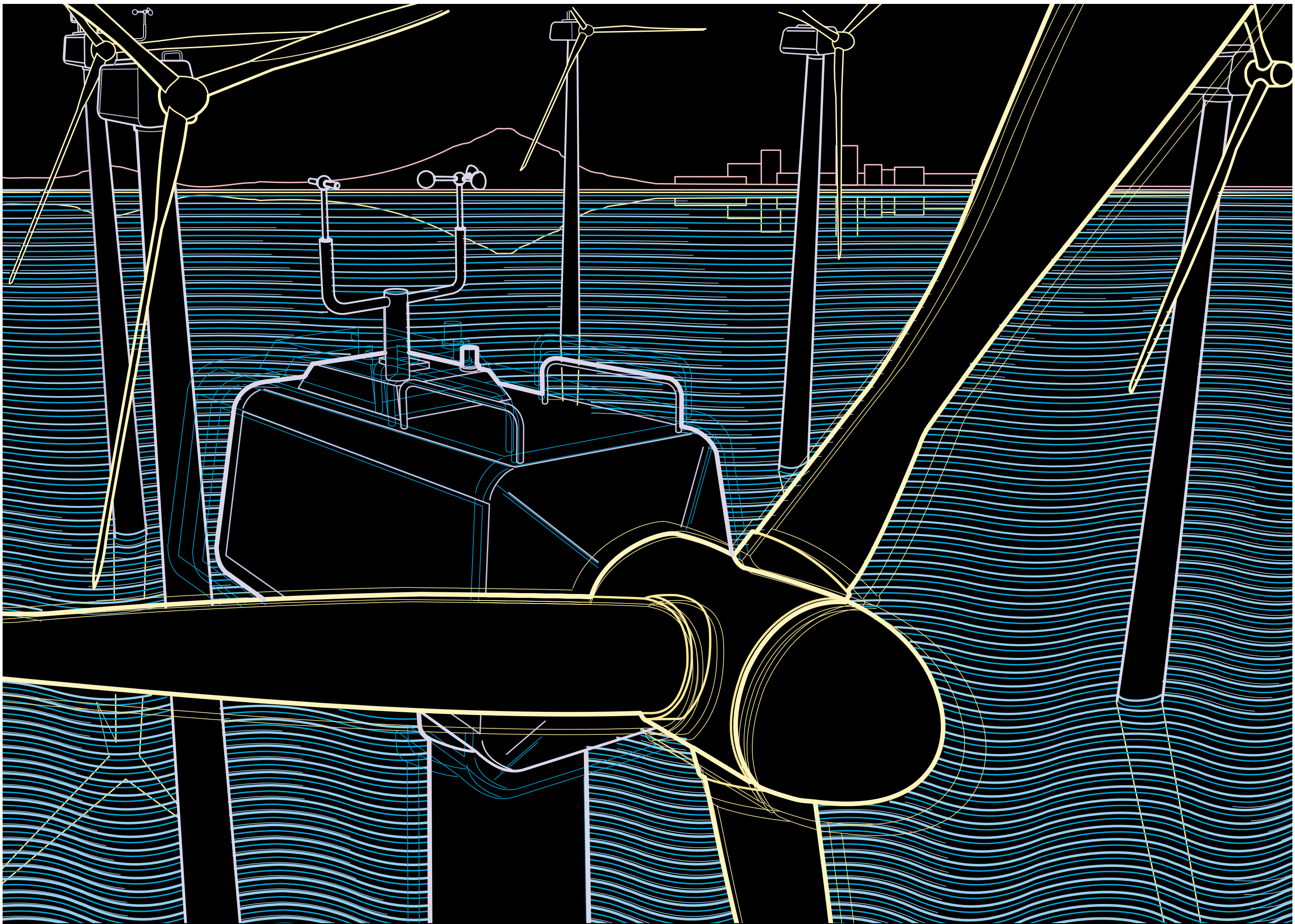

Technical Application Papers No.13
Wind power plants

Power and productivity
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Wind power plants

