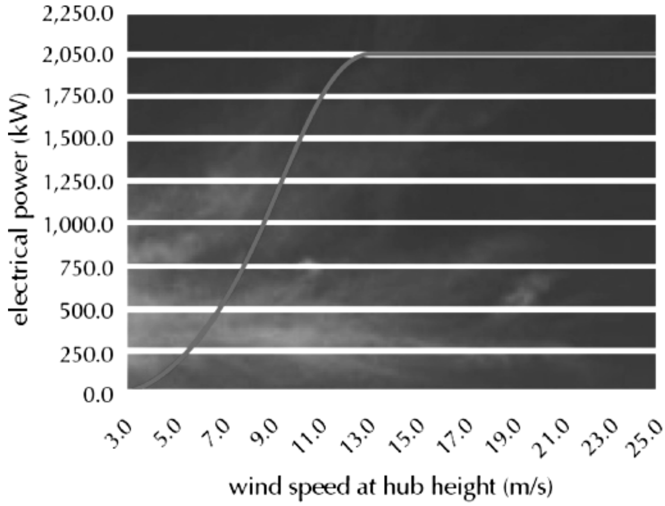


Figure 1.55 Power curve of the MM82 wind turbine. (*Source:* Repower.)

- Pitch system: Virtually maintenance-free electronic system. High quality, generously dimensioned blade bearing with permanent track lubrication. Maximum reliability via redundant blade angle detection by means of two separate measuring systems. Fail-safe design with separate control and regulation systems for each rotor blade.

Figure 1.55 shows the power curve.

1.7.1.7 Nordex Nordex started with the VSWT DFIG based technology with model S70 rated at 1.5 MW and actually also offers models N80 and N90 rated at 2500 and 2300 kW.

Figure 1.56 shows the N80 nacelle in different versions, a picture, and the CAD representation.

The main characteristics of the design are:

- The rotor consists of three rotor blades made of fiberglass-reinforced polyester, the hub, the pitch bearings, and drives to change the pitch angle of the rotor blades.
- The drive train consists of the rotor shaft, the gearbox, an elastic cardanic coupling, and the generator.
- The gearbox is designed as a two-stage planetary gearbox with a one-stage spur gear. The gearbox is cooled by means of an oil–water–air cooling circuit with stepped cooling capacity. The bearings and tooth engagements are kept continuously lubricated with cooled oil.
- The generator is a double-fed asynchronous machine. The generator is kept in its optimum temperature range by means of a cooling circuit.

Figure 1.56 Nordex N90 variable speed pitch regulated wind turbine. (*Source:* Nordex).

- The gearbox, generator, and converter have cooling systems that are independent from each other. The cooling system for the generator and converter is based on a water circuit. This ensures optimum operating conditions in all types of weather.
- The three redundant and independently controlled rotor blades can be set at full right angles to the rotation direction for aerodynamic braking. In addition, the hydraulic disk brake provides support in the event of an emergency stop.
- The hydraulic system provides the oil pressure for the operation of different components: the yaw brakes, rotor brake, and nacelle roof.
- The nacelle consists of the cast machine frame and the nacelle housing. The nacelle housing is made of high-quality fiberglass-reinforced polyester (GRP). The roof of the nacelle is opened hydraulically.
- The wind direction is continuously monitored by two redundant wind direction sensors on the nacelle. If the permissible deviation is exceeded, the yaw angle of the nacelle is actively adjusted by means of two geared motors.
- The wind turbine has two anemometers. One anemometer is used for controlling the turbine, the second for monitoring the first. All operational data can be monitored and checked on a control screen located in the switch cabinet.

Figure 1.57 shows the power curve of the turbine.

1.7.1.8 Mitsubishi Mitsubishi started with the VSWT DFIG based technology with model MWT 92 rated at 2.4 MW and actually also offers models MWT 95, 100, and 102 rated at 2400 kW and MWT 92 rated at 2300 kW.

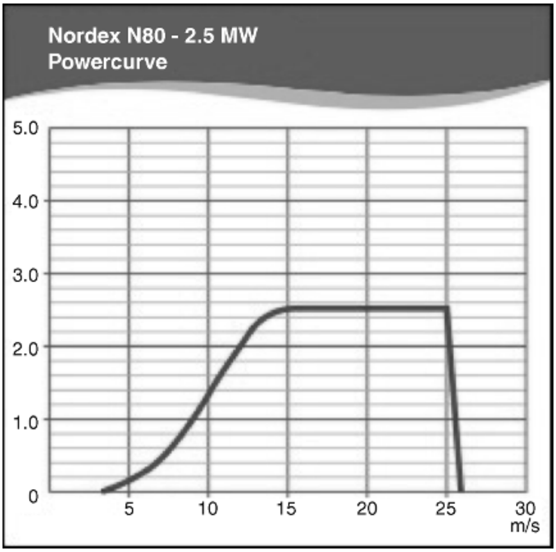


Figure 1.57 Power curve of the wind turbine. (*Source:* Nordex.)

Figure 1.58 shows some pictures of the MWT92 wind turbine and the components' distribution in the nacelle.

The main characteristics of the turbine design are:

- All the components of the drive train (low speed axle, gearbox, disk brake, and generator) are located in series in a lateral of the nacelle.
- The transformer is in the other lateral to equilibrate the weight.
- The power electronic converters are located at the bottom of the nacelle, and the water to air heat exchanger after the cabinets.
- Individual blade pitch control for aerodynamic load reduction.
- "Smart yaw" technology to minimize extreme wind load.

Figure 1.59 shows the power curve of the turbine.

1.7.2 Modeling a 2.4 MW Wind Turbine

Notice that the information that manufacturers provide in their brochures is very restrained. The aim of this section is to provide some basic numbers and ideas for modeling a wind turbine.

A typical wind turbine has a nominal power between 1.5 and 3 MW as shown in preceding sections. In this section a 2.4 MW wind turbine has been selected for modeling. The most significant models on market are the GE 2.5, the Nordex N80, and the Mitsubishi MWT 92.

Wind turbine sizing is a complex task that requires knowledge of multiple disciplines, starting with the aerodynamic behavior and finishing with the electrical machine.

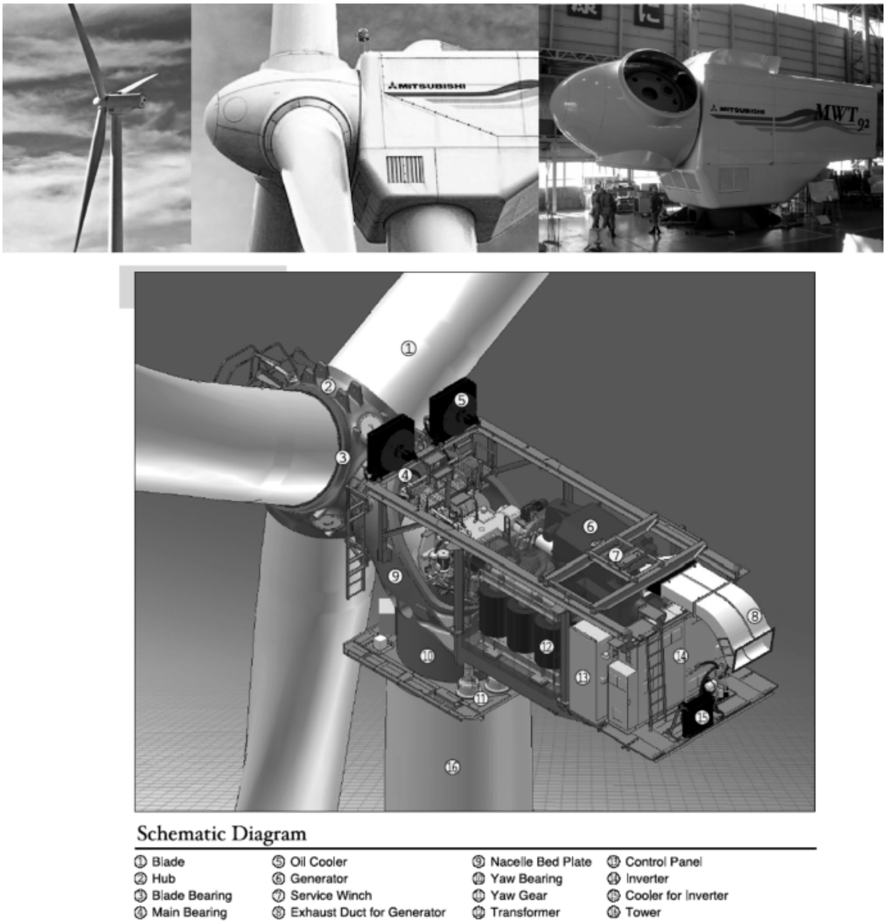


Figure 1.58 Mitshibishi MWT 92 wind turbine. (*Source:* Mitsubishi.)

From data extracted from manufacturers' brochures and other specialized references, it's possible to propose some parameters that represent the energetic behavior of the wind turbine and its main mechanical and electrical dynamics.

The two main aspects to take into account are:

- The aerodynamic behavior of the rotor. In our case the analytic expression defined in Section 1.3 must be parameterized.
- The wind turbine control strategy parameters must be selected; that is, the maximum and minimum turbine speed for a nominal wind speed and a minimum wind speed.

Once the energetic behavior of the turbine is defined, it's possible to proceed to the sizing of the power electronic converters.

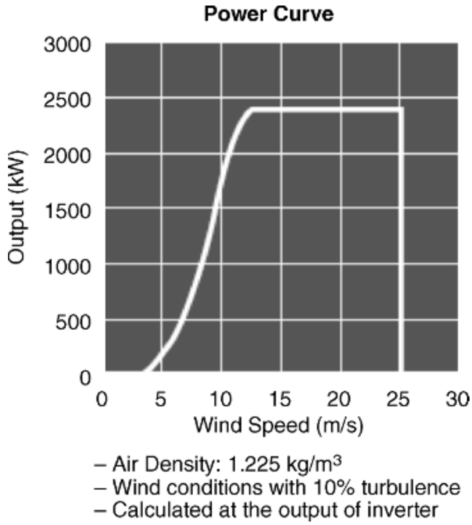


Figure 1.59 Power curve of the wind turbine. (*Source:* Mitsubishi.)

1.7.2.1 Model of the Aerodynamic System From manufacturers' brochures it's possible to get the basic data for a 2.4 MW turbine:

- The radius of the blade is in the range of 40–45 meters, depending on the wind class of the turbine.
- The nominal power is extracted for a wind speed between 11 and 13 m/s.
- The rotor speed (low speed axle) is in the range of 8.5 to 20 rpm.
- The gearbox ratio is around 100 for a two-pole generator and 50 Hz grid.

Another important parameter is the tip blade maximum speed, which is around 80–90 m/s (325 km/h), directly dependent on the turbine radius and maximum speed.

The aerodynamic behavior of the turbine rotor is more complicated because it is one of the differential factors between manufacturers; only Nordex in their N80–90 brochure gives some information about the power coefficient of their turbine. In this sense the only available information is the typical power versus wind speed curve.

Table 1.6 summarizes the selected parameters for turbine sizing.

It's possible to adjust the coefficients of Equation (1.7) for the 2 MW wind turbine. The next expression shows the numerical result:

$$\begin{aligned} C_p &= 0.46\left(\frac{151}{\lambda_i} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)\left(e^{-18.4/\lambda_i}\right) \\ \lambda_i &= \frac{1}{\lambda + 0.02\beta} - \frac{0.003}{\beta^3 + 1} \end{aligned} \tag{1.22}$$

TABLE 1.6 Turbine Parameters

Parameter	Value	Unit
Radius	42	m
Nominal wind speed	12.5	m/s
Variable speed ratio (minimum–maximum turbine speed)	9–18	rpm
Optimum tip speed ratio λ_{opt}	7.2	—
Maximum power coefficient C_{p_max}	0.44	—
Air density ρ	1.1225	kg/m^3

Figure 1.60 shows the plot of power coefficient as a function of tip speed ratio for Equation (1.7); notice that the maximum power coefficient is 0.44, and the optimum tip speed ratio is 7.2.

The power curves as a function of wind speed are shown in Figure 1.61, along with the typical speed limits (9 and 18 rpm) and the nominal power (2.4 MW).

1.7.2.2 Gearbox and Mechanical Model The gearbox ratio is a function of the machine nominal and maximum speed and the turbine maximum speed, so a ratio *N* of 100 has been chosen for a two-pole generator.

Table 1.7 shows the selected two mass mechanical system parameters translated to the high speed axle.

The corresponding resonance frequency is 2 Hz.

1.7.2.3 Generator Characteristics Table 1.8 shows the electrical generator's main characteristics.

Table 1.9 shows the electrical generator's equivalent schema parameters.

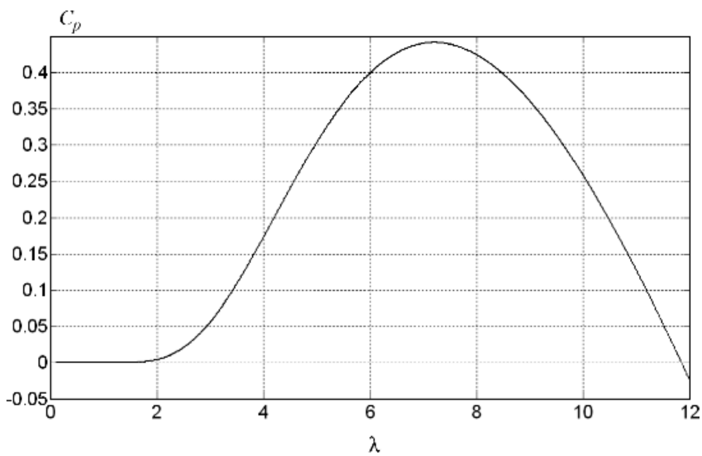


Figure 1.60 Power coefficient versus tip speed ratio.

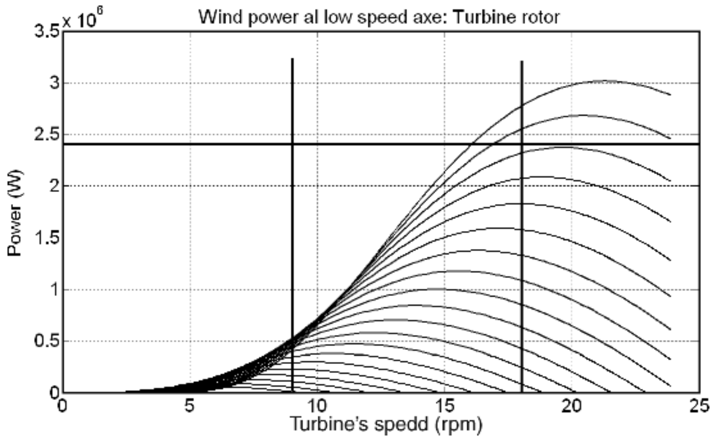


Figure 1.61 Power versus tip speed ratio for wind speeds between 3.5 and 13 m/s in steps of 0.5 m/s.

TABLE 1.7 Mechanical System Parameters

Parameter	Value	Unit
Low speed axle inertia $J_{t,a}$	800	kg·m^2
Low speed axle friction $D_{t,a}$	0.1	Nm·s/rad
Coupling stiffness K_{tm}	12500	Nm/rad
Coupling damping D_{tm}	130	Nm·s/rad
High speed axle inertia J_m	90	kg·m^2
High speed axle friction D_m	0.1	Nm·s/rad

TABLE 1.8 Main Characteristics of the Generator

Parameter	Value	Unit
Nominal stator active power	2.0	MW
Nominal torque	12732	Nm
Stator voltage	690	V
Nominal speed	1500	rpm
Speed range	900–2000	rpm
Pole pairs	2	—

TABLE 1.9 Equivalent Model of the Generator

Parameter	Value	Unit
Magnetizing inductance L_m	2.5×10^{-3}	H
Rotor leakage inductance L_{or}	87×10^{-6}	H
Stator leakage inductance L_{os}	87×10^{-6}	H
Rotor resistance R_r	0.026	Ω
Stator resistance R_s	0.029	Ω

1.7.2.4 Power Curves as a Function of the Wind Turbine Control Strategy In order to select the wind turbine control strategy, it is very important to keep three parameters in mind:

1. The optimum tip speed ratio of 7.2
2. The rotor radius of 42
3. The speed range of the turbine from 900 to 1800 rpm

The next range of wind speed for the variable speed turbine is 5.5 m/s for 900 rpm and 11 m/s for 1800 rpm (maximum power tracking region). The nominal power of the turbine is reached around 12.5 m/s and 1800 rpm.

Figure 1.62 represents the evolution of generator speed as a function of wind speed (averaged wind speed in the turbine swept area).

Notice that the incident wind on the turbine is not constant and varies widely. Figure 1.62 shows that the average behavior of the turbine, during real operation, must be defined as an envelope as a function of the control dynamics (maximum and minimum values of turbine speed for each ideal operating point).

For that reason the turbine is designed to work in an overspeed range, for example, 2050 rpm.

Figure 1.63 shows the mechanical power of the turbine. In a real wind turbine, the transition between variable speed–partial load operation is much smoother because:

1. The real turbines currently operate with a slight speed slope (e.g., between 1850 and 1900 rpm).
2. At nominal speed the turbine operates in a stall mode in region 3 (from wind speed of 11m/s until the nominal power is achieved).

Figure 1.64 shows the resulting torque of the turbine, resulting in a nominal torque for the turbine of 12,700 Nm.

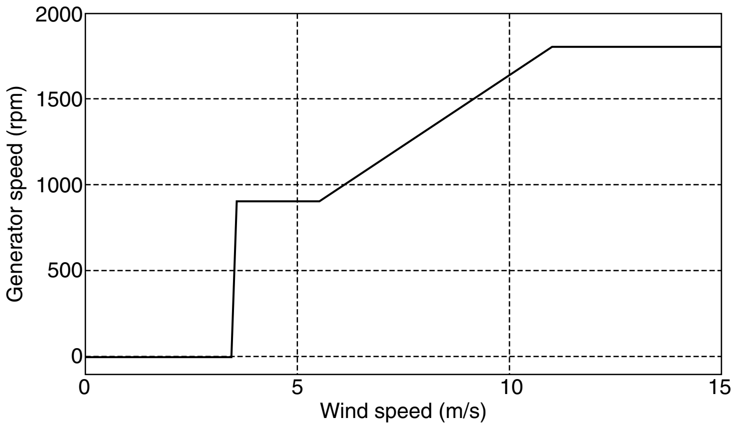


Figure 1.62 Wind turbine speed control.

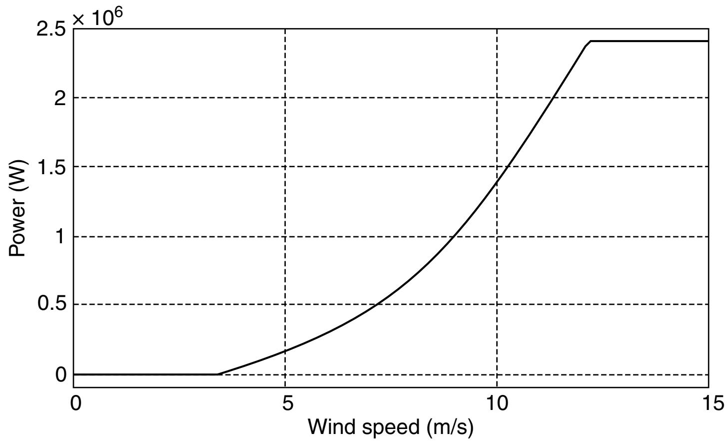


Figure 1.63 Wind turbine power versus wind speed.

Once the wind turbine control strategy has been defined, the power extraction as a function of the wind speed is represented in Figure 1.65.

The different control regions of the turbine are as follows:

1. Constant low speed region for wind speed in the range of 3.5–5.5 m/s.
2. Maximum power tracking region for wind speed in the range of 5.5–11 m/s.
3. Constant nominal speed region for wind speed in the range of 11–12 m/s.

For increasing wind speeds, the pitch control will work in order to diminish the aerodynamic performance of the turbine and limit the power extraction.

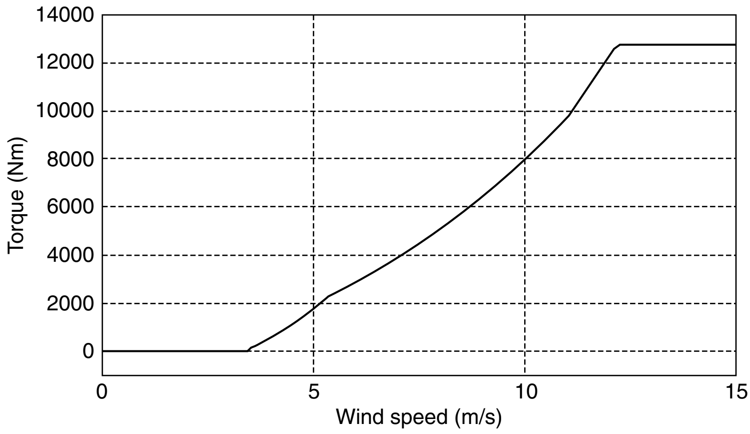


Figure 1.64 Wind turbine torque versus wind speed.

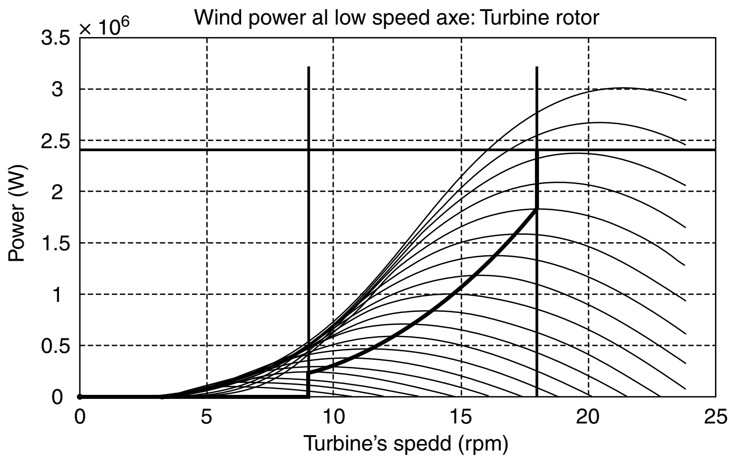


Figure 1.65 Wind turbine control strategy as a function of different wind speeds.

1.7.3 Steady State Generator and Power Converter Sizing

From the wind turbine power and speed, it's possible to calculate all the main electrical magnitudes of the wind turbine generator and its associated converters.

The starting point is the characteristic power as a function of the mechanical speed. To simplify Table 1.10, only some points of Figure 1.65 have been

TABLE 1.10 Operating Points for the Generator

Point	Generator Speed (rpm)	Electric Power Output (kW)	Power Factor	Line Voltage (V_{RMS})
1	**900**	**212**	**1.0**	**690**
2	**1013**	**326**	**1.0**	**690**
3	**1216**	**563**	**1.0**	**690**
4	**1397**	**852**	**1.0**	**690**
5	**1509**	**1075**	**1.0**	**690**
6	**1600**	**1280**	**1.0**	**690**
7	**1712**	**1580**	**1.0**	**690**
8	**1800**	**1831**	**1.0**	**690**
9	**1800**	**2400**	**1.0**	**690**
10	**1800**	**2400**	**1.0**	**621**
11	**1800**	**2400**	**1.0**	**759**
12	**1800**	**2400**	**0.9 inductive**	**690**
13	**1800**	**2400**	**0.95 capacitive**	**690**
14	**1944**	**2592**	**0.95 capacitive**	**690**
15	**1944**	**2592**	**0.9 inductive**	**690**

taken, and some others have been added in order to consider special operating points:

- Normal operation at nominal stator voltage and unity power factor is represented in points 1 to 9.
- Operation at rated power with voltage variation of ±10% from the nominal one are represented in points 10 and 11.
- Operation at rated power and nominal voltage with 0.9 power factor inductive and 0.95 capacitive is represented in points 12 and 13.
- Operation at rated voltage and overspeed of 8% is represented in points 14 and 15. This is a typical situation when the turbine is delivering the nominal power and the speed is controlled by means of a pitch control that has a low dynamic response, and it is normal to overpass the nominal speed (overspeed operation).
- Operating point 14 is a transient operating point; the control system maintains nominal torque while the generator speed rises from 1800 to 1944 rpm.
- The last point defines the operating capacity of the system overload control. The power factor under overload conditions must be inductive 0.9 or better.

The resulting operating table for the generator and converters is illustrated in Table 1.10.

As mentioned in preceding subsections, the machine can be magnetized from the stator or from the rotor; both solutions produce different sizing for the rotor and grid side converter. The next few paragraphs will show the results for the first case. All variables that can be seen in the following figures are represented as in-phase RMS values.

Figure 1.66 shows the evolution of electromagnetic torque and the generator slip. In the first graph you can see the generator electromagnetic torque, calculated from the mechanical generator and speed in Table 1.10. The torque increases as the wind speed increases and thus the speed of the turbine until it arrives at this nominal value.

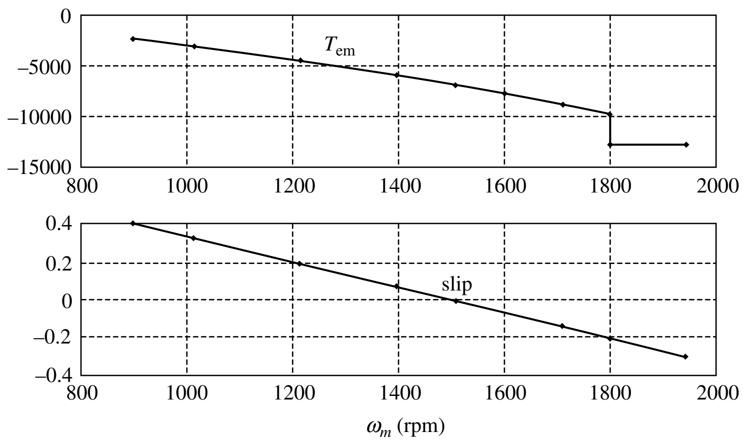


Figure 1.66 Wind turbine torque and sliding versus generator speed.

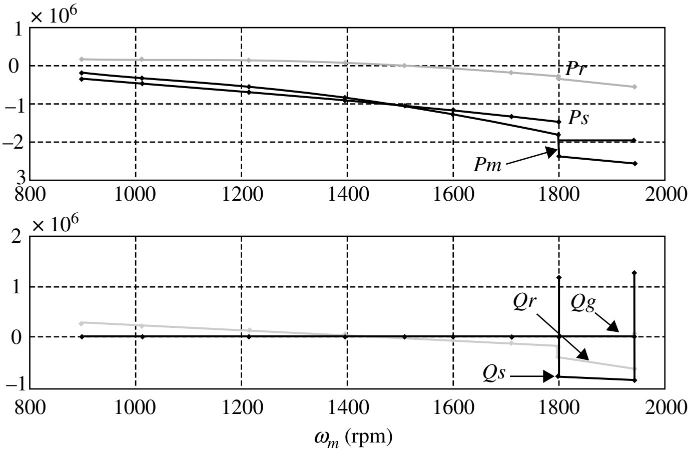


Figure 1.67 Active and reactive power for stator, rotor, and grid side converter.

In the second graph the motor slip can be seen; as the speed increases, a change from the hyper-to subsynchronous operating mode appears at synchronous speed (1500 rpm). If the motor mechanical speed is less than the synchronous speed, the engine is running in subsynchronous operating mode, while if it is greater it is running in hypersynchronous operating mode. In this particular case, the slip rises 40% at minimum speed and 30% at overload speed.

Figure 1.67 represents the mechanical power and the active and reactive power delivered by the rotor (RSC), the stator, and the grid side converter.

In the first graph we can see that the machine is running as a generator, the mechanical power and the stator active power are always negative; in subsynchronous operation, the rotor power is positive (the rotor is taking power from the grid). However, in the hypersynchronous mode, the stator and rotor are delivering active power to the grid (both take negative values).

In the second graph we can see the following:

- The power factor is unitary for the grid side converter (Q_g is zero).
- The stator reactive power (Q_s) is equal to zero while the RSC provides the reactive power necessary to magnetize the machine; the first few dots occur while the speed is lower than 1800 rpm. It is also seen that the rotor of the generator consumes reactive power in subsynchronous operation (as an inductor), while in hyper synchronous mode power returns (as a capacitor).
- However, when the power factor is different from one, the stator must provide the necessary reactive power to reach the required power factor (0.95 or 0.9). For capacitive ones the reactive power of the rotor must increase while for inductive ones it must decrease.

Figure 1.68 shows the rotor voltage and current; that is, the amplitude of the rotor side converter (RSC) voltage and current.

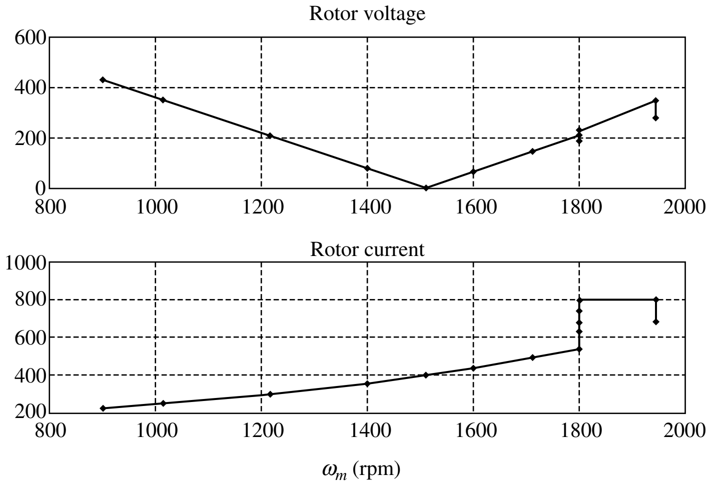


Figure 1.68 Rotor voltage and current.

In the first graph we can see that the magnitude of the rotor voltage is minimal near the synchronism speed, while at subsynchronous and hypersynchronous operation, the voltage increases. This voltage is proportional to the slip, but it's modified by the rotor resistance voltage. For a 690 V grid (line-to-line voltage), the phase voltage is 400 V; it can be appreciated that the rotor voltage is slightly lower at overspeed operation (around 350 V). For this example the relation between the rotor and stator voltages has been selected as 2.6.

In the second graph you can see that as the electromagnetic torque increases, the rotor current increases because the electromagnetic torque is controlled by the quadrature component of the rotor current.

Figure 1.69 plots the stator voltage and current.

The stator voltage is established in the initial table, but the plotted value corresponds to the calculated value once the magnetizing levels of the machine are derived. That's the reason for the slight difference from the 400 V indicated.

The stator current increases as the machine torque grows. The reason is that this current is directly related to the electromagnetic torque due to the fact that the machine is magnetized from the rotor side.

Figure 1.70 plots the grid side converter voltage and current.

When the power factor is unitary, the voltage of the grid side inverter is nearly equal to the grid voltage; only a low voltage difference is introduced by the filter.

The current evolution is proportional to the active power of the grid side converter as the power factor is one:

- In subsynchronous operation the rotor power is positive and decreasing to zero.
- At synchronous speed the rotor power is zero.
- In hypersynchronous operation the rotor power is increasing from zero to their maximum value at maximum speed. Note than maximum rotor current is higher than GSC one, due to the fact that generator is magnetized from rotor.

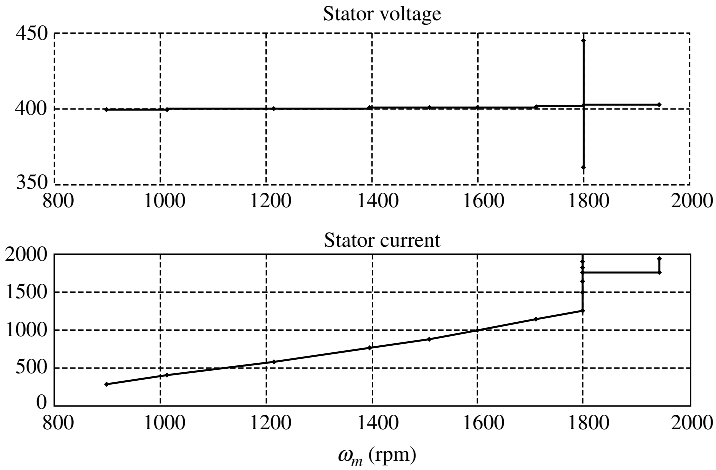


Figure 1.69 Stator voltage and current.

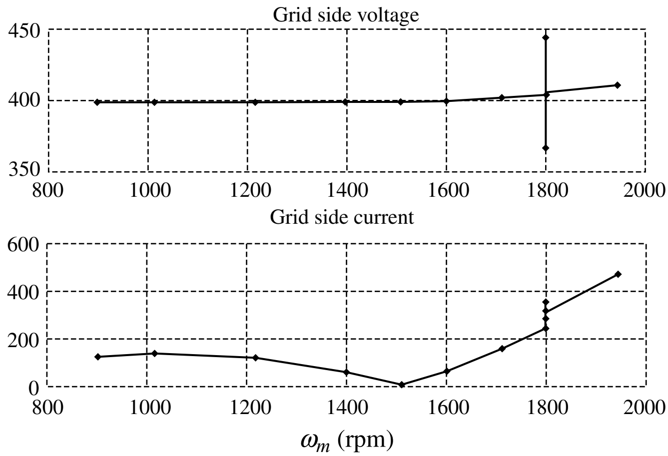


Figure 1.70 Grid side converter voltage and current.

1.8 INTRODUCTION TO THE NEXT CHAPTERS

Once this introductory chapter has immersed the reader in the most basic and general knowledge about doubly fed induction machine based wind turbines, the following chapters cover topics related to more technical electronic aspects.

Chapter 2 presents the back-to-back converter employed to supply the rotor of the wind turbine's generator, that is, the DFIM. It is possible to make the wind turbine operate at variable speed, delivering energy from the wind to the grid and meeting the grid code requirements. Thus, this chapter includes detailed and basic knowledge related to converter modeling and control, permitting one to understand the function of this element in the wind turbine system, as well as the supply capacities and limitations of these kind of converters.

Chapter 3 deals exclusively with the DFIM model at steady state operation. By inclusion of mathematical models and equivalent electric circuits, the basic operation of this machine is analyzed. Then an exhaustive evaluation of the machine is carried out, revealing the performance characteristics of this machine at steady state.

Chapter 4 studies the dynamic modeling of the DFIM. Thanks to this more general modeling approach, it is possible to study the machine in a more complete way. Dynamic behavior as well as the steady state regime can be analyzed in detail, enabling the reader to reach a reasonably high level of understanding of the machine.

Chapter 5 discusses the testing procedure of the DFIM. It includes practical information to characterize machines on the basis of off-line experimental tests, when they are performed during a realistic wind energy generation scenario.

Chapter 6 goes further with modeling, analyzing the dynamic behavior of the DFIM supplied by a disturbed voltage. Grid voltage dips can strongly deteriorate the performance of grid connected DFIM based wind turbines. Knowledge of how these types of turbines are affected is crucial, in order to be able to improve their behavior, by adopting the necessary corrective actions.

Chapters 7 and 8 present a wide range of control philosophies for machine DFIM wind turbines. These control techniques can be grouped into two major concepts, known as vector control (field oriented control, also a widely adopted notation) and direct control. Both control philosophies and several alternative variants are analyzed and evaluated in detail. Their adaptation to the wind energy generation environment is considered, by studying their capacity to solve faulty situations such as grid voltage dips and imbalances. These two chapters containing basic and advanced control concepts allow the reader to reach a high level of knowledge of DFIM based wind turbines.

Chapter 9 emphasizes analysis of the particular sensitivity of DFIM based wind turbines to grid voltage dips. Additional hardware elements are required, to handle the strong perturbations caused by voltage dips and meet the connection requirements of grid codes. Therefore, several philosophies based on different hardware elements are presented and discussed in this chapter.

Chapter 10 deals mainly with some particular needs of DFIM based wind turbines, when they operate with a reduced size of back-to-back converter (cost-effective solution). The specific start-up procedure of these kinds of wind turbines is analyzed, accompanied by several illustrative examples.

Chapter 11 ends the comprehensive study of DFIM based wind turbines, extending the analysis to a slightly different scenario: stand-alone operation. Thus, this concept of wind turbines not connected to the grid, but supplying energy directly to one or several loads, can be studied with most of the knowledge acquired in the preceding chapters. However, there is also new and important modeling and control aspects covered in this chapter, necessary to understand the stand-alone generation system and its special traits.

Finally, Chapter 12 discusses the future challenges and technological tendencies of wind turbines in general, focusing not only on DFIM based ones, but also looking at different and innovative wind turbine concepts and their supporting technology.

BIBLIOGRAPHY

1. J. L. R. Amenedo, et al. *Sistemas eólicos de producción de energía eléctrica*. Rueda, 2003 (in Spanish).
2. I. Munteanu, I. U. Bratcu, N. A. Cutululis, and E. Ceanga, *Optimal Control of Wind energy Systems*. Springer, 2008.
3. M. Stiebler, *Wind Energy Systems for Electric Power Generation*. Springer, 2008.
4. E. Hau, *Wind Turbines: Fundamentals, Technologies, Applications, Economics*. Springer, 2000.
5. F Bianchi, Wind turbine control systems: principles, modelling & gain scheduling design, Springer, 2006.
6. M. P. Kazmierkowski, R. Krishnan, and F. Blaagberg, *Control in Power Electronics Selected Problems*. Academic Press, 2002.
7. F. Blaagberg and Z. Chen, *Power Electronics for Modern Wind Turbines*. Morgan & Claypool Publishers, 2006.
8. I. Boldea, *Variable Speed Generators*. CRC Press/Taylor & Francis, 2006.
9. I. Boldea, *Synchronous Generators*. CRC Press/Taylor & Francis, 2005.
10. T. Ackerman, *Wind Power in Power Systems*. Wiley, 2005.
11. H. Camblong,"Minimización del impacto de las perturbaciones de origen eólico sobre la producción de electricidad en aerogeneradores de velocidad variable." Ph.D. Thesis from University of Mondragon, 2003 (in French).
12. Math Bollen et al. "Voltage Dip Immunity of Equipment and Installations", CIGRE Brochure 412, 2010.
13. J.A. Martinez-Velasco et al. "Voltage dip Evaluation and Prediction Tools", CIGRE Brochure 372, 2009.
14. M. Santos,"Aportaciones al control centralizado de un parque eólico." Ph.D. Thesis from University of Mondragon, 2007 (in Spanish).
15. Catalogs from wind turbine manufacturers on the Internet.