# Chapter 2

# Wind Energy

The aim of this chapter is to introduce the reader to the wind energy. In this way, as the primary source of wind energy, how the wind is created and its characteristics are evaluated.

Due to its nature, the wind is an un-programmable energy source. However, it is possible to estimate the wind speed and direction for a specific location using wind patterns. Therefore, in the present chapter, how to describe the wind behavior for a specific location, the kinetic energy contained in the wind and its probability to occur is described.

To convert the wind energy into a useful energy has to be harvested. The uptake of wind energy in all the wind machines is achieved through the action of wind on the blades, is in these blades where the kinetic energy contained in the wind is converted into mechanic energy. Thus, the different ways to harvest this energy are evaluated, such as: different kind of blades, generators, turbines…

Once, the wind and the fundamentals of the wind machines are familiar, the advantages / disadvantages between offshore and onshore energy are discussed.

### 2.1 The wind

The unequal heat of the Earth surface by the sun is the main reason in the generation of the wind. So, wind energy is a converted form of solar energy.

The sun's radiation heats different parts of the earth at different rates; this causes the unequal heat of the atmosphere. Hot air rises, reducing the atmospheric pressure at the earth's surface, and cooler air is drawn in to replace it, causing wind. But not all air mass displacement can be denominate as wind, only horizontal air movements. When air mass has vertical displacement is called as "convection air current"

The wind in a specific location is determinate by global and local factors. Global winds are caused by global factors and upon this large scale wind systems are always superimposed local winds.

<u>Global or geostrophic winds</u>

The geostrophic wind is found at altitudes above 1000 m from ground level and it's not very much influenced by the surface of the earth.

The regions around equator, at 0° latitude are heated more by the sun than the regions in the poles. So, the wind rises from the equator and moves north and south in the higher layers of the atmosphere. At the Poles, due to the cooling of the air, the air mass sinks down, and returns to the equator.

If the globe did not rotate, the air would simply arrive at the North Pole and the South Pole, sink down, and return to the equator. Thus, the rotation with the unequal heating of the surface determines the prevailing wind directions on earth. The general wind pattern of the main regions on earth is depicted in Figure 2.1

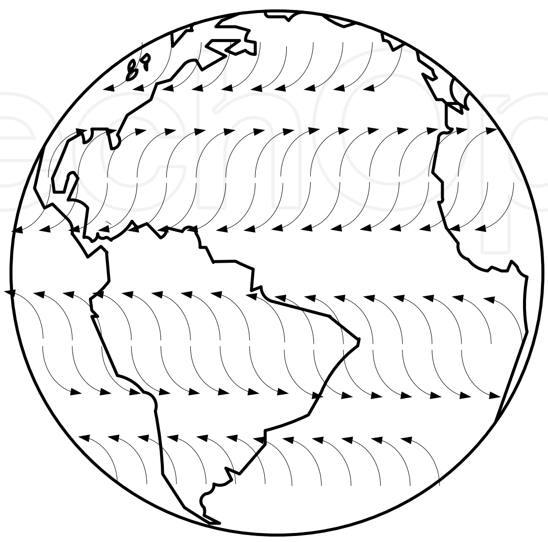


Figure 2.1 Representation of the global wind on the earth.

Besides the earth rotation, the relative position of the earth with the sun also varies during the year (year seasons). Due to these seasonal variations of the sun's radiation the intensity and direction of the global winds have variations too.

Local Winds

The wind intensity and direction is influenced by global and local effects. Nevertheless, when global scale winds are light, local winds may dominate the wind patterns. The main local wind structures are sea breezes and mountain / valley breezes. The breeze is a light and periodic wind which appears in locations with periodic thermal gradient variations.

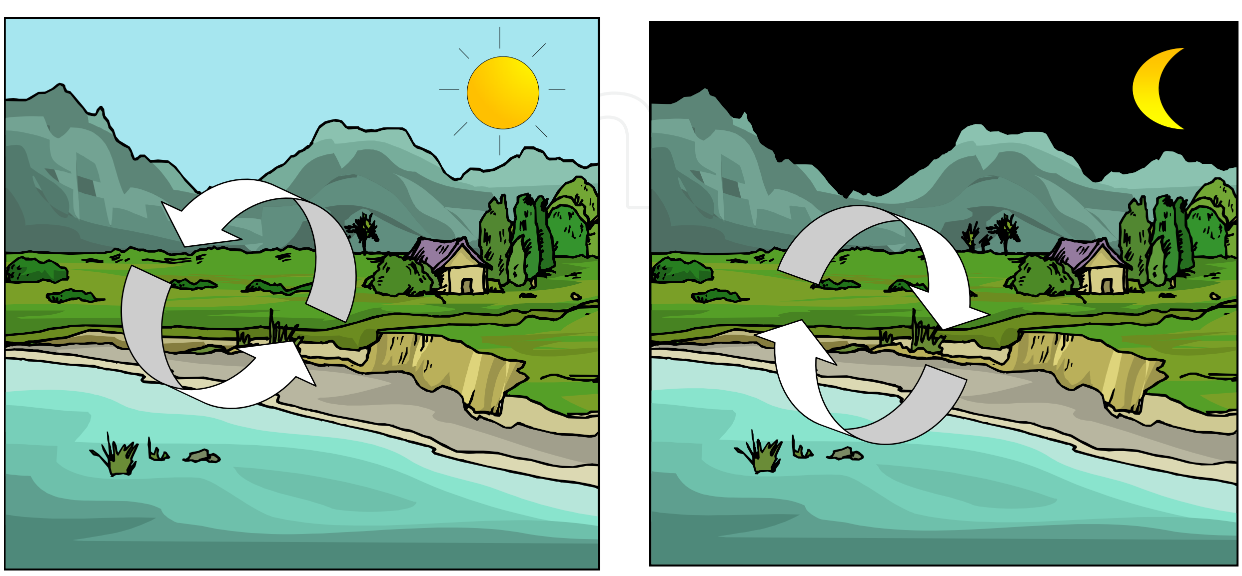


Figure 2.2 Illustration of the sea breezes direction.

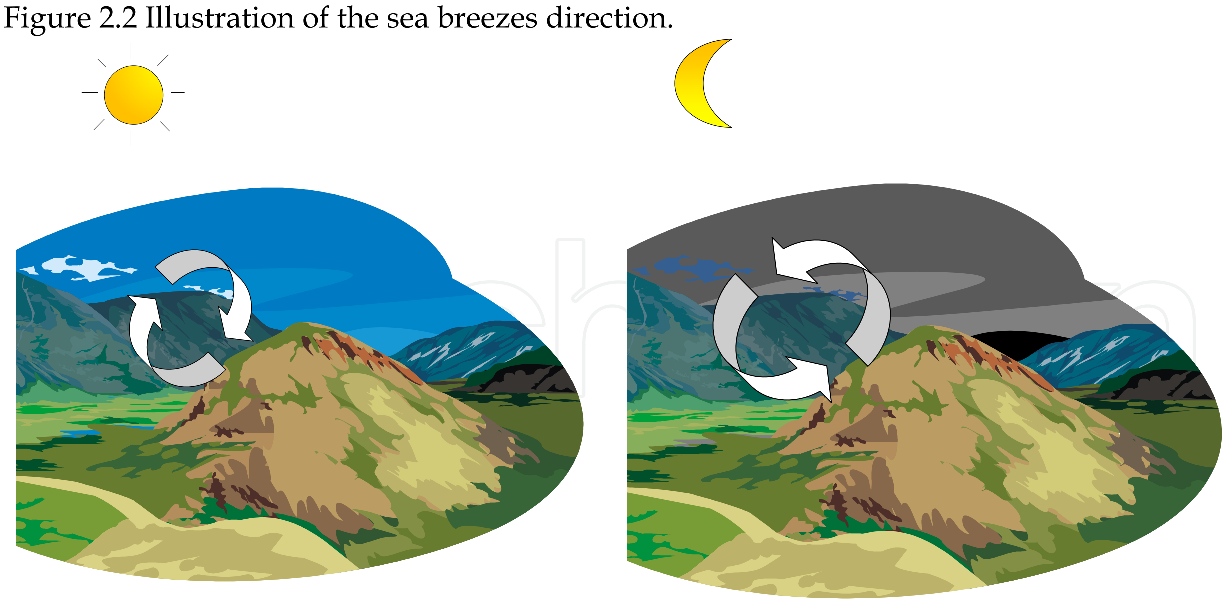


Figure 2.3 Illustration of the mountain / valley breezes direction.

Land masses are heated by the sun more quickly than the sea in the daytime. The hot air rises, flows out to the sea, and creates a low pressure at ground level which attracts the cool air from the sea. This is called a sea breeze. At nightfall land and sea temperatures are equal and wind blows in the opposite direction [10].

A similar phenomenon occurs in mountain / valleys. During the day, the sun heats up the slopes and the neighboring air. This causes it to rise, causing a warm, up-slope wind. At night the wind direction is reversed, and turns into a down-slope wind.

### 2.1.1 The roughness of the wind

About 1 Km above the ground level the wind is hardly influenced by the surface of the earth at all. But in the lower layers of the atmosphere, wind speeds are affected by the friction against the surface of the earth. Therefore, close to the surface the wind speed and wind turbulences are high influenced by the roughness of the area.

In general, the more pronounced the roughness of the earth's surface, the more the wind will be slowed down.

Trees and high buildings slow the wind down considerably, while completely open terrain will only slow the wind down a little. Water surfaces are even smoother than completely open terrain, and will have even less influence on the wind.

The fact that the wind profile is twisted towards a lower speed as we move closer to ground level is usually called wind shear. The wind speed variation depending on the height can be described with the following equation (1) [11]:

$$\frac{V'_{wind}}{V_{wind}} = \left(\frac{h'}{h}\right)^{\alpha_w} \tag{1}$$

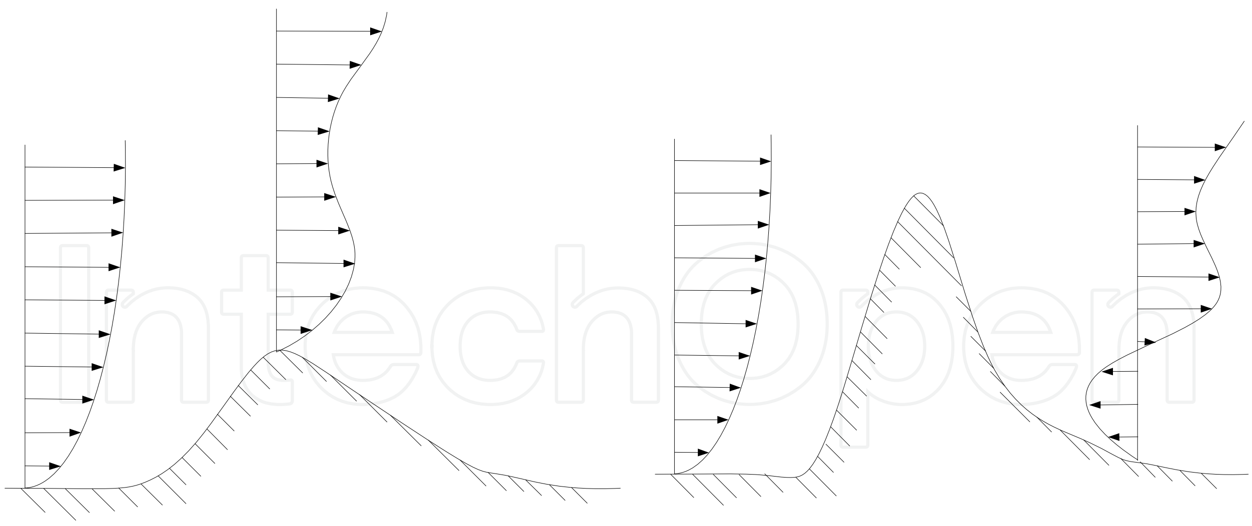


Figure 2.4 Illustration of the wind speed variation due to the obstacles in the earth surface.

Where: $V'_{wind}$= the velocity of the wind (m/s) at height $h'$ above ground level. $V_{wind}$ = reference wind speed, i.e. a wind speed is already known at height $h$. $h'$ = height above ground level for the desired velocity, $\alpha_w$ = roughness length in the current wind direction. $h$ = reference height (the height where is known the exact wind speed, usually =10m).

As well as the wind speed the energy content in the wind changes with the height. Consequently, the wind power variations are described in equation (2) [12]:

$$\frac{P'_{wind}}{P_{wind}} = \left(\frac{h'}{h}\right)^{3\alpha_w} \tag{2}$$

Where: $P'_{wind}$ = wind power at height $h'$ above ground level. $P_{wind}$ = reference wind power, i.e. a wind power is already known at height $h$. $h'$ = height above ground level for the desired velocity, $\alpha_w$ = roughness length in the current wind direction. $h$ = reference height (the height where is known the exact wind speed, usually =10m).

At the following table, the different values of $\alpha_w$ (The roughness coefficient) for different kind of surfaces, according to European Wind Atlas [13] are shown.

| | |
|---|---|
| 0 0,0002 | *Water surface* |
| 0,0024-0,5 | *Completely open terrain with a smooth surface, e.g. concrete runways in airports, mowed grass, etc.* |
| 0,03-1 | *Open agricultural area without fences and hedgerows and very scattered buildings. Only softly rounded hills* |
| 0,4-3 | *Villages, small towns, agricultural land with many or tall sheltering hedgerows, forests and very rough and uneven terrain* |
| 1,6-4 | *Very large cities with tall buildings and skyscrapers* |

Table 2.1 Different α values for different kind of surfaces.

### 2.1.2 The general pattern of wind: Speed variations and average wind

Wind is an un-programmable energy source, but this does not mean unpredictable. It is possible to estimate the wind speed and direction for a specific location. In fact, wind predictions and wind patterns help turbine designers to optimize their designs and investors to estimate their incomes from electricity generation.

The wind variation for a typical location is usually described using the so-called "Weibull" distribution. Due to the fact that this distribution has been experimentally verified as a pretty accurate estimation for wind speed [14], [15] The weibull's expression for probability density (3) depends on two adjustable parameters.

$$\phi(v) = \frac{k}{c} \cdot \left(\frac{v_{wind}}{c}\right)^{k-1} \cdot e^{-\left(\frac{v_{wind}}{c}\right)^{k}} \quad (3)$$

Where: $\phi(v)$= Weibull's expression for probability density depending on the wind, $v_{wind}$ = the velocity of the wind measured in m/s, $c$ = scale factor and $k$ = shape parameter.

The curves for weibulls distribution for different average wind speeds are shown in Figure 2.5. This particular figure has a mean wind speed of 5 to 10 meters per second, and the shape of the curve is determined by a so called shape parameter of 2.

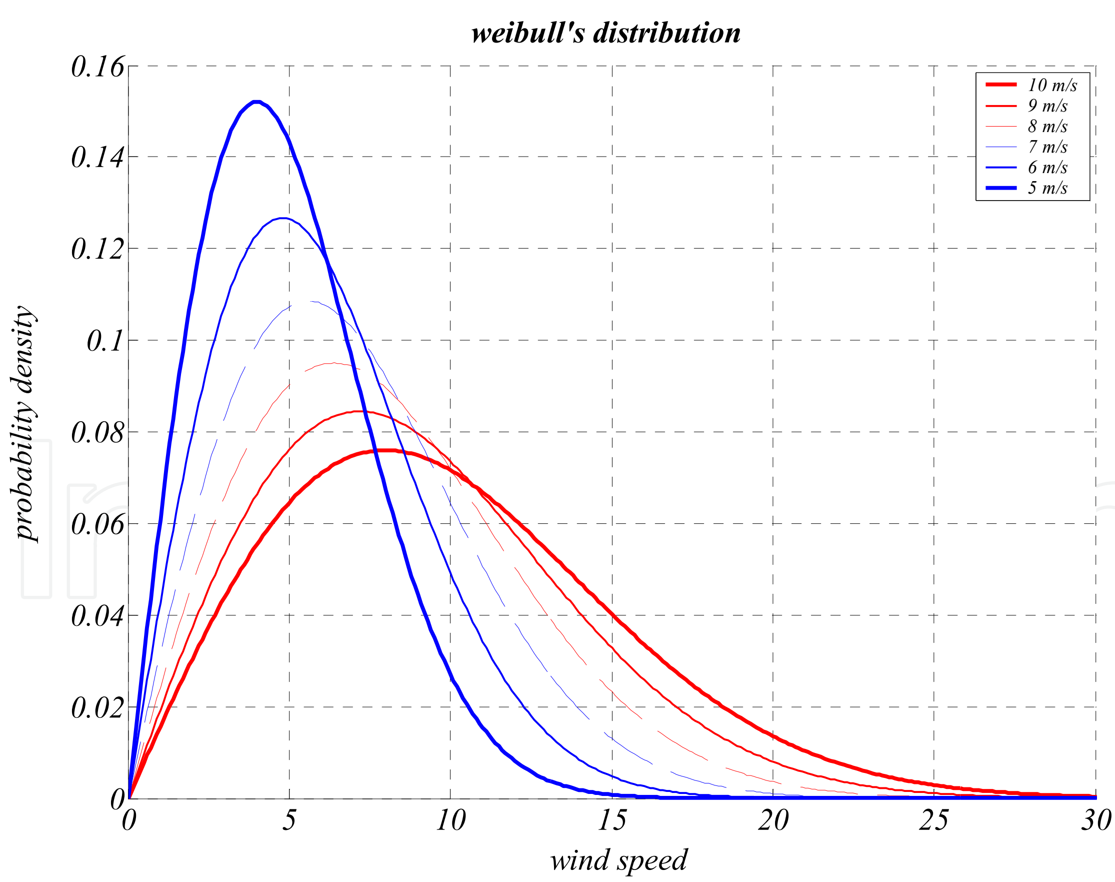



Figure 2.5 Curves of weibull's distribution for different average wind speeds 5, 6, 7, 8, 9 and 10 m/s.

The graph shows a probability density distribution. Therefore, the area under the curve is always exactly 1, since the probability that the wind will be blowing at some wind speed including zero must be 100 per cent.

The statistical distribution of wind speed varies from one location to another depending on local conditions like the surfaces roughness. Thus to fit the Weibull distribution to a specific location is necessary to set two parameters: the shape and the wind speeds mean value.

If the shape parameter is 2, as in Figure 2.5, the distribution is known as a Rayleigh distribution. Wind turbine manufacturers often give standard performance figures for their machines using the Rayleigh distribution.

The distribution of wind speeds is skewed, is not symmetrical. Sometimes the wind presents very high wind speeds, but they are very rare. On the contrary, the probability of the wind to presents slow wind speeds is pretty high.

To calculate the mean wind speed, the wind speed value and its probability is used. Thus, the mean or average wind speed is the average of all the wind speeds measured in this location. The average wind speed is given by equation (4) [16]:

$$\bar{v}_{wind} = \int_0^{\infty} v_{wind} \cdot \phi\left(v_{wind}\right) \cdot dv_{wind} \tag{4}$$

Where: $\phi( v_{wind} )$ = Weibull's expression for probability density depending on the wind, $v_{wind}$ =the velocity of the wind measured in m/s.

### 2.2 The power of the wind

The uptake of wind energy in all the wind machines is achieved through the action of wind on the blades, is in these blades where the kinetic energy contained in the wind is converted into mechanic energy. Therefore, in the present section the analysis of the power contained in the wind is oriented to those devices.

#### 2.2.1 The kinetic energy of the wind

The input power of a wind turbine is through its blades, converting wind power into a torque. Consequently, the input power depends on the rotor swept area, the air density and the wind speed.

Air density

The kinetic energy of a moving body is proportional to its mass. So, the kinetic energy of the wind depends on the air density, the air mass per unit of volume. At normal atmospheric pressure (and at 15° C) air weigh is 1.225 kg per cubic meter, but the density decreases slightly with increasing humidity.

Also, the air is denser when it is cold than when it is warm. At high altitudes, (in mountains) the air pressure is lower, and the air is less dense.

The rotor area

The rotor area determines how much energy a wind turbine is able to harvest from the wind. Due to the fact that the amount of the air mass flow upon which the rotor can actuate is determined by this area, this amount increases with the square of the rotor diameter, equation (5)

$$A_r = \pi \cdot r^2 \tag{5}$$

Where: $A_r$ = the rotor swept area in square meters and $r$ = the radius of the rotor measured in meters.

Equation of the winds kinetic energy

The input air mass flow of a wind turbine with a specific rotor swept area determined by $A_r$ is given by equation (6). This input air mass flow depends on the wind speed and the rotor swept area.

$$M = \rho A_r v_{wind} \tag{6}$$

Where: $M$ = Air mass flow, $\rho$ = the density of dry air ( 1.225 measured in kg/m$^3$ at average atmospheric pressure at sea level at 15° C) and $V_{wind}$ = the velocity of the wind measured in m/s.

Therefore, the winds kinetic energy is given by equation (7).

$$P_{wind} = \frac{1}{2} M v^2{}_{wind} = \frac{1}{2} \rho A_r v^3{}_{wind} \tag{7}$$

Where: $P_{wind}$ = the power of the wind measured in Watts, $\rho$ = the density of dry air ( 1.225 measured in kg/m $^3$ at average atmospheric pressure at sea level at 15° C), $V_{wind}$ = the velocity of the wind measured in m/s and $r$ = the radius of the rotor measured in meters.

The wind speed determines the amount of energy that a wind turbine can convert to electricity. The potential energy per second in the wind varies in proportion to the cube of the wind speed, and in proportion to the density of the air.

### 2.2.2 Usable input power, Betz law

The more kinetic energy a wind turbine pulls out of the wind, the more the wind will be slowed down. In one hand if the wind turbines extract all the energy from the wind, the air could not leave the turbine and the turbine would not extract any energy at all. On the other hand, if wind could pass though the turbine without being hindered at all. The turbine would not extract any energy from the wind.

Therefore is possible to assume that there must be some way of breaking the wind between these two extremes, to extract useful mechanical energy from the wind.

Betz law

Betz law says that it's only possible convert less than 16/27 (or 59%) of the kinetic energy in the wind to mechanical energy using a wind turbine. This law can be applied to any kind of wind generators with disc turbines. Besides this limit, also must be considered the aerodynamic and mechanic efficiency from the turbines.

### 2.2.3 Useful electric energy from wind

As said before, from the winds kinetic energy it's only possible convert less than 16/27 (Betz's law). However, the process to harvest the wind also has other losses, even the best blades have above 10% of aerodynamic losses [17].

So, the electric power that can be extracted from the kinetic energy of the wind with a turbine is given by the well-known equation (8).

$$P_t(v) = \frac{1}{2} \cdot \rho \cdot \pi \cdot r^2 \cdot V_{wind}^3 \cdot Cp \tag{8}$$

Where: $P_t$ $(v)$ = the input power of the generator, $\rho$ = the density of dry air ( 1.225 measured in kg/m $^3$ for average atmospheric pressure at sea level with 15° C), $r$ = the radius of the rotor measured in meters, $V_{wind}$ = the velocity of the wind measured in m/s and $Cp$ = the power coefficient.

As any machine in movement, the generator has mechanic losses whether they are: at the bearings, brushes, gear...Equally any electric machine has electric losses. Hence, only a part of the winds kinetic energy can be converted to electric power Figure 2.6.

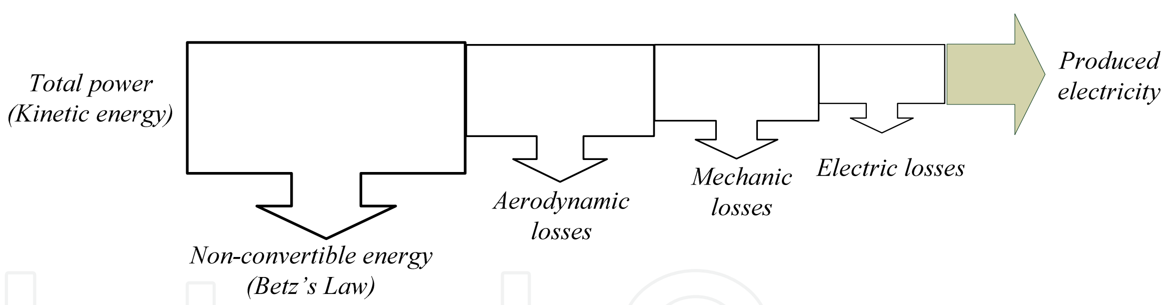



Figure 2.6 Representation of the power losses at different steps of electric wind energy generation.

#### 2.2.3.1 The power coefficient

The power coefficient tells how efficient is a turbine capturing the energy contained in the wind. To measure this efficiency, the energy captured by the rotor is divided by the input wind energy. In other words, the power coefficient is the relation between the kinetic energy in the rotor swept area and the input power of the generator.

### 2.3 Fundamentals of wind machines

Wind machines convert the kinetic energy contained in the wind into mechanic energy through the action of wind on the blades. The aerodynamic principle in this transformation (kinetic to mechanic energy) is similar to the principle that makes airplanes fly.

According to this principle, the air is forced to flow over the top and bottom of a blade (see Figure 2.7) generating a pressure difference between both sides. The pressure difference causes a resultant force upon the blade. This force can be decomposed in two components:

**a)** ***Lift force***, which is perpendicular to the direction of the wind.

**b)** ***Drag force*****,** which is parallel to the direction of the wind. This force helps the circulation of air over the surface of the blades.

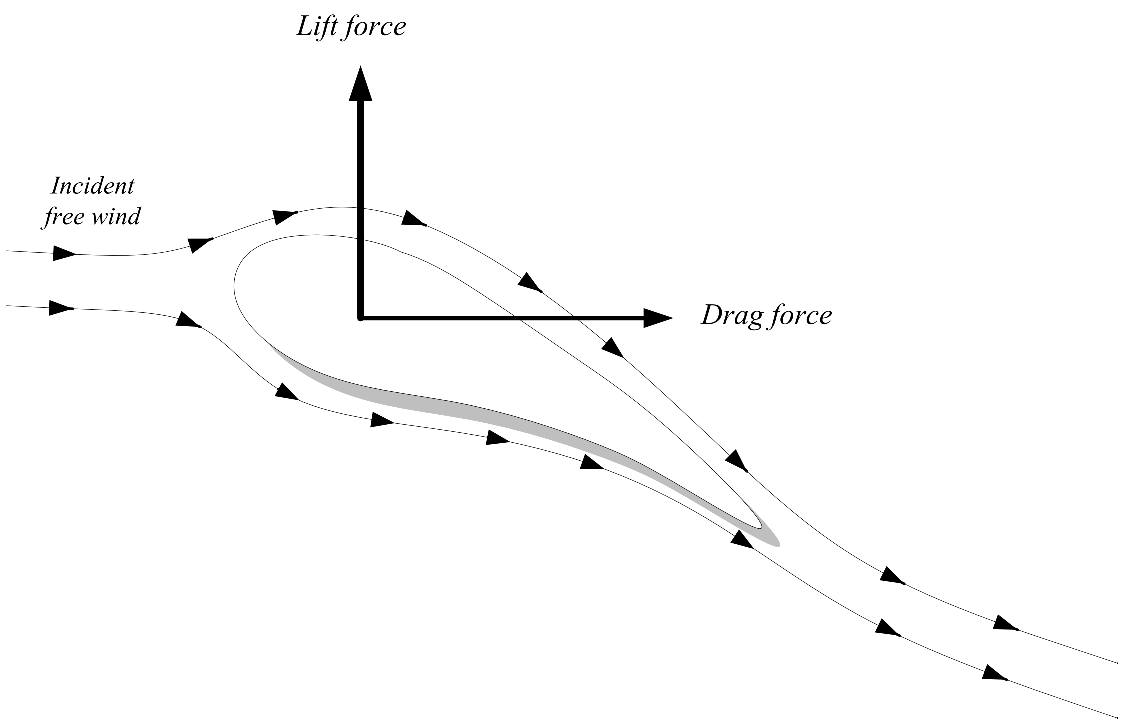



Figure 2.7 Representation of lift force and drag force generated on the blades.

The force which will generate a torque is lift force or drag force depending on the relative position of the blades with the axis and the wind.

In wind turbines with horizontal axis, the lift component of the force is the only one that gives the torque. Therefore, as the lift force gives torque, the profile of the blade has to be designed setting the attack angle (α), the relative position of the blade with the wind (see Figure 2.8), to make maximum lift / drag force ratio [12].

This simple analysis is only valid when the blades of a wind turbine are at rest. If the rotation of the rotor is allowed, the resultant force on the blades will be the result from the combination of direct action of the real wind and the action of the wind created by the blades.

The incident wind on the blades is called apparent wind (Figure 2.8), is the result from the composition of the vector of the true wind vector and the wind created by the blade.

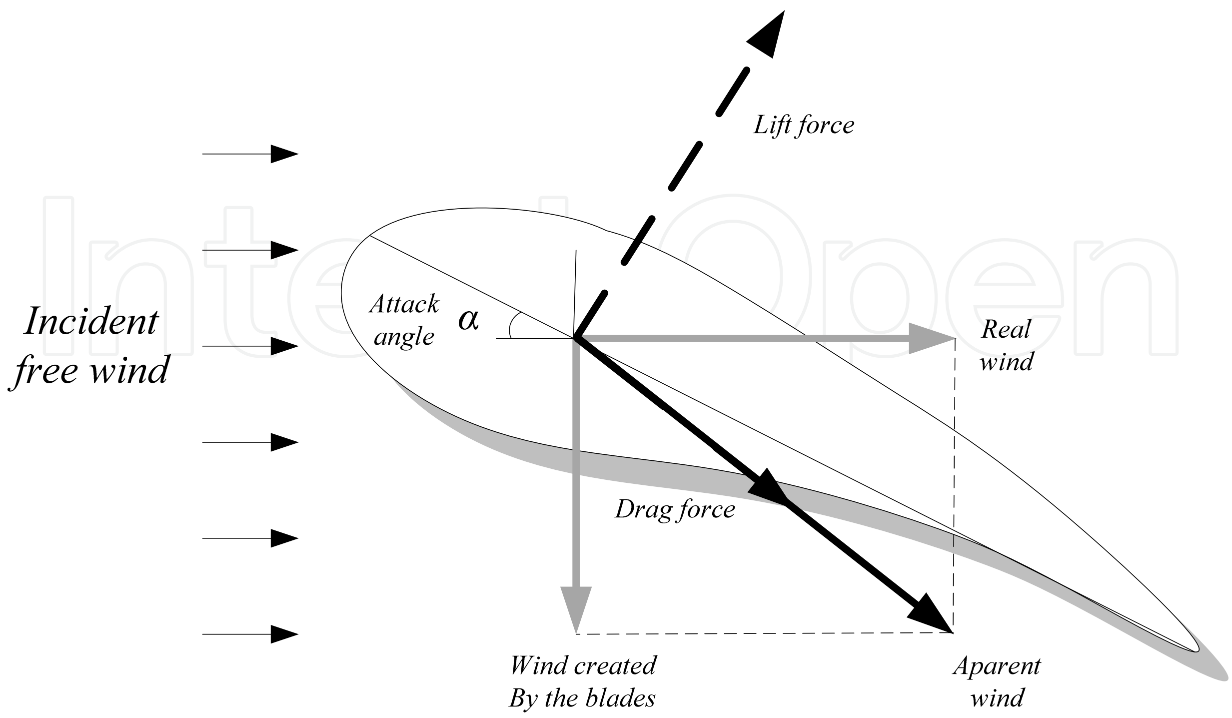



Figure 2.8 Wind created by the blade and the apparent wind.

Each section of the blade has a different speed and the wind speed is higher in terms of the height, thus, the apparent wind in each section is different. To obtain the same resultant force along its length, the profile of the blade has to have different dimensions. Therefore, to achieve this homogeneous resultant force, the rotor blade is twisted. The wing does not change its shape, but changes the angle of the wing in relation to the general direction of the airflow (also known as the angle of attack).

To start a wind turbine, wind speed must exceed the so-called cut in speed (minimum value needed to overcome friction and start producing energy) usually between 3-5 m/s. With higher speeds the turbine starts generating power depending on the known equation (8) of section 2.2.3.

This will be so until it reaches the nominal power. At this point the turbine activates its regulation mechanisms to maintain the same output power. At very high wind speeds the turbine stops in order to avoid any damage. This stop wind speed is called the cut out wind speed.

### 2.4 Wind turbine classification

According to the most of the authors [12], [15] and [17] wind turbines can be classified by three parameters: the direction of the rotor axis, the number of rotor blades and the rotor position.

### 2.4.1 Horizontal or vertical axes classification

Vertical axis wind turbines are the machines where drag force causes the torque in the perpendicular direction of the rotation axis. The basic theoretical advantages of a vertical axis turbines are [15]:

- The possibility to place the generator, gearbox etc. on the ground avoiding a tower for the machine.
- Do not need a yaw mechanism to turn the rotor against the wind.
- Vertical axes machine does not needs regulation with wind speed variations since it is self-regulated at high wind speeds

The basic disadvantages are:

- The machine is not self-starting.
- The overall efficiency of the vertical axis machines is usually worst than horizontal axes machines.
- To replace the main bearing for the rotor, it requires removing the rotor on both horizontal and vertical axis machines. But, in the case of vertical axes machine, this means tearing the whole machine down.

Today, all grid-connected commercial wind turbines are built with a propeller-type rotor on a horizontal axis (i.e. a horizontal main shaft), Figure 2.9.

Figure 2.9 Commercial wind turbine with horizontal axis.

### 2.4.2 Classification by the number of blades

A wind turbine does not give more power with more blades. If the machines are well designed, the harvested power is more or less the same with different number of blades [17].

Wind turbines do not harvest power from the aerodynamic resistance; they do from the blades shape. So, the difference between two wind turbines with a different number of blades is the torque generated by each blade and consequently, the rotational speed of the rotor. Besides, wind turbines with multiple blades starts working at low wind speeds, due to their high start-up torque.

A rotor with an odd number of blades (and at least three blades) can be considered as a disk when calculating the dynamic properties of the machine.

In the other hand, a rotor with an even number of blades will give stability problems for a machine with a stiff structure. At the very moment when the uppermost blade bends backwards, because it gets the maximum power from the wind, the lowermost blade gets the minimum energy from the wind, which generates mechanic stress to the structure. Thus most of the modern wind turbines have three blades [12].

### 2.4.3 Upwind or downwind classification

In this classification the machines can be upwind or downwind depending on the position of the rotor, Figure 2.10. Upwind machines have the rotor facing the wind, on the contrary downwind machines have the rotor placed on the lee side of the tower.

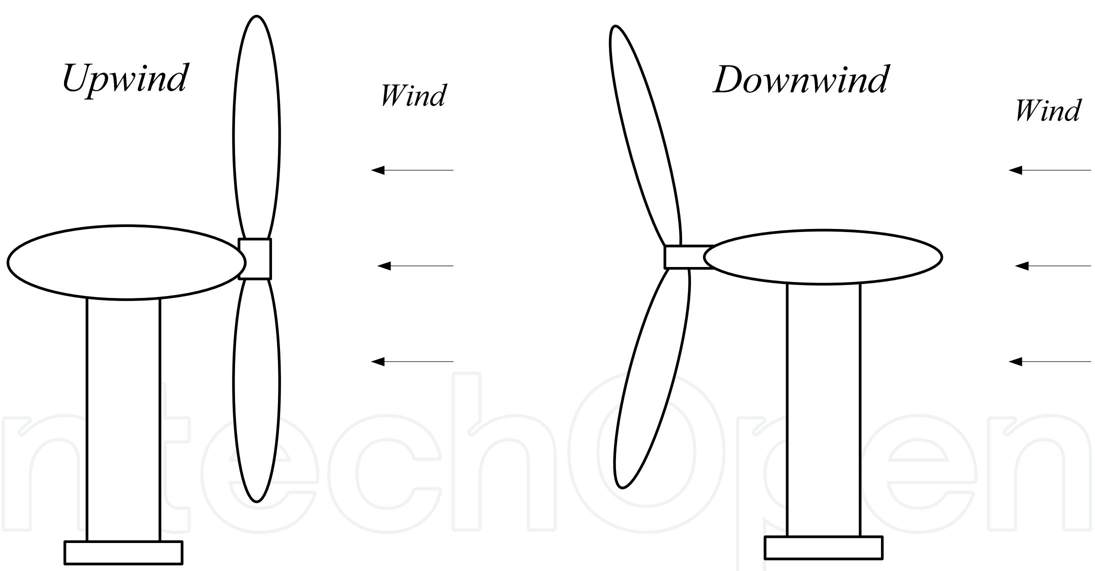



Figure 2.10 Illustration of upwind and downwind turbines.

Downwind machines have the theoretical advantage that they may be built without a yaw mechanism. If the rotor and the nacelle have a suitable design that makes the nacelle follows the wind passively. Another advantage is that the rotor may be made using more flexible materials. Thus, the blades will bend at high wind speeds, taking part of the load off the tower. Therefore, downwind machines may be built somewhat lighter than upwind machines.

The main drawback on downwind machines is that they are influenced by the wind shade behind the tower. When blades cross the wind shade behind the tower, they lose torque and get it back again, causing periodic effort variations in the rotor [17]. Therefore, by far the vast majority of wind turbines have upwind design.

## 2.5 Wind turbines

### 2.5.1 Wind turbine components

A general outline of the components of a wind turbine is given by the following figure:

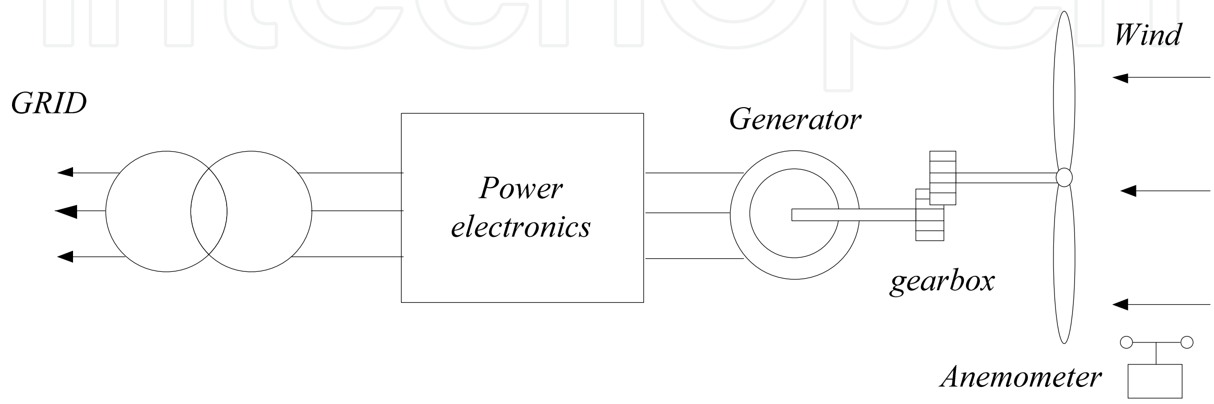



Figure 2.11 Illustration of wind turbine components.

**Rotor blades:** Device to harvest the energy for the wind. At this part the kinetic energy of the wind is transformed into a mechanical torque.

**Anemometer and wind vane**: Devices for measuring wind speed and direction.

**Gearbox:** To convert the slowly rotating, high torque power from the wind turbine rotor to a high speed, low torque power rotation.

**Electrical generator**: Device to transform mechanical energy into electrical energy.

**Associated power electronics:** The part of the wind turbine where electric power is adapted to the frequency and the voltage amplitude of the grid.

**Transformer:** The turbines have their own transformer to step-up the voltage level of the wind turbine to the medium voltage line.

### 2.5.2 Electric generator

An electric generator converts mechanical energy into electrical energy. Synchronous generators are used in most traditional generators (hydro, thermal, nuclear ...). But if these kinds of generators are directly connected to the main grid, they must have fixed rotational speed in synchronism to the frequency of the grid. Thus, torque fluctuations in the rotor (like the fluctuations caused by the wind speed variations) are propagated through the machine to the output electric power.

Furthermore, with fixed speed of the rotor, the turbine cannot vary the rotational speed in order to achieve the optimum speed and extract the maximum torque from the wind. So, with fixed speed the aerodynamic losses are bigger.

Due to these drawbacks, synchronous generators are only used in wind turbines with indirect grid connection. The synchronous generator is controlled electronically (using an inverter), as a result the frequency of the alternating current in the stator of the generator may be varied. In this way, it is possible to run the turbine at variable rotational speed. Consequently, the turbine will generate alternating current at exactly the variable frequency applied to the stator.

On the other hand, asynchronous generators can be used directly or indirectly connected to the grid. Due to the fact that this kind of generators allows speed variations (little) when is connected directly to the grid. Hence, until the present day, most wind turbines in the world connected directly to the grid use a so-called three phase asynchronous generator (also called induction generator) to generate electric power.

### 2.5.3 Wind turbine systems

#### 2.5.3.1 Fixed Speed (one or two speeds)

Introduced and widely used in the 80s, the concept is based on a 'squirrel cage' asynchronous generator (SCIG), the rotor is driven by the turbine and its stator is directly connected to the grid. Its rotation speed can only vary slightly (between 1% and 2%), which is almost "fixed speed" in comparison with other wind turbine concepts. So, as its name says, this type of generators cannot vary the speed of the turbine to the optimum speed and extract the maximum torque from the wind.

Aerodynamic control is mostly performed using passive stall, and as a result only a few active control options can be implemented in this kind of wind turbines.

SCIGs directly connected to the grid do not have the capability of independent control of active and reactive power, therefore, the reactive power control is performed usually by mechanically switched capacitors.

Their great advantage is their simple and robust construction, which leads to lower capital cost. In contrast to other generator topologies, FSIGs (Fixed Speed Induction Generators) offer no inherent means of torque oscillation damping which places greater burden and cost on their gearbox.

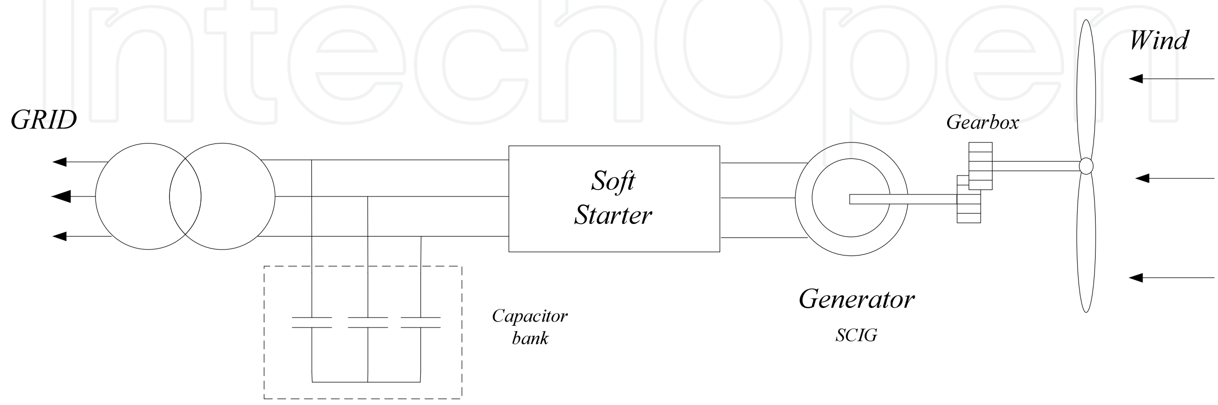



Figure 2.12 The main scheme of fixed speed wind turbine.

The concept exists in both single and double speed versions. The double speed operation gives an improved performance and lower noise production at low wind speeds [18].

European market share: 30% (2005)

Manufacturers: Suzlon, Nordex, Siemens Bonus, Ecotecnia. [18].

#### 2.5.3.2 Limited variable speed

Limited variable Speed wind turbines used by Vestas in the 80s and 90s are equipped with a 'wound rotor' induction generator (WRIG). Power electronics are applied to control the rotor electrical resistance, which allows both the rotor and the generator to vary their speed up and down to ± 10% [18].

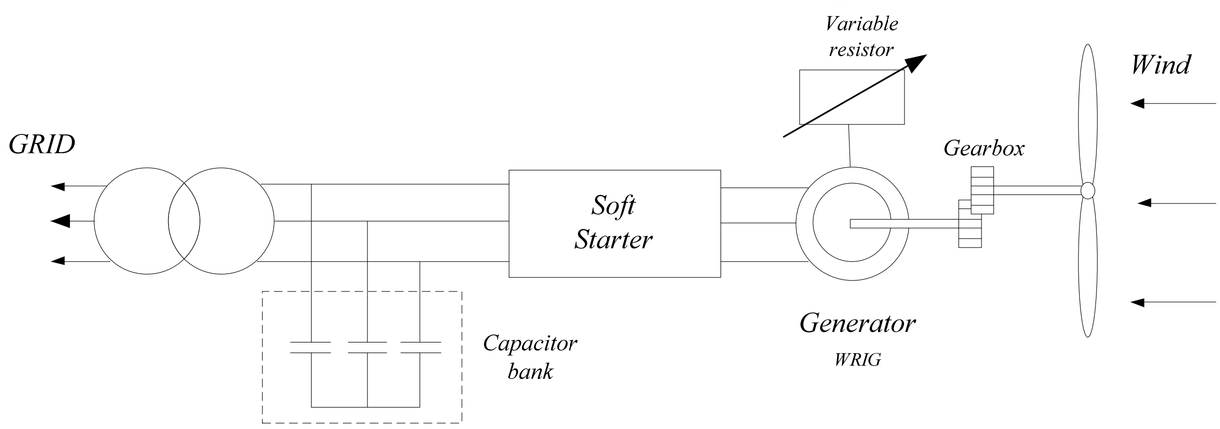



Figure 2.13 The main scheme of limited variable speed wind turbine.

European market share: 10% (2005)

Manufacturers: Vestas (V27, V34, V47). [18].

#### 2.5.3.3 Improved variable Speed with DFIG

This system combines advantages of previous systems with advances in power electronics. The DFIG is a wound rotor induction generator whose rotor is connected through frequency converter. In the other hand, stator is directly connected to the grid. As a result of the use of the frequency converter, the grid frequency is decoupled from the mechanical speed of the machine allowing a variable speed operation. Thus maximum absorption of wind power is possible.

Approximately 30% - 40% of the output power goes through the inverter to the grid, the other part goes directly through the stator. The speed variations window is approximately 40% up and down from synchronous speed. The application of power electronics also provides control of active and reactive power, i.e. the DFIG wind turbine has the capability to control independently active and reactive power.

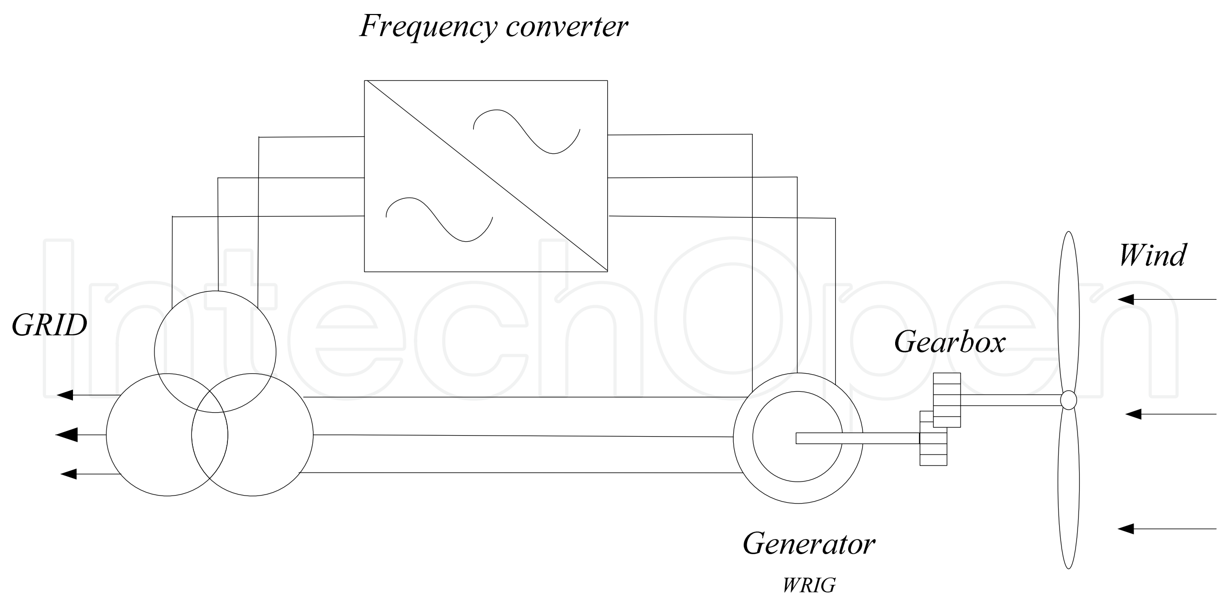



Figure 2.14 The main scheme of improved variable speed with DFIG wind turbine.

European market share: 45% (2005)

Manufacturers: General Electric (series 1.5 y 3.6), Repower, Vestas, Nordex, Gamesa, Alstom, Ecotecnia, Ingetur, Suzlon. [18].

#### 2.5.3.4 Variable Speed with full scale frequency converter

The stator of the generator is connected to the grid through a full-power electronic converter. Various types of generators are being used: SCIG, WRIG (Wound rotor induction generator), PMSG (permanent magnet synchronous generator) or WRSG (wound rotor synchronous generator). The rotor has excitation windings or permanent magnets. Being completely decoupled from the grid, it can provide even a more wide range of operating speeds than DFIGs. This kind of wind turbines has two variants: direct drive and with gearbox.

The basic theoretical characteristics of a variable speed with full scale frequency converters are [19]:

- The DC link decouples completely the generator from the Grid. As the grid frequency is completely decoupled, the generator can work at any rotational speed. Besides changes in grid voltage does not affect the dynamics of the generator.
- The converters have equal rated power as the generator does, not 30% - 40% like DFIG wind turbines.
- The converters have full control over the generator.
- This kind of wind turbine provides complete control over active and reactive power exchanged with the grid. Moreover, it is possible to control the voltage and reactive power in the grid without affecting the dynamics in the generator. As long as there is not a grid fault.

European market share: 15% (2005)

Manufacturers: Enercon, MEG (Multibrid M5000), GE (2.x series), Zephyros, Winwind, Siemens (2.3 MW), Made, Leitner, Mtorres, Jeumont. [18].

#### 2.5.3.4.1 Full scale frequency converter with gearbox

The generator uses a two stage gearbox to connect the low-speed shaft to the high-speed shaft, with all the problems associated to the gearbox, like the maintenance or the torque losses.

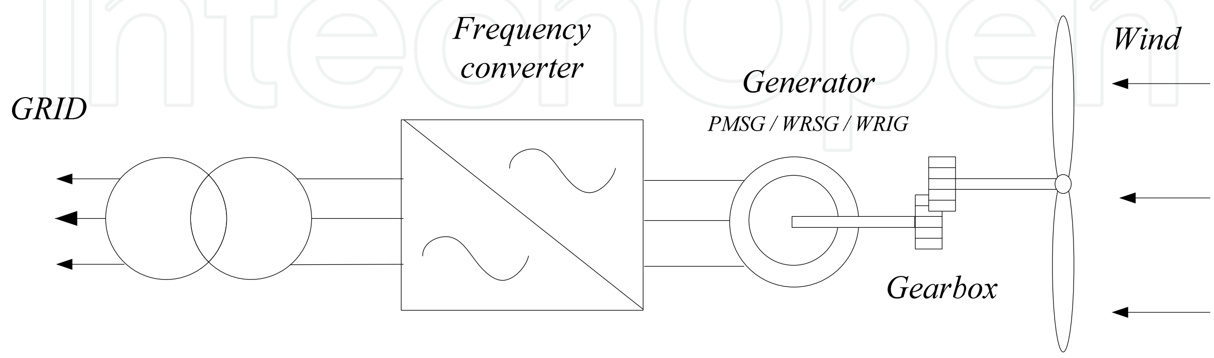



Figure 2.15 The main scheme of variable speed geared with full scale frequency converter wind turbine.

#### 2.5.3.4.2 Full scale frequency converter with direct drive

This kind of solutions avoids the gearbox and brushes, so, the implementation of the direct drive in a wind turbine improves the mechanic reliability and produces less noise.

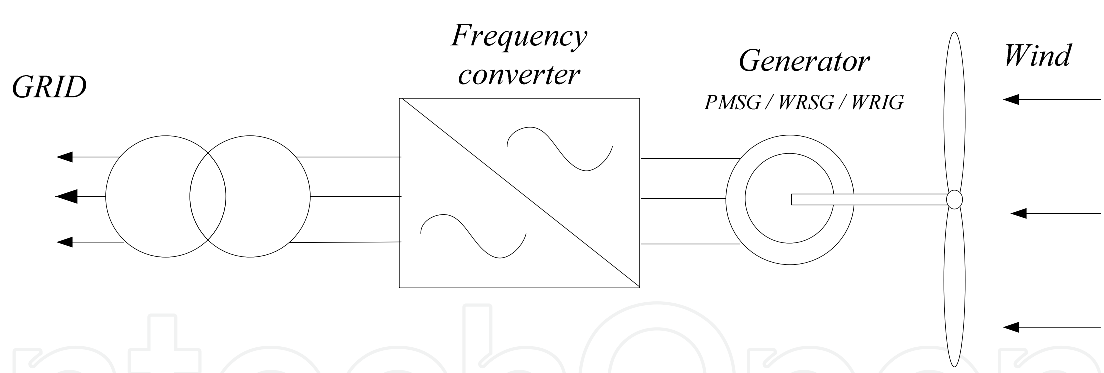



Figure 2.16 The main scheme of variable speed direct drive with full scale frequency converter wind turbine.

### 2.5.4 Active power control

Pitch controlled

On a pitch controlled wind turbine, an electronic controller checks the output power of the turbine several times per second. If the output power is bigger than the rated power, it sends an order to the blade pitch mechanism to pitches (turns) the rotor blades out of the wind. In the other hand, if the output power is lower than the rated power the blades are turned back into the wind, in order to harvest the maximum energy.

Stall controlled

The stall controlled wind turbines are regulated by the aerodynamic loss in the blades. The geometry of the rotor blade profile is aerodynamically designed, to create turbulences on the side of the rotor blade which is not facing the wind, at the moment which the wind speed becomes too high. In this way, it is possible to waste the excess energy in the wind.

Control using ailerons (flaps)

Some older wind turbines use ailerons (flaps) to control the power of the rotor, just like aircraft use flaps to alter the geometry of the wings. But mechanical stress caused by the use of these flaps can damage the structure. Therefore this kind of control only is used in low power generators.

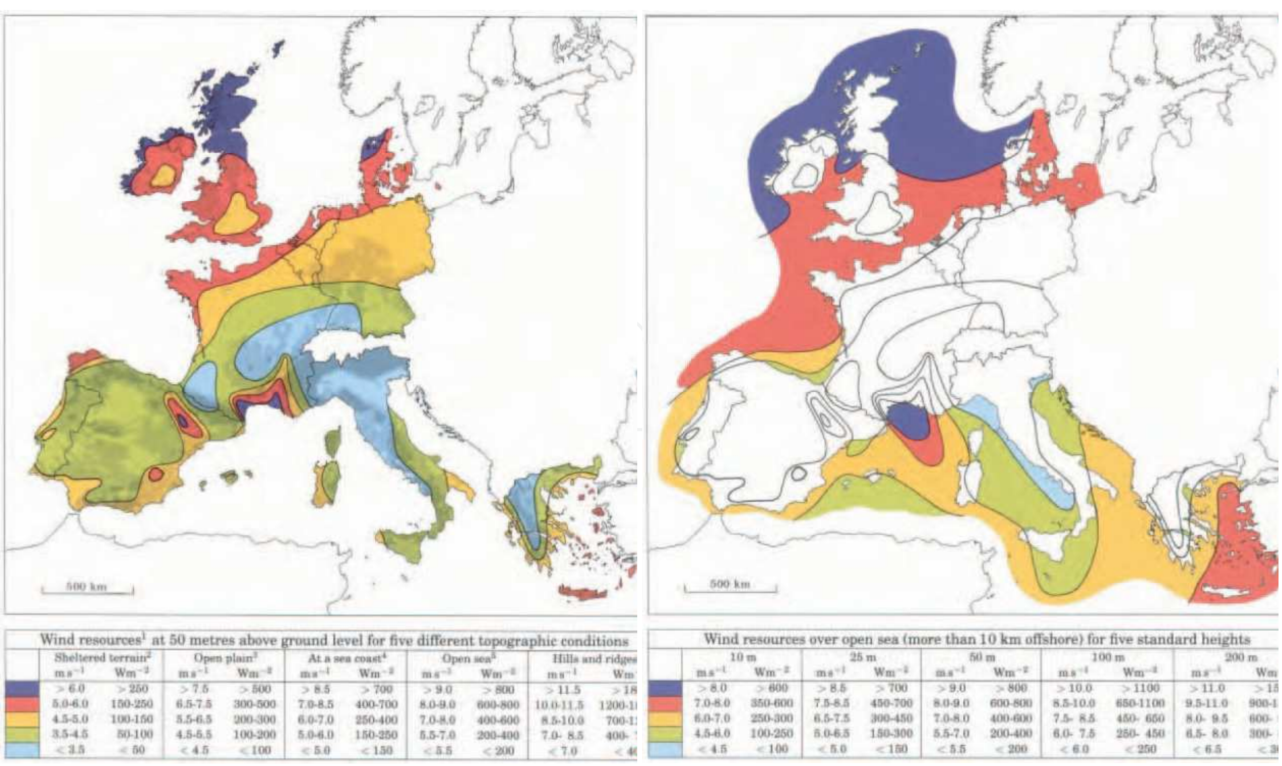
### 2.6 Offshore wind energy vs onshore wind energy

Offshore wind energy in comparison with onshore wind energy has the following advantages / disadvantages [20], [21]:

Advantages:

- **Bigger resource.**
- **Less roughness.**
- **Easier to transport big structures.**
- **Less environmental impact.**

**Bigger resource:** Winds are typically stronger at sea than on land. In the European wind atlas is clearly shown how the wind resource is more abundant in the sea Figure 2.17.




(a) (b)

Figure 2.17 The average wind speed in Europe, in land (a) and offshore (b) [22].

Besides, the sea has huge spaces to place wind turbines, thus it is possible to install much larger wind farms than in land. The Arklow Bank wind farm has plans to expand its rated power to 520 MW and in Germany and France are proposals to create wind farms with over 1,000 MW.

**Less roughness:** At sea the roughness is lower than in land. As seen in section 2.1.1, the power coefficient (alpha) is much smaller and wind power potential at the same height (equation (2)) is bigger. Moreover, the wind at sea is less turbulent than on land, as a result, wind turbines located at sea may therefore be expected to have a longer lifetime than land based turbines.

In the same way, at sea there are not obstacles to disturb the wind. Consequently, it is possible to build wind turbines with smaller towers, only the sum between the maximum height of the expected wave and the rotor radius.

**Easier to transport big structures:** To transport very large turbine components from the place of manufacturing by road to installation sites on land are logistical difficulties. However, the pieces for offshore wind farms are easily transported by special vessels called Jack-ups.

**Less environmental impact:** Offshore wind farms are too far from the populated areas and they do not have visual impact. Thus they have less noise restrictions than in land, making possible higher speeds for the blade. As a result, it is possible a weight reduction of the blades and mechanical structures, achieving a significant reduction in manufacturing cost.

On the other hand, offshore wind farms present the following disadvantages in comparison with onshore wind farms:

<u>Disadvantages:</u>

- **Operation and maintenance more complicated than in land.**
- **Corrosive environment.**
- **Bigger invest cost.**
- **The energy transmission system to shore.**
- **The depth of the seabed.**

**Operation and maintenance more complicated than in land:** It is not easy access to a facility installed many kilometers into the sea. Therefore it's more complicated the ensemble and maintenance of the facility.

**Corrosive environment:** At sea the salinity and humidity increases the corrosion rate of materials.

**Bigger investment cost:** The cost of the foundations and the transmission system of these facilities is more expensive than onshore wind farms. So the cost per MW installed offshore is about 2.5 times bigger than the cost of installed MW in land.

**The energy transmission system to shore:** The electrical facilities to connect the areas with big offshore wind energy potential with the energy consumption areas are not prepared to transport huge amount of energy.

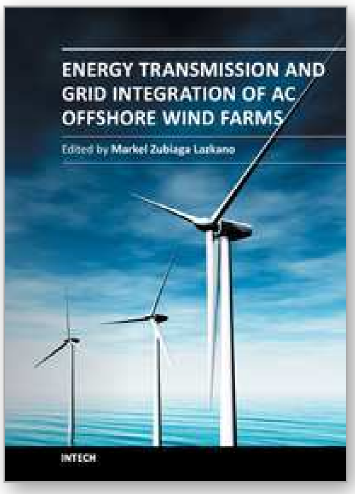
**The depth of the seabed:** The cost and construction difficulties for an offshore wind farm increases with the water depth.

## 2.7 Chapter conclusions

Offshore wind presents great advantages to develop wind energy, due to the fact that it has a high potential that today still remains largely untapped. However, the opportunities for advancing offshore wind technologies are accompanied by significant challenges, such as: the exposure of the components to more extreme open ocean conditions, the long distance electrical transmission systems on high-voltage submarine cables or turbine maintenance at sea.

Despite of those technological challenges, also have significant advantages. Turbine blades can be much larger without land-based transportation / construction constraints and the blades also are allowed to rotate faster offshore (no noise constraints), so at sea can be installed wind turbines with higher rated powers. Furthermore, the wind at sea is less turbulent than on land.

Thus, the bigger capital costs (twice as high as land-based) can be partially compensated by the higher energy of the wind at sea. In this way, in recent years the average rated power of installed new offshore wind farms has been multiplied by 15. In conclusion, offshore wind is a real opportunity to develop wind energy in the upcoming years.




**Energy Transmission and Grid Integration of AC Offshore Wind Farms**

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This book analyses the key issues of the offshore wind farm's energy transmission and grid integration infrastructure. But, for this purpose, there are not evaluated all the electric configurations. In the present book is deeply evaluated a representative case. This representative case is built starting from three generic characteristics of an offshore wind farm: the rated power, the distance to shore and the average wind speed of the location. Thus, after a brief description of concepts related to wind power and several subsea cable modeling options, an offshore wind farm is modeled and its parameters defined to use as a base case. Upon this base case, several analyses of the key aspects of the connection infrastructure are performed. The first aspect to analyze is the management of the reactive power flowing through the submarine cable. Then, the undesired harmonic amplifications in the offshore wind farms due to the resonances and after this, transient over-voltage problems in the electric infrastructure are characterized. Finally, an offshore wind farm connection infrastructure is proposed in order to achieve the grid code requirements for a specific system operator, but not as a close solution, as a result of a methodology based on analyses and simulations to define the most suitable layout depending on the size and location of each offshore wind farm.