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Wind power plants

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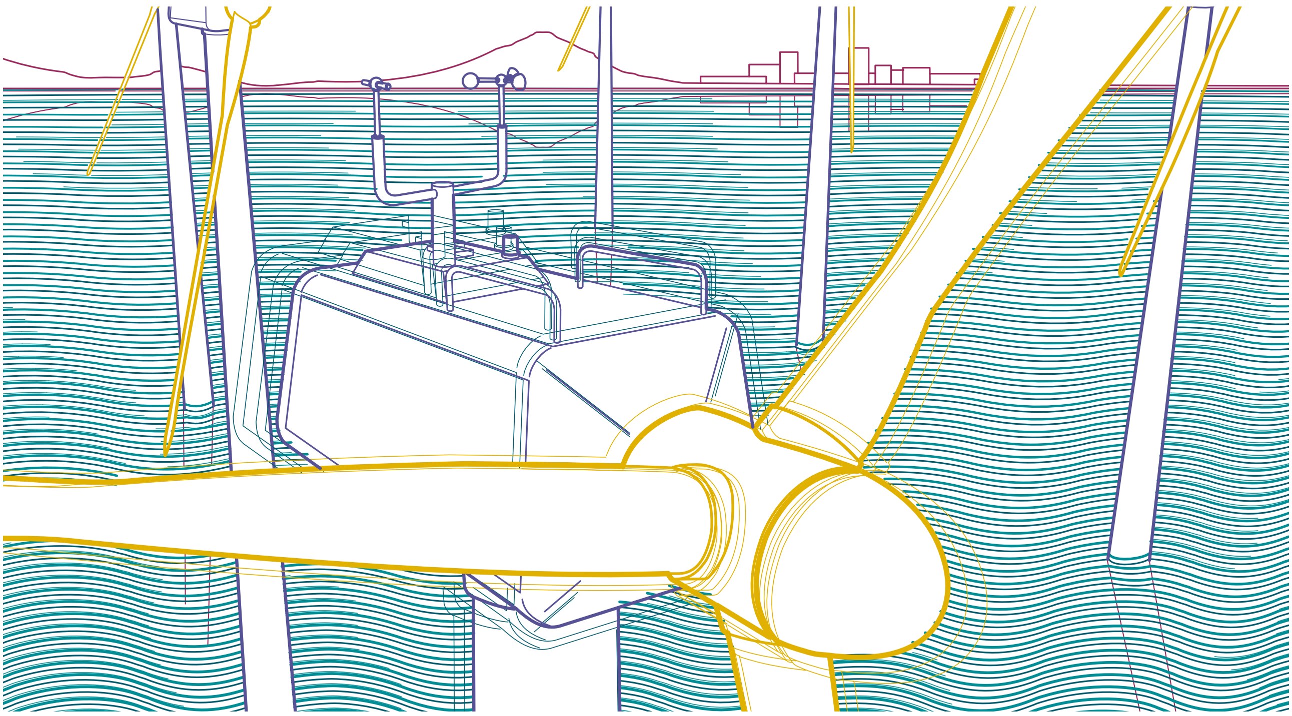
Introduction

Wind power has always given the necessary propulsive force to sailing ships and has been also used to run windmills.
Then, this type of energy has fallen into disuse due to the spreading of electric power and thanks to the availability of low cost machines supplied by fossil fuel.
However, the recent attention paid to climate changes, the demand to increase the amount of green energy and fear of a decrease of oil fuel in the future have promoted a renewed interest in the production of electrical energy from renewable sources and also from the wind power. This type of energy, with respect to other renewable energies, requires lower investments and uses a natural energy source usually available everywhere and particularly usable in the temperate zones, that is where most of the industrialized countries are.
During the last decade of the Twentieth century, different models of wind turbines have been built and tested: with vertical and horizontal axis, with variable number of blades, with the rotor positioned upstream or downstream of the tower, etc. The horizontal axis wind turbine (HAWT) with upstream three-blade rotor has resulted to be the most suitable typology and consequently has found a remarkable development, characterized both by a quick grow in size and power, as well as by a wide spread.

This Technical Application Paper is intended to define the basic concepts which characterize this application and to analyze the problems met when designing a wind power plant. Starting from a general description of the modalities for the exploitation of the wind energy through wind power plants, the technical characteristics of a wind turbine as a whole are described and the methods of protection against overload, earth faults and overvoltages are presented with the purpose of helping to choose the most suitable switching and protection devices for the different components of the plant.
In particular, in the first general Part, the operating principle of wind power plants is described, together with their typology, the main components, the installation methods and the different configurations. Besides, the power output of a plant and how it can vary as a function of determined quantities are analyzed. The second Part, after an overview of the main protection techniques against overcurrents, earth faults and overvoltages, analyzes the effects of wind turbines on the grid to which they are connected. Finally, the third Part presents the solutions offered by ABB for wind power applications.
To complete this Technical Application Paper there are four annexes.
The first three annexes refer to the Italian context and Standards and to the resolutions and decrees in force at the moment of draft. Particular attention is paid to an analysis of the economic incentives and the valorization of the produced energy; moreover there are information about the connection to medium and high voltage grid and about the measure of the energy and some hints at the general dimensioning of the earthing arrangement for a wind turbine connected to a MV grid. The last annex instead offers a comparison between drag type and lift type turbines.

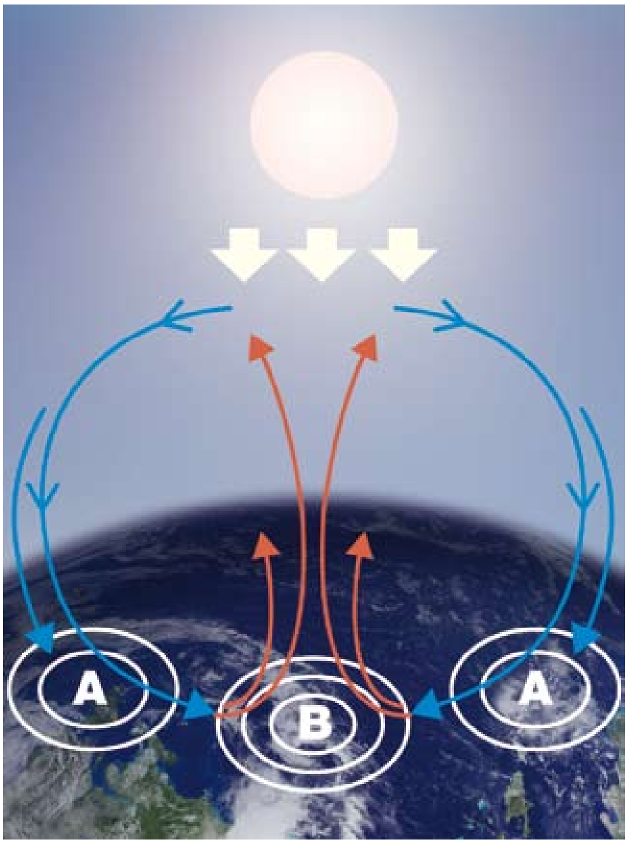


1 Generalities on wind power plants

1.1 Physics and nature of wind

The Earth continuously releases into the atmosphere the heat received by the sun, but unevenly. In the areas where less heat is released (cool air zones) the pressure of atmospheric gases increases, whereas where more heat is released, air warms up and gas pressure decreases.
As a consequence, a macro-circulation due to the convective motions is created: air masses get warm, reduce their density and rise, thus drawing cooler air flowing over the earth surface.
This motion of warm and cool air masses generates high pressure and low pressure areas permanently present in the atmosphere and also influenced by the rotation of the earth (Figure 1.1).

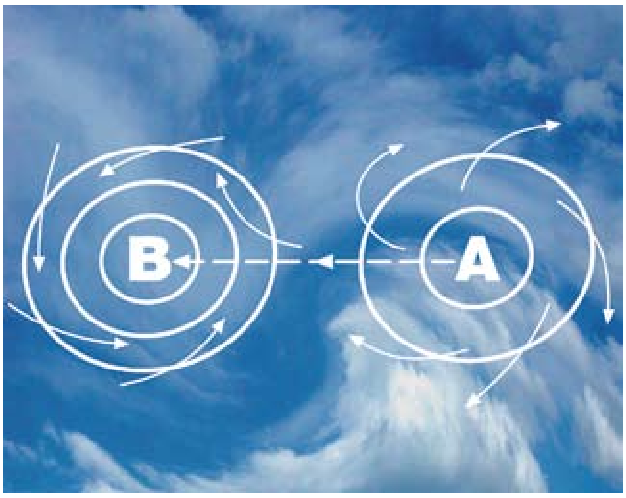
Figure 1.1



Since the atmosphere tends to constantly re-establish the pressure balance, the air moves from the areas where the pressure is higher towards those where it is lower; therefore, wind is the movement of an air mass, more or less quick, between zones at different pressure.
The greater the pressure difference, the quicker the air flow and consequently the stronger the wind.

In reality, the wind does not blow in the direction joining the centre of the high pressure with that of the low pressure, but in the northern hemisphere it veers to the right , circulating around the high pressure centers with clockwise rotation and around the low pressure ones in the opposite direction.
In the practice, who keeps his back to the wind has on his left the low pressure area "B" and on his right the high pressure area "A" (Figure 1.2). In the southern hemisphere the opposite occurs.

Figura 1.2



On a large scale, at different latitudes, a circulation of air masses can be noticed, which is cyclically influenced by the seasons. On a smaller scale, there is a different heating between the dry land and the water masses, with the consequent formation of the daily sea and earth breezes.

The profile and unevenness of the surface of the dry land or of the sea deeply affect the wind and its local characteristics; in fact the wind blows with higher intensity on large and flat surfaces, such as the sea: this represents the main element of interest for wind plants on- and off shore.

Moreover, the wind gets stronger on the top of the rises or in the valleys oriented parallel to the direction of the dominant wind, whereas it slows down on uneven surfaces, such as towns or forests, and its speed with respect to the height above ground is influenced by the conditions of atmospheric stability.

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[1] The deflection is caused by the terrestrial rotation and by the consequent Coriolis fictitious force. In fact, excepted for the equatorial belt, in any other point on earth, a moving object is affected by the rotation of the Earth, the more noticeably, the closer to the poles; thus, the air flowing to the north in the northern hemisphere tends to deflect to north-east, whereas if it flows to the south, it will deflect to south-west.

1.2 Wind as energy source

In order to exploit wind energy, it is very important to take into account the strong speed variations between different places: sites separated by few kilometers may be subject to very different wind conditions and have different implication for the installation purposes of wind turbines. The strength of the wind changes on a daily, hour or minute scale, according to the weather conditions.

Moreover, the direction and intensity of the wind fluctuate rapidly around the average value: it is the turbulence[2], which represents an important characteristic of wind since it causes fluctuations of the strength exerted on the blades of the turbines, thus increasing wear and tear and reducing their mean life. On complex terrain, the turbulence level may vary between 15% and 20%, whereas in open sea this value can be comprised in the range from 10% to 14%.

Variability and uncertainty of winds represent the main disadvantages of the electrical energy derived from the wind source. In fact, as far as the amount of power produced by the wind plant is small in comparison with the "size" of the grid to which it is connected, the variability of energy production from wind source does not destabilize the grid itself and can be considered as a change in the demand for conventional generators.

In some countries large-size wind plants are being considered, prevailingly offshore groups of turbines. Such wind farms shall have a power of hundreds of MW, equivalent to that of conventional plants, and therefore shall be able to foresee their energy production 24 hours in advance; this since the electrical grid manager must be able to know in advance the predictable offer of the various producers with respect to the consumers' demand.

When taking into consideration a site for the installation of a wind turbine, an assessment of the real size of the wind resource is fundamental. Therefore an anemometric tower is usually installed on site for different months in order to monitor the wind speed and direction and the turbulence levels at different heights. The recorded data allow an evaluation of both the prospective energy production as well as the economic feasibility of the project.

[2] *The turbulence intensity is defined, over each time interval, as the ratio between the standard deviation of the wind speed and the mean wind speed. The characteristic time interval is often defined at 10min.*

Figure 1.3 – Worldwide wind map: average wind speed in m/s at 10m height

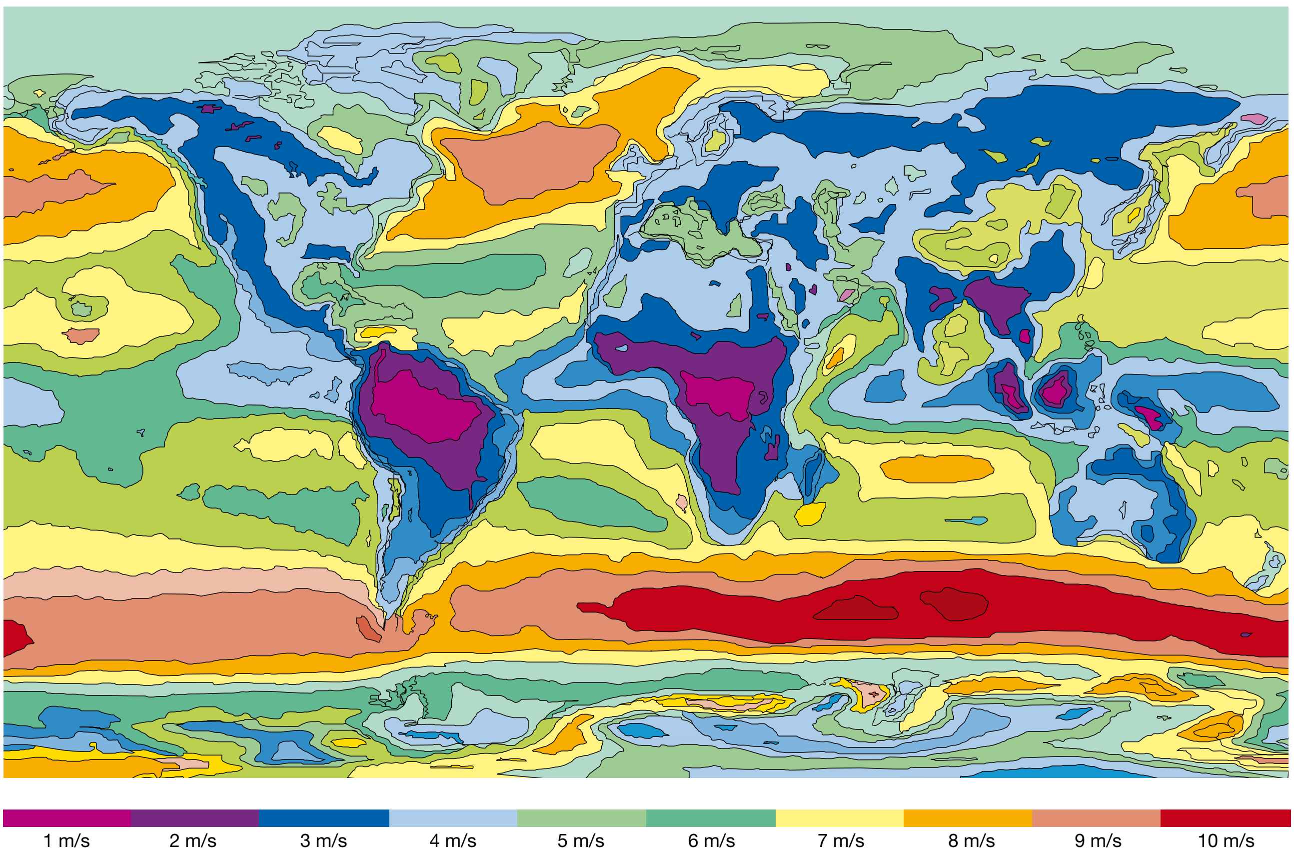
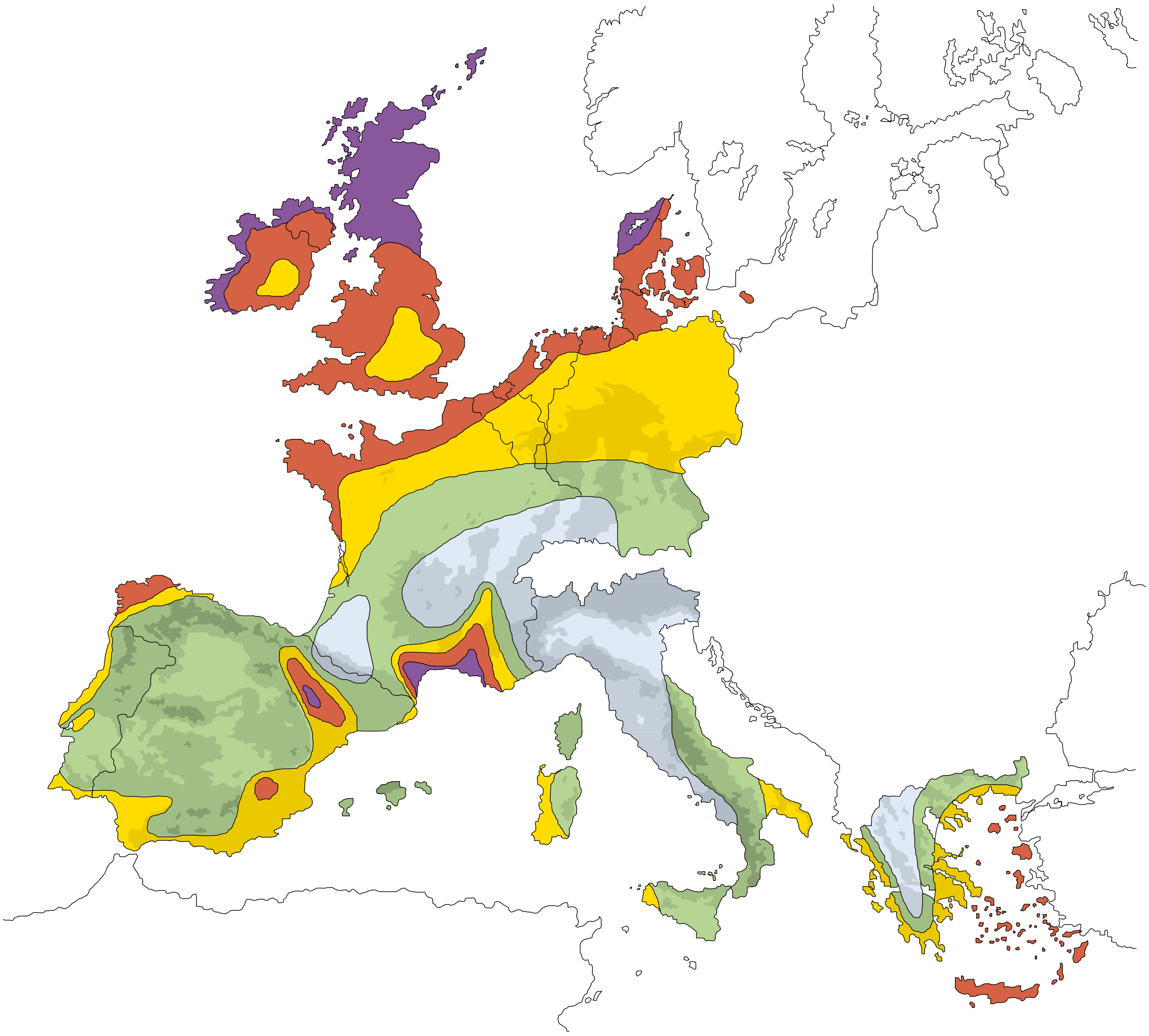


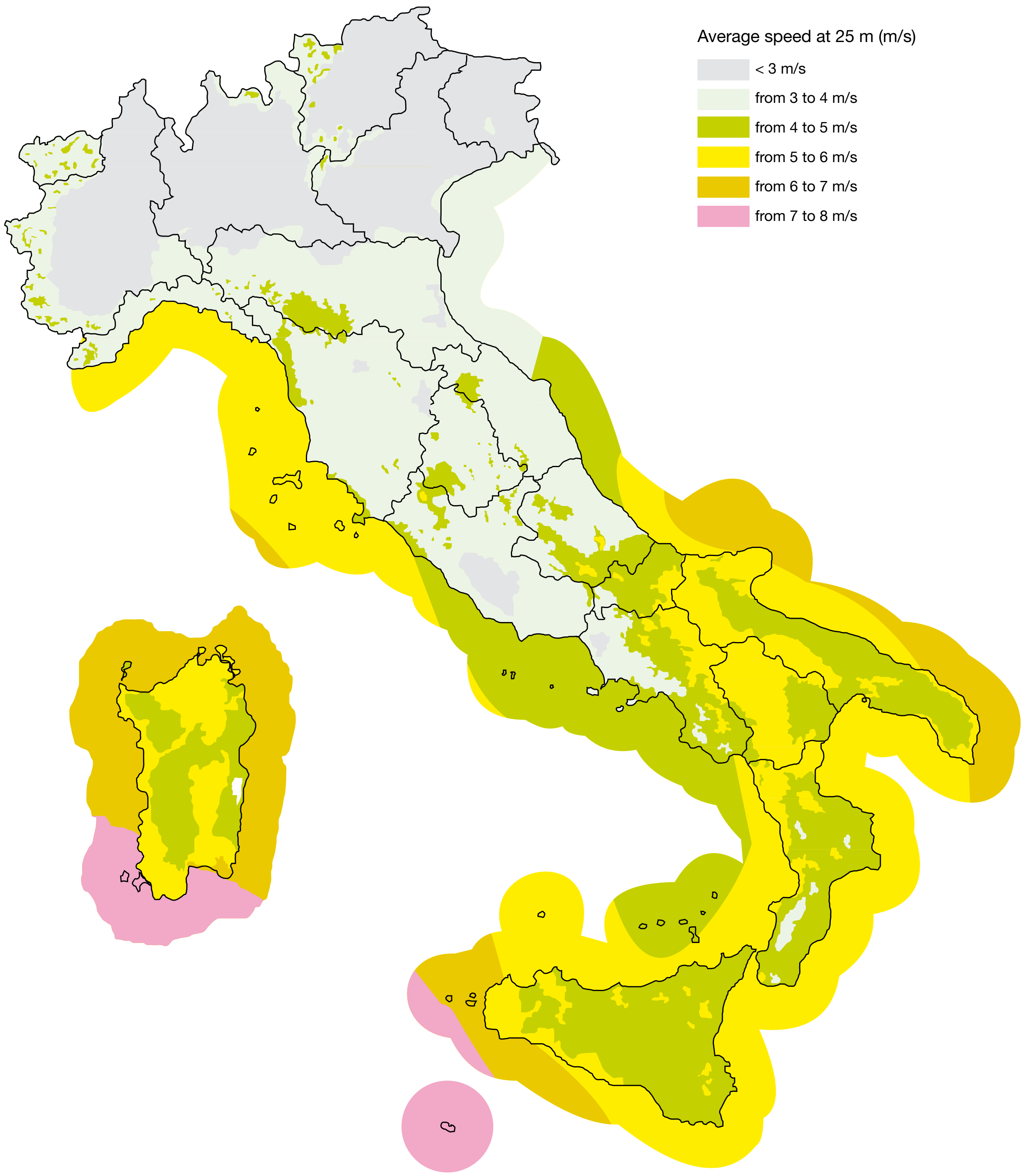
Figure 1.4 – European Community wind resource map



Wind resources at 50 metres above ground level for five different topographic conditions

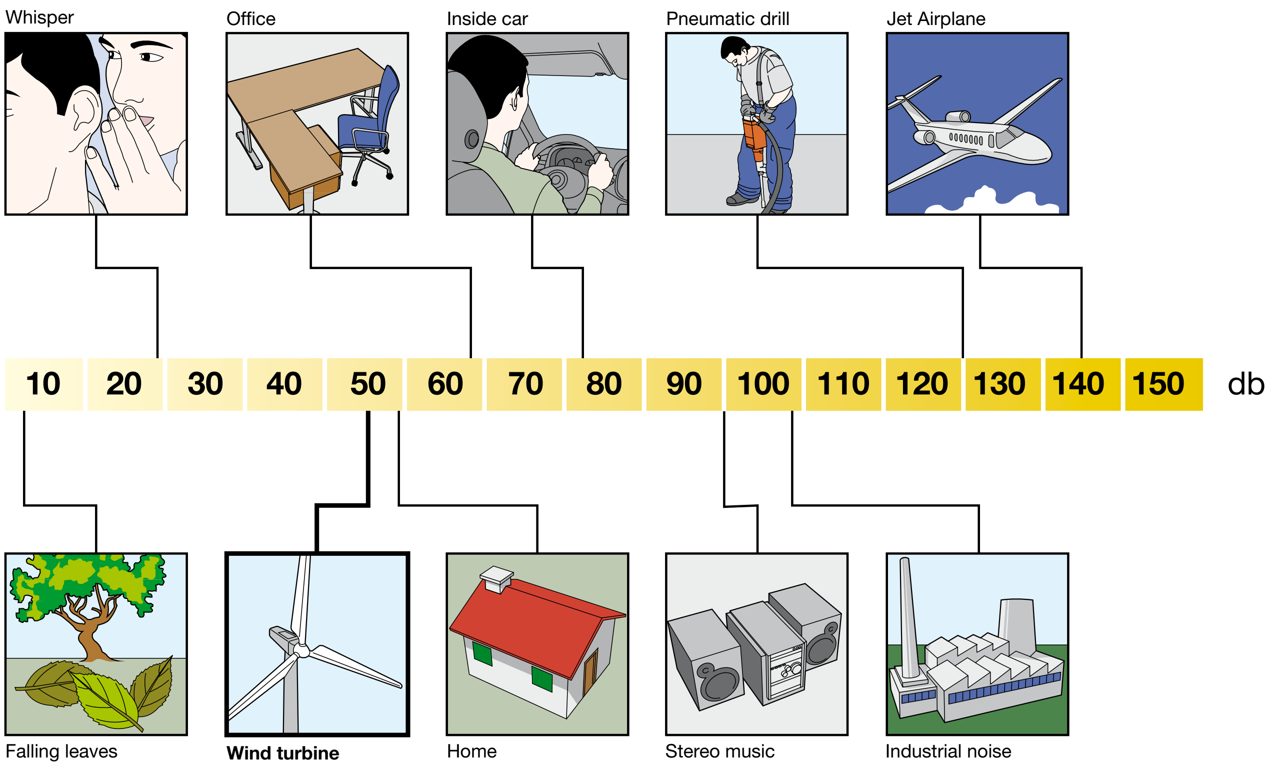
	Sheltered terrain		Open plain		At a sea coast		Open sea		Hills and ridges	
	m/s	**W/m²**	**m/s**	**W/m²**	**m/s**	**W/m²**	**m/s**	**W/m²**	**m/s**	**W/m²**
(purple)	> 6.0	> 250	> 7.5	> 500	> 8.5	> 700	> 9.0	> 800	> 11.5	> 1800
(red)	5.6-6.0	150-250	6.5-7.5	300-500	7.0-8.5	400-700	8.0-9.0	600-800	10.0-11.5	1200-1800
(yellow)	4.5-5.0	100-150	5.5-6.5	200-300	6.0-7.0	250-400	7.0-8.0	400-600	8.5-10.0	700-1200
(green)	3.5-4.5	50-100	4.5-5.5	100-200	5.0-6.0	150-250	5.5-7.0	200-400	7.0-8.5	400-700
(light blue)	< 3.5	< 50	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 7.0	< 400

Figure 1.5 – Italy wind resource map



The environmental impact has always been a big deterrent to the installation of wind power plants. In fact, in the most cases, the windiest places are the peaks and the slopes of the mountains relieves, where the wind installations result to be visible also from a great distance, with an impact on the landscape not always tolerable. It is possible to reduce the visual impact due to the presence of the turbines by adopting constructional solutions such as the use of neutral colors to help integration into the landscape.
Then, since the ground actually occupied by wind turbines is a minimum part of the wind farm area because the remaining part is necessary only for requirements of distance between the turbines to avoid aerodynamic interference, it is possible to continue using the area also for other purposes, such as agriculture or sheep farming.
Also the noise of the wind turbines has to be considered: such noise is caused by the electromechanical components and above all by the aerodynamic phenomena due to the blade rotation and depending on the characteristics of the blades and on their peripheral speed.
The problem of the noise may become negligible when considering two factors: the first one is that the noise perceived near to the wind turbines is sometimes attributed solely to wind generators, but, in reality, in windy areas and hundreds of meters from the generators, the background noise caused by the wind can be compared to that of the turbines; the second factor is that at a short distance from the wind turbines, the noise perceived has an intensity near to that of common daily situations and therefore also the personnel working in the area of the wind power station would be subject to acceptable acoustic disturbances (Figure 1.6).
However, at 400-500m distance from the turbine, the sound effects are practically negligible.

Figure 1.6 - Decibel chart



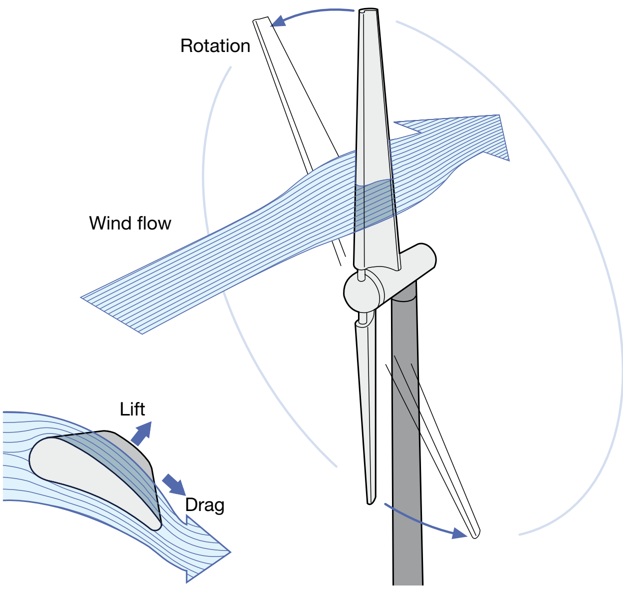
Moreover, the authorities charged with the control of the air traffic in some countries have recently raised doubts about the installation of new wind plants since these could interfere with radars, which cannot easily eliminate the echoes due to the wind towers because of their high RCS (Radar Cross Section)[3].
Always in the field of electromagnetic disturbances, wind blades (particularly if made of metal or reflecting materials or if having metal structures inside) and supports can interfere with telecommunication electromagnetic fields. However these interferences can be avoided above all by using non-metal materials for turbine construction.
As for the effects of the installation and service of a wind turbine on the surrounding flora, there are no quantifiable effects resulting from the experiences in countries with high distribution of wind power.
On the contrary, as regards the fauna, above all birds and bats might suffer damages caused by the presence of turbines due to the risk of collision with the blades. However, from some data relevant to wind power plants in the United States and in Spain only limited damages to birds have resulted (from 1 to 6 collisions for MW installed). Moreover, a research carried out in Spain on about a thousand of wind turbines, has highlighted a sort of "adaptive evolution" of the birds to the environmental conditions, with a reduction of the number of injured specimens.

1.3 Operation principle of wind turbines

Wind turbines or *aerogenerators* transform the kinetic energy of the wind into electrical energy with no use of fuel and passing through the phase of conversion into mechanical rotation energy carried out by the blades.
Turbines can be divided into "*lift*" machines and "*drag*" machines according to which force is generated by the wind and exploited as "motive force".
To understand the operation principle of a wind turbine, reference is to be made to the most widespread turbines, that is the "lift" ones. In the "lift" turbines, with respect to the "drag" type, the wind flows on both blade surfaces, which have different profiles, thus creating at the upper surface a depression area with respect to the pressure on the lower surface.

This pressure difference creates on the surface of the wind blade a force called aerodynamic lift (Figure 1.7), as it occurs for aircraft wings.

Figure 1.7



Lift force on the wings of an airplane can lift it from the ground and support it in flight, whereas in a wind turbine, since the blades are bound to the ground, it determines the rotation about the hub axis.
At the same time a drag force is generated, which is opposed to the motion and is perpendicular to the lift force. In the turbines correctly designed, the ratio lift-drag is high in the field of normal operation.
An aerogenerator requires a minimum wind velocity (cut-in speed) of 3-5 m/s and delivers the nameplate capacity at a wind velocity of 12-14 m/s. At high speeds, usually exceeding 25 m/s (cut-off speed) the turbine is blocked by the braking system for safety reasons. The block can be carried out by means of real mechanical brakes which slow down the rotor or, for variable pitch blades, "hiding" the blades from the wind, by putting them in the so-called "flag" position.

[3] *RCS reflection coefficient (Radar Cross Section) is a measure of how detectable an object is with a radar since when radar waves are beamed at a target, only a certain amount are reflected back towards the source. Different factors determine how much electromagnetic energy returns to the source, such as the angles created by surface plane intersections. For example, a stealth aircraft (which is designed to be undetectable) will have design features that give it a low RCS, as opposed to a passenger airliner that will have a high RCS.*

[4] *The airfoil of the wind blade determines a different speed of the fluid vein which passes the upper surface with respect to the speed of the fluid vein flowing over the lower surface. Such difference of speed is at the origin of the pressure variation.*

[5] *Position in which the chord of the blade profile is parallel to the rotor shaft with the edge of attack facing the wind direction. In such position the aerodynamic load on the blades is reduced to the minimum.*

The main advantages of the wind plants can be summarized as:

- distributed generation
- effective conversion of the wind energy into electrical energy (59% theoretical efficiency)
- lack of emission of polluting substances
- saving of fossil fuels
- reduced service (there are no costs for the fuel supply) and maintenance costs
- easy dismantlement of the wind turbines at end of life (20/25 years)
- the generation capability of the wind turbine ranges from few hundreds of Watts to some MWatts, thus meeting the requirements of both single dwelling-houses, as well as of industrial applications or of injection into the network (through wind power stations).

1.4 Types of wind turbines

Wind turbines can be divided according to their construction technology into two macro-families:

- *Vertical Axis Wind Turbines - VAWT*
- *Horizontal Axis Wind Turbines – HAWT*

VAWT turbines, which constitutes 1% of the turbines used at present, are divided into:

- *Savonius turbines*
- *Darrieus turbines*
- *hybrid turbines, Darrieus-Savonius type*

whereas HAWT turbines, which constitutes 99% of the turbines used at present, are divided into:

- *upwind turbines*
- *downwind turbines.*

About 99% of the installed horizontal axis wind turbines is three-blade, whereas 1% is two-blade.

1.4.1 Vertical axis wind turbines-Savonius type

It is the simplest model of turbines and it consists of two (or four) vertical sheets, without airfoil, and curved to form a semicircumference (Figure 1.8). It is also called "drag turbine", since the motive torque is based on the difference in resistance (friction) offered against the wind by the vertical surfaces symmetrically arranged with respect to the axis.

Figure 1.8 - Turbