2

Wind Energy Conversion Systems

2.1 Wind Energy Resource

The characteristics of the wind energy resource are important in different aspects regarding wind energy exploitation. The first step in every wind energy project is the identification of suitable sites and prediction of the economic viability of the wind project.

The energy available in the wind varies as the cube of wind speed. Wind is highly variable, both in space and in time. The importance of this variability becomes critical since it is amplified by the cubic relation of the available energy.

The variability in time of the wind can be divided into three distinct time scales (Burton *et al.* 2001). First, the large time scale variability describes the variations of the amount of wind from one year to another, or even over periods of decades or more. The second is the medium time scale, covering periods up to a year. These seasonal variations of the wind are much more predictable. Therefore, the suitability of a given site, in terms of wind variability, is usually assessed in terms of monthly variations, covering one year. The assessment is done by statistical analysis of long time (several years) measurements of wind speed. Finally, the short term time scale variability, covering time scales of minutes to seconds, called turbulence, is also well known and it presents interest in the wind turbine design process.

The medium time scale wind variability, further called monthly variation, is typically characterized in terms of probability distribution over one year. The Weibull distribution is commonly used to fit the wind speed frequency distribution (Burton *et al.* 2001).

The Weibull distribution is a two-parameter function widely used in statistical analysis and is given by Seguro and Lambert (2000)

$$P\left(v < v_i < v + \mathrm{d}v\right) = P\left(v > 0\right)\left(\frac{k}{c}\right)\left(\frac{v_i}{c}\right)^{k-1} \exp\left[-\left(\frac{v_i}{c}\right)^k\right], \qquad (2.1)$$

where c is the Weibull *scale parameter*, with units equal to the wind speed units, k is the unitless Weibull *shape parameter*, v is the wind speed, v_i is a particular wind speed, dv is the wind speed increment, $P(v < v_i < v + dv)$ is the probability that the wind speed is between v and $v + dv$ and $P(v > 0)$ is the probability that the wind speed exceeds zero.

The cumulative distribution function is given by

$$P(v < v_i) = P(v \geq 0)\left\{1 - \exp\left[-\left(\frac{v_i}{c}\right)^k\right]\right\} \tag{2.2}$$

The two Weibull parameters and the average wind speed are related by

$$\overline{v} = c \cdot \Gamma\left(1 + \frac{1}{k}\right), \tag{2.3}$$

where $\overline{v}$ is the average wind speed and $\Gamma(\cdot)$ is the complete gamma function.

A special case is when $k = 2$, the Weibull distribution becoming a Rayleigh distribution. In this case, the factor $\Gamma(1 + 1/k)$ has the value $\sqrt{\pi}/2 = 0.8862$. The influence of the k parameter on the probability density function is presented in Figure 2.1, with the scale factor kept constant. Simply speaking, the variation of the hourly mean speed around the annual mean is small as k is higher, as depicted in Figure 2.1.
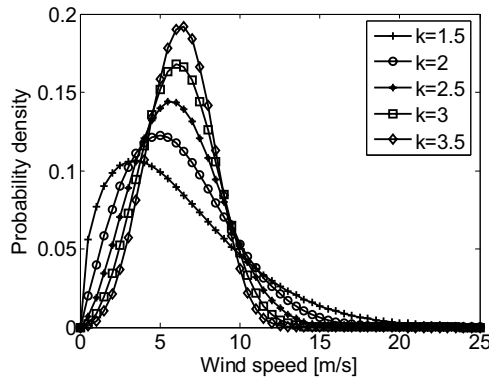

Figure 2.1. Weibull distributions as a function of k (constant c)

The scale factor c shows how "windy" a location is or, in other words, how high the annual mean speed is. The influence of the scale factor on the probability density function is presented in Figure 2.2, with the shape factor kept constant.

The estimation of the Weibull distribution parameters – c and k – is usually done with two methods.

One method for calculating parameters c and k is starting from Equation 2.2 and taking the natural logarithm of both sides:
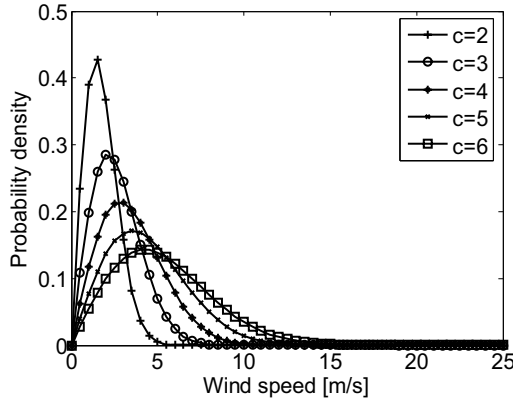
Figure 2.2. Weibull distributions as a function of c (constant k)

$$\ln\left[-\ln\left(1-P\left(v_i\right)\right)\right] = k\left(\ln v_i - \ln c\right) \tag{2.4}$$

Using the notation

$$y = \ln\left[-\ln\left(1-P\left(v_i\right)\right)\right]; \quad u = \ln v_i; \quad k_0 - \ln c, \tag{2.5}$$

Equation 2.4 becomes:

$$y = ku + k_0, \tag{2.6}$$

where k and k_0 are calculated using linear regression of the cumulative distribution function.

Finally, the scale factor c is calculated:

$$c = \exp\left(-\frac{k}{k_0}\right) \tag{2.7}$$

The second method, the maximum likelihood method (Seguro and Lambert 2000), uses the time-series wind data instead of the cumulative distribution function. The two parameters are calculated respectively with

$$k = \left(\frac{\sum\limits_{i=1}^{n} v_i^k \ln\left(v_i\right)}{\sum\limits_{i=1}^{n} v_i^k} - \frac{\sum\limits_{i=1}^{n} \ln\left(v_i\right)}{n}\right)^{-1}, \tag{2.8}$$

$$c = \left(\frac{1}{n}\sum\limits_{i=1}^{n} v_i^k\right)^{1/k}, \tag{2.9}$$

where v_i is the wind speed in time step i and n is the number of nonzero wind speed data points. Since Equation 2.8 must be solved using an iterative procedure, it is suitable to start with the initial guess $k = 2$.

Knowing the annual variation of the wind on a given site is important, but it is not sufficient for assessing the economic viability of the wind turbine installation. For that purpose, the level of wind resource is often defined in terms of the wind-power-density value, expressed in watts per square meter (W/m²). This value incorporates the combined effects of the wind speed frequency distribution and the dependence on the air density and the cube of the wind speed.

The power of the wind over an area A is given by

$$P_t = \frac{1}{2}\rho A v^3 , \tag{2.10}$$

where ρ is the air density.

Thus, the *mean wind power density*, over an area A, can be calculated with

$$\frac{P_{t_{mean}}}{A} = \frac{1}{2}\rho \langle v^3 \rangle , \tag{2.11}$$

where the mean value of the cube of the wind speed is

$$\langle v^3 \rangle = \int_0^\infty v^3 p(v) \, dv , \tag{2.12}$$

with $p(v)$ being the probability density function.

After integrating Equation 2.12 and using the Weibull function

$$\langle v^3 \rangle = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)} \langle v^3 \rangle , \tag{2.13}$$

where

$$e(k) = \frac{\Gamma(1+3/k)}{\Gamma^3(1+1/k)} \tag{2.14}$$

is called *energy pattern factor* (EFP – Jamil 1990). Using Equations 2.13 and 2.14, Equation 2.11 becomes

$$\frac{P_{t_{mean}}}{A} = \frac{1}{2}\rho \cdot e(k) \cdot \langle v^3 \rangle \tag{2.15}$$

Thus, the mean wind power density is proportional to the EFP and the cube of the wind speed.

The evolution of the mean wind power density as a function of the Weibull distribution function parameters, c and k, is presented in Figure 2.3.
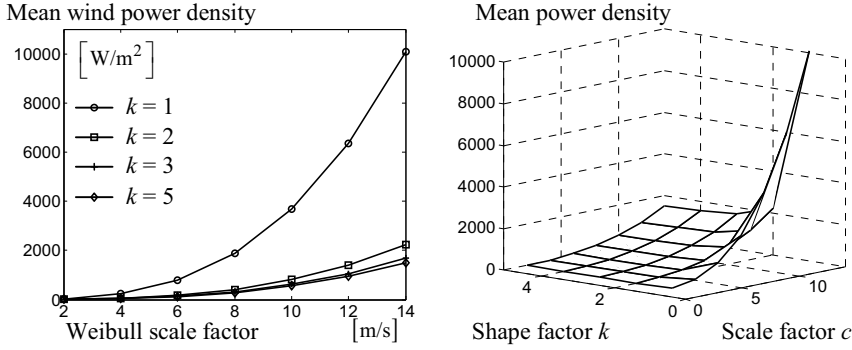
Figure 2.3. Mean wind power density

When the power conversion efficiency (power coefficient; see Section 2.3.1) is constant, the wind speed, denoted v_{opt}, for which the maximum energy is obtained from the condition

$$\frac{\mathrm{d}}{\mathrm{d}v}\left[v^3 p(v)\right] = 0, \tag{2.16}$$

which, using the Weibull distribution, results in (Jamil 1990)

$$v_{opt} = c \cdot \left(1 + 2/k\right)^{1/k} \tag{2.17}$$

On the other hand, the *most probable wind speed*, denoted v^* for the given site, can be deduced from the condition

$$\frac{\mathrm{d}}{\mathrm{d}v}[v \cdot p(v)] = 0 \tag{2.18}$$

as

$$v^* = c \cdot \left(1 - 1/k\right)^{1/k} \tag{2.19}$$

The pair $\left(v_{opt}, v^*\right)$ calculated for a given site by using the Weibull distribution, can offer useful *qualitative* information about the wind energy resource.

In conclusion, the Weibull distribution gives information about the annual variation of the wind speed as well as on the mean power density of a given site. A good case scenario is having a site which can be characterized by a Weibull distribution with a high scale factor (*c*) and a reduced shape factor (*k*).

2.2 WECS Technology

A WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows.

The extraction device, named *wind turbine rotor* turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power.

Several wind turbine concepts have been proposed over the years. A historical survey of wind turbine technology is beyond the scope here, but someone interested can find that in Ackermann (2005). There are two basic configurations, namely *vertical axis wind turbines* (VAWT) and, *horizontal axis wind turbines* (HAWT). Today, the vast majority of manufactured wind turbines are horizontal axis, with either two or three blades.

HAWT is comprised of the tower and the nacelle, mounted on the top of the tower (Figure 2.4). Except for the energy conversion chain elements, the nacelle contains some control subsystems and some auxiliary elements (*e.g.*, cooling and braking systems, *etc.*).
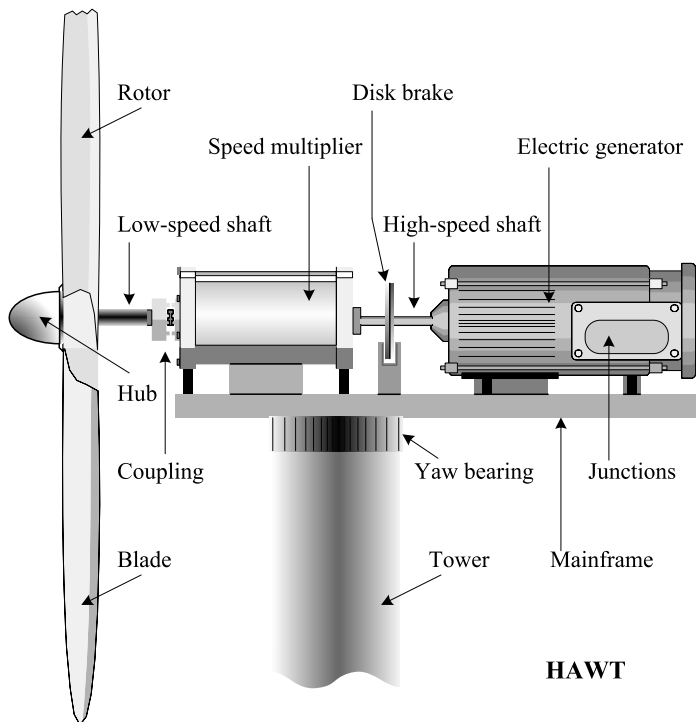
Figure 2.4. Main elements of a two-bladed HAWT

The energy conversion chain is organised into four subsystems:
− aerodynamic subsystem, consisting mainly of the turbine rotor, which is composed of blades, and turbine hub, which is the support for blades;
− drive train, generally composed of: low-speed shaft – coupled with the turbine hub, speed multiplier and high-speed shaft – driving the electrical generator;
− electromagnetic subsystem, consisting mainly of the electric generator;
− electric subsystem, including the elements for grid connection and local grid.

All wind turbines have a mechanism that moves the nacelle such that the blades are perpendicular to the wind direction. This mechanism could be a tail vane (small wind turbines) or an electric yaw device (medium and large wind turbines).

Concerning the power conversion chain, it involves naturally some loss of power. Because of the nonzero wind velocity behind the wind turbine rotor one can easily understand that its efficiency is less than unity. Also, depending on the operating regime, both the motion transmission and the electrical power generation involve losses by friction and by Joule effect respectively. Being directly coupled one with the other, the energy conversion chain elements dynamically interact, mutually influencing their operation.

2.3   Wind Turbine Aerodynamics

The wind turbine rotor interacts with the wind stream, resulting in a behaviour named aerodynamics, which greatly depends on the blade profile.

2.3.1   Actuator Disc Concept

The analysis of the aerodynamic behaviour of a wind turbine can be done, in a generic manner, by considering the extraction process (Burton *et al.* 2001).

Consider an actuator disc (Figure 2.5) and an air mass passing across, creating a stream-tube.
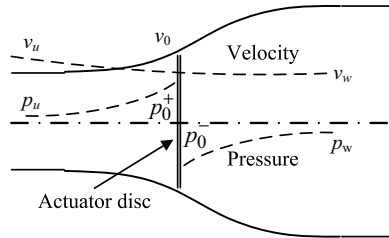

Figure 2.5. Energy extracting actuator disc

The conditions (velocity and pressure) in front of the actuator disc are denoted with subscript u, the ones at the disc are denoted with 0 and, finally, the conditions behind the disc are denoted with w.

The momentum $H = m(v_u - v_w)$ transmitted to the disc by the air mass m passing through the disc with cross-section A produces a force, expressed as

$$T = \frac{\Delta H}{\Delta t} = \frac{\Delta m(v_u - v_w)}{\Delta t} = \frac{\rho A v_0 \Delta t(v_u - v_w)}{\Delta t} = \rho A v_0(v_u - v_w) \qquad (2.20)$$

or

$$T = A\left(p_0^+ - p_0^-\right) \qquad (2.21)$$

Using Bernoulli's equation, the pressure difference is

$$p_0^+ - p_0^- = \frac{1}{2}\rho\left(v_u^2 - v_w^2\right) \tag{2.22}$$

and, replacing Equation 2.12 in Equation 2.21, results

$$T = \frac{1}{2}\rho A\left(v_u^2 - v_w^2\right) \tag{2.23}$$

From Equations 2.20 and 2.23 one gets

$$v_0 = \frac{1}{2}(v_u + v_w) \Rightarrow v_u - v_w = 2(v_u - v_0) \tag{2.24}$$

The kinetic energy of an air mass travelling with a speed v is

$$E_k = \frac{1}{2}mv^2, \tag{2.25}$$

where m is the air mass that passes the disc in a unit length of time, $e.g.$, $m = \rho A v_0$; then the power extracted by the disc is

$$P = \frac{1}{2}\rho A v_0\left(v_u^2 - v_w^2\right) \tag{2.26}$$

or

$$P = \frac{1}{2}\rho A v^3 4a(1-a)^2, \tag{2.27}$$

with $a = 1 - v_0/v_u$.

The *power coefficient*, denoting the power extraction efficiency, is defined as

$$C_p = \frac{P}{P_t} = \frac{0.5 \cdot \rho A v^3 \cdot 4a(1-a)^2}{0.5 \cdot \rho A v^3} \tag{2.28}$$

Therefore

$$C_p = 4a(1-a)^2 \tag{2.29}$$

The maximum value of C_p occurs for $a = 1/3$ and is $C_{p\max} = 0.59$, known as the Betz limit (Betz 1926) and represents the maximum power extraction efficiency of a wind turbine.

2.3.2 Wind Turbine Performance

A wind turbine is a power extracting device. Thus, the performance of a wind turbine is primarily characterized by the manner in which the main indicator – power – varies with wind speed. Besides that, other indicators like torque and

thrust are important when the performances of a wind turbine are assessed.

The generally accepted way to characterize the performances of a wind turbine is by expressing them by means of non-dimensional characteristic performance curves (Burton *et al.* 2001).

The *tip speed ratio* of a wind turbine is a variable expressing the ratio between the peripheral blade speed and the wind speed. It is denoted by λ and computed as

$$\lambda = \frac{R \cdot \Omega_l}{v} \, , \tag{2.30}$$

where R is the blade length, Ω_l is the rotor speed (the low-speed shaft rotational speed) and v is the wind speed. The tip speed ratio is a key variable in wind turbine control and will be extensively used in the rest of the book. It characterizes the power conversion efficiency and it is also used to define the acoustic noise levels.

The power coefficient, C_p, describes the power extraction efficiency of a wind turbine. The aerodynamic performance of a wind turbine is usually characterized by the variation of the non-dimensional C_p *vs.* λ curve. Based upon Equation 2.28, the power extracted by a wind turbine whose blade length is R is expressed as

$$P_{wt} = \frac{1}{2} \cdot \rho \cdot \pi R^2 \cdot v^3 \cdot C_p(\lambda) \tag{2.31}$$

Therefore, the $C_p(\lambda)$ performance curve gives information about the power efficiency of a wind turbine. Figure 2.6 presents this curve for a typical two-bladed wind turbine. One can see that the conversion efficiency is lower than the Betz limit (0.59), which is normal since the Betz limit assumes perfect blade design. The theoretical reasons for such an allure of the $C_p - \lambda$ curve lie in the aerodynamic blade theory; some justifications are given in Chapter 3.
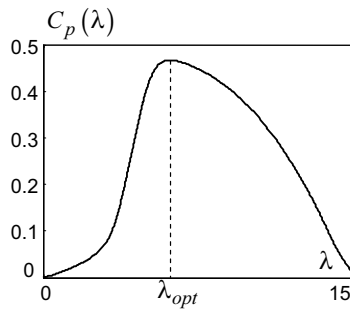

Figure 2.6. $C_p(\lambda)$ performance curve

For control purposes, useful information arising from the $C_p - \lambda$ performance curve is the fact that the power conversion efficiency has a well determined maximum for a specific tip speed ratio, denoted by λ_{opt}.

From Equation 2.31, one finds that the captured power characteristic, $P_{wt} - \Omega_l$, at constant wind velocity, has the same allure as in Figure 2.6. This means that the turbine rotor outputs non-negligible mechanical power if rotating in an intermediary speed range, which depends on the wind speed.

The *torque coefficient*, denoted by C_Γ, characterizes the rotor output (wind) torque, Γ_{wt}. It is derived from the power coefficient simply by dividing it by the tip speed ratio:

$$C_\Gamma(\lambda) = \frac{C_p(\lambda)}{\lambda} \qquad (2.32)$$

The torque coefficient *vs.* the tip speed ratio curve, compared to the power coefficient curve, does not give any additional information about the wind turbine performance but it is useful for torque assessment and for control purposes (*e.g.*, assisted start-up process). $C_\Gamma(\lambda)$ gives the rotor mechanical characteristic allure, $\Gamma_{wt} - \Omega_l$, for a fixed wind velocity.

The rotor has a finite number of blades, usually two or three. This number has an impact on the supporting structure; thus, two-bladed wind turbines have a lighter tower top and can be built with a lighter support structure, reducing costs (Gasch and Twelve 2002). On the other hand, three-bladed wind turbines have a balanced rotor inertia and are therefore easier to handle (Thresher *et al.* 1998). Their speed range is smaller than that of the two-bladed wind turbines but the peak output torque is larger.

The wind turbine operates, with different dynamics, from the *cut-in wind speed* (usually 3–4 m/s, for modern wind turbines) to the *cut-out wind speed* (around 25 m/s), as shown in Figure 2.7. The output power evolves according to Equation 2.31 (proportionally with the wind speed cubed), until it reaches the wind turbine rated power. This happens at *rated wind velocity*, which splits the wind turbine operation range in two: below rated (also called partial load region) and full load region, where the captured power must be limited to rated.
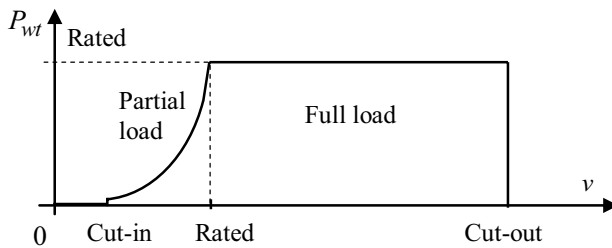

Figure 2.7. Output power *vs.* wind speed characteristic

Therefore, for safety reasons, above the rated wind speed the captured power is prevented from increasing further by using an aerodynamic power control

subsystem. This modifies the aerodynamic properties of the rotor by severely decreasing its power coefficient, C_p. To this end, multiple power control solutions are usually employed in WECS. Some of them are passive (*e.g.*, stall control), using blade profile properties; others are active (*e.g.*, pitch control), changing blades position relative to the rotating plane. As further detailed in Section 4.2, the blades can be turned into the wind (upwind) or away from the wind (downwind). Some control solutions aim at turning the entire rotor away from the wind in order to diminish the aerodynamic efficiency.

2.4   Drive Train

The rotational motion of the turbine rotor is transmitted to the electrical generator by means of a mechanical transmission called drive train. Its structure strongly depends on each particular WECS technology. For example, the turbines employing multipole synchronous generators use the direct drive transmission (the generator and the rotor are coupled on the same shaft). But most of the systems (*e.g.*, those employing induction machines) employ speed multipliers (*i.e.*, gearboxes with a certain multiplying ratio) for the mechanical power transmission. Therefore, the electrical machine will experience an increased rotational speed and a reduced electromagnetic torque.

   The speed multiplier dissociates the transmission in two parts: the low-speed shaft (LSS) on which the rotor is coupled and the high-speed shaft (HSS) relied on by the electrical generator.

   The coupling between the two shafts can be either rigid or flexible. In the second case, the LSS and HSS have different instantaneous rotational speeds. This kind of decoupling is used for damping the mechanical efforts generated either by wind speed or by electromagnetic torque variations. The result is a "compliant" and more reliable transmission, which is less affected by load transients and therefore by mechanical fatigue.

   The technology used for speed multiplier construction is out of interest in this book, but one must note that the multiplying ratio depends mostly on the rated power and can generally involve more than one stage (*e.g.*, based on spur or helical gears). The speed multiplier is critical equipment, severely affecting the WECS in terms of weight and reliability, and therefore overall efficiency.

2.5   Power Generation System

The electrical power generation structure contains both electromagnetic and electrical subsystems. Besides the electrical generator and power electronics converter it generally contains an electrical transformer to ensure the grid voltage compatibility. However, its configuration depends on the electrical machine type and on its grid interface (Heier 2006).

2.5.1   Fixed-speed WECS

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), softstarter and capacitor bank and they are connected directly to the grid, as shown in Figure 2.8. This WECS configuration is also known as the "*Danish concept*" because it was developed and widely used in Denmark (Hansen and Hansen 2007).
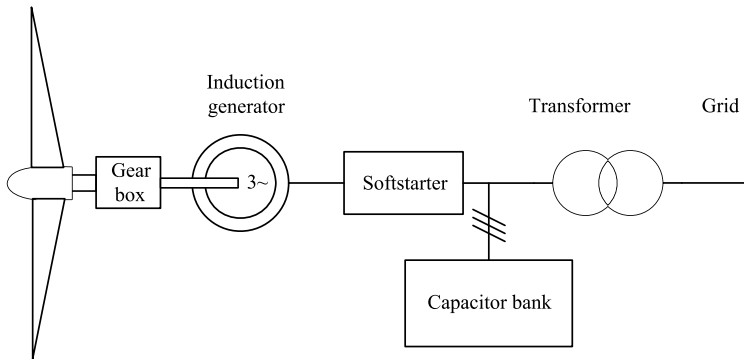

Figure 2.8. General structure of a fixed-speed WECS

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode (or in the over-synchronous regime – Bose 2001). As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important.

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed (Ackermann 2005). That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG-based WECS are equipped with capacitor banks. The softstarter's role is to smooth the inrush currents during the grid connection (Iov 2003).

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some

fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).

Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

An evolution of the fixed-speed SCIG-based WECS are the limited variable-speed WECS. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance; see Figure 2.9. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% over the synchronous speed.
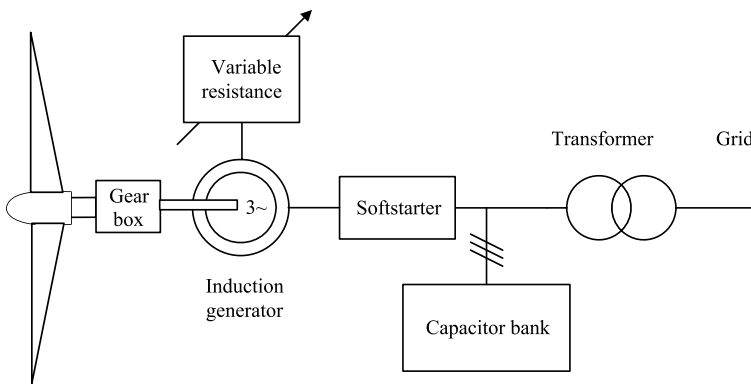

Figure 2.9. General structure of a limited variable-speed WECS

2.5.2 Variable-speed WECS

Variable-speed wind turbines are currently the most used WECS. The variable-speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid.

The doubly-fed-induction-generator (DFIG)-based WECS (Figure 2.10), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry.
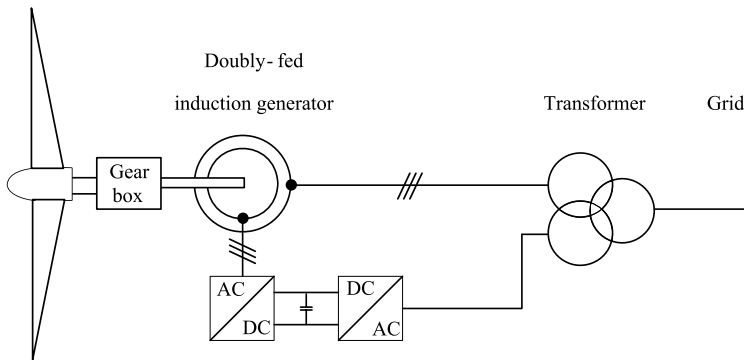
Figure 2.10. General structure of an improved variable-speed WECS

The DFIG is a WRIG with the stator windings connected directly to the three-phase, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter (Akhmatov 2003; Ackermann 2005). Thus, the term "doubly-fed" comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behaviour being governed by the power electronics converter and its controllers.

The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor.

The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over-synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip (Lund *et al.* 2007).

The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of ±40% around the synchronous speed is used (Akhmatov 2003).

DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

Full variable-speed WECS are very flexible in terms of which type of generator is used. As presented in Figure 2.11, it can be equipped with either an induction (SCIG) or a synchronous generator. The synchronous generator can be either a wound-rotor synchronous generator (WRSG) or a permanent-magnet synchronous generator (PMSG), the latter being the one mostly used by the wind turbine industry. The back-to-back power inverter is rated to the generator power and its operation is similar to that in DFIG-based WECS. Its rotor-side ensures the

rotational speed being adjusted within a large range, whereas its grid-side transfers the active power to the grid and attempts to cancel the reactive power consumption. This latter feature is important especially in the case of SCIG-equipped WECS.
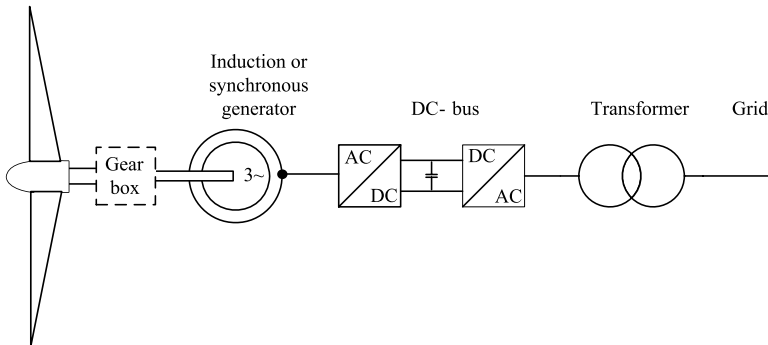

Figure 2.11. General structure of a full variable-speed WECS

The PMSG is considered, in many research articles, a good option to be used in WECS, due to its self-excitation property, which allows operation at high power factor and efficiency (Alatalo 1996).

PMSG does not require energy supply for excitation, as it is supplied by the permanent magnets. The stator of a PMSG is wound and the rotor has a permanent-magnet pole system. The salient pole of PMSG operates at low speeds, and thus the gearbox (Figure 2.11) can be removed. This is a big advantage of PMSG-based WECS as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multipole PMSG with large diameter.

The synchronous nature of PMSG may cause problems during start-up, synchronization and voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature and they can loose their magnetic properties if exposed to high temperatures (Ackermann 2005).

2.6   Wind Turbine Generators in Hybrid Power Systems

Two main types of hybrid generation structures embedding WECS can be found in insulated grid utilities (Cutululis 2005). Typically, the generators feed energy into a common AC bus, as Figure 2.12 depicts (Manwell *et al.* 1993; Jeffries *et al.* 1996; Tomilson *et al.* 1998; Papathanassiou and Papadopoulos 2001; Bialasiewicz and Muljadi 2002; Baring-Gould *et al.* 2004; Cutululis *et al.* 2006a). An alternative solution envisages the power sources coupling on a common DC-bus, the electrical power being further transformed by an inverter in order to feed AC loads (Figure 2.13 – Borowy and Salameh 1997; De Broe *et al.* 1999; Ruin and Carlson 2000; Vechiu *et al.* 2004; Cutululis *et al.* 2006b; El Mokadem *et al.* 2003).

In Figure 2.12 the example of two sources is taken, namely a wind turbine and a diesel generator feed common AC bus. This structure presents two kinds of energy storage. The first, envisaging the long-term electro-chemical energy

storage, is realised by the accumulator battery. The second, acting in the short-term, stores kinetic energy by means of a high-speed flywheel. These two storage elements allow bidirectional power flow.
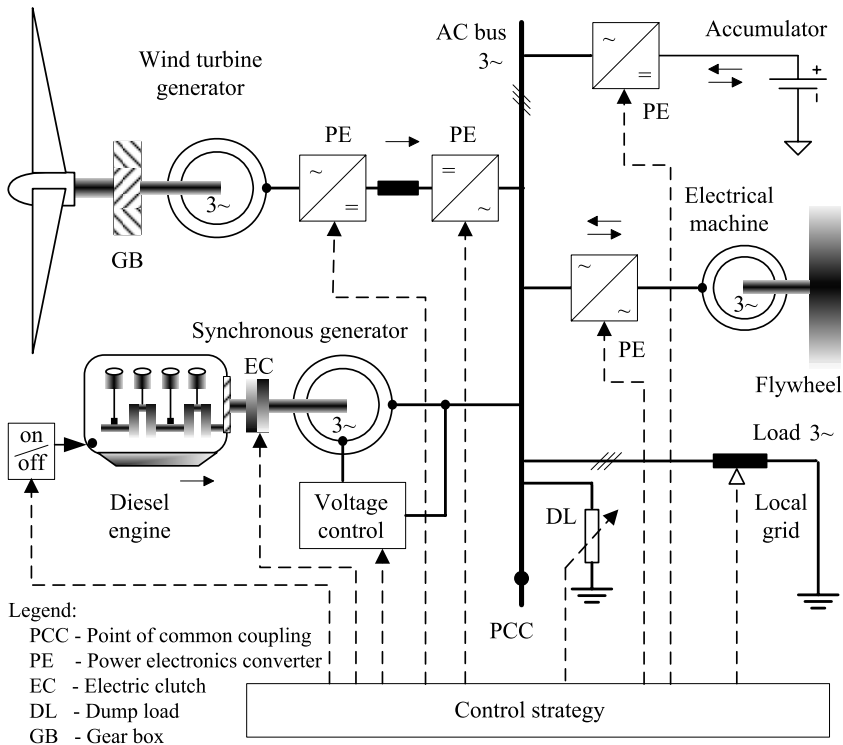

Figure 2.12. AC-coupled hybrid generation system

Here are the guidelines of how the system in Figure 2.12 operates. When the wind speed is low, WECS generates less power than the load (local utilities) needs, and the diesel engine is turned on, compensating the active power imbalance. When the wind velocity is sufficiently high, the diesel engine is shut down, and the synchronous generator acts as reactive power compensator. Concerning the flywheel, it accumulates kinetic energy when the high winds induce energy in excess. In case of short wind gaps the flywheel delivers power to the AC bus. The accumulator represents the emergency solution.

Concerning the DC-connected generation system, an example is given in Figure 2.13. In this configuration some short-term energy storage units can be supplementary introduced (*e.g.*, the flywheel device driven by a switched-reluctance machine used by El Mokadem *et al.* 2006).

Figure 2.13 is self-explanatory; each moment the power fed into the DC-bus is the result of the wind turbine, diesel-generator, photovoltaic array and accumulator power contributions, depending on their operating regimes.

The control objective aims at the AC load being continuously supplied with

energy. Depending on the operating regime the turbine can be controlled either for maximum power point tracking or for power limiting. The reliability requirements are important in these structures. The control of hybrid generation structure envisages the entire system; its management and supervision are beyond the scope of this book.
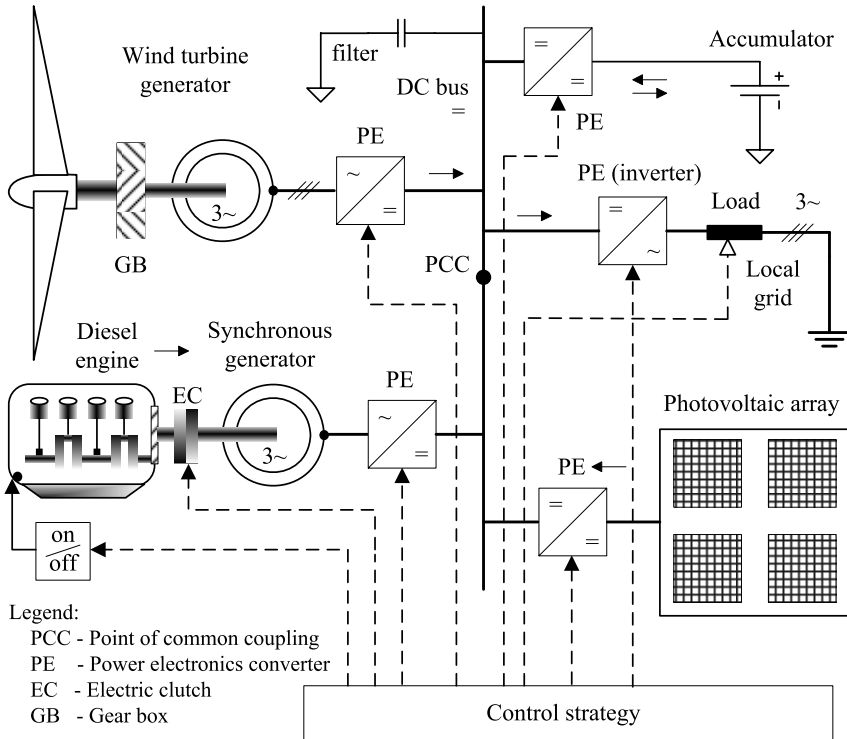

Figure 2.13. DC-coupled hybrid generation system

2.7   Control Objectives

Control plays an ever increasing role in modern WECS. There are numerous research articles dedicated to WECS control, all of them having starting from the idea that control can and does significantly improve all aspects of WECS.

In any process, control has two main objectives: protection and optimization of operation. Furthermore, when applied to WECS, control becomes more important, in all aspects, as the main characteristic of WECS is that they have to cope with the highly variable, intermittent and unpredictable nature of the wind.

To this end, as previously mentioned, all WECS have some sort of power control. The passive-stall wind turbines manage to limit the aerodynamic power, for protection reasons, without any active controllers. This approach is simple and offers hardware robustness, but can lead to unacceptable levels of mechanical loads

(Burton *et al.* 2001). Thus, control in that sense has as its only objective the protection of wind turbines.

Active stall implies that WECS are equipped with several additional hardware components: electromechanical or hydraulic actuators used to move the blades (or parts of them), sensors and controllers. All of these add complexity and increase the operation and maintenance costs but they also allow one to extend the control objectives to increase the power capture, thus optimizing the WECS operation.

Fixed-speed WECS, with either passive or active stall, dominated the wind power industry for a long time. Their main drawback is their rigidity, as the fixed generator speed does not offer any control flexibility. This disappears with the use of DFIG-based WECS and, later, with the use of full scale power converter WECS. Variable-speed operation became possible by incorporating power electronics converters.

Variable-speed WECS control system generally includes three main control subsystems:
− aerodynamic power control, through pitch control;
− variable-speed operation and energy capture maximization, by means of generator control;
− grid power transfer control, through the power electronics converter.

Furthermore, the specific objectives of each control subsystem vary in accordance to the operating regime (see Figure 2.7).

When the wind speed is between the cut-in and the rated speed (partial load regime), the pitch control system is typically inactive, with two exceptions: when the pitch system is used to assist the start-up process, as the two- or three-bladed wind turbines have a relatively low starting torque, and when the rotational speed is limited by pitch control as the wind speed approaches the rated value. The pitch control system is active when the wind speed exceeds the rated wind speed. Its objective is to limit the aerodynamic power to the rated one and, when the wind speed reaches the cut-out value, to stop the wind turbine. Thus, the pitch control system deals mainly with alleviating the mechanical loads on the wind turbine structure.

During the partial load regime, the generator control is the only active control and aims at maximizing the energy captured from the wind and/or at limiting the rotational speed at rated. This is possible by continuously accelerating or decelerating the generator speed in such a way that the optimum tip speed ratio is tracked. At rated wind speed, the generator control limits the generator speed. Thus, the generator control deals mainly with the power conversion efficiency optimization. Sometimes this means that the generator torque varies along with the wind speed and, in some conditions, can induce supplementary mechanical stress to the drive train. Consequently, maximizing the power conversion efficiency through generator control should be done, bearing in mind the possibility that supplementary loads are induced to the mechanical structure.

Finally, the power electronics converter control ensures that the strict power quality standards (frequency, power factor, harmonics, flicker, *etc.*) are met. Recently, the increasing requirements for WECS to remain connected and to provide active grid support have added control objectives for the power electronics converters. In the case of a grid fault, the WECS should remain connected; thus

they should cope with sudden and important loads, and even assist the grid in voltage or frequency control (Akhmatov 2003; Ackermann 2005; Sørensen *et al.* 2005). Thus, the power electronics converter control deals mainly with power quality standards.

The role and objectives of WECS control, as presented above, can be summarized as follows (De La Salle *et al.* 1990; Leithead *et al.* 1991):

− starting on the WECS at the cut-in speed, stopping it at the cut-out speed and switching controllers corresponding to the specific operating conditions;
− controlling the aerodynamic power and the rotational speed above rated wind speed;
− maximising the wind harvested power in partial load zone, with respect to the speed and captured power constraints;
− alleviating the variable loads, in order to guarantee a certain level of resilience of the mechanical parts, in all operating regimes;
− guaranteeing a desired response to isolated wind gusts;
− transferring the electrical power to the grid at an imposed level, for wide range of wind velocities;
− meeting strict power quality standards (power factor, harmonics, flicker, *etc.*);
− protecting the WECS and, at the same time, offer active grid support during grid faults.

The list is not exhaustive; several other control objectives, deriving from those listed above, can be formulated. Variable-speed WECS is a highly nonlinear time-variant system excited by stochastic inputs which significantly affect its reliability and leads to non-negligible variations in the dynamic behaviour of the system over its operating range. This is the reason why the control of variable-speed wind turbines is still in the phase of searching technical solutions suitable to be widely implemented in the wind turbine industry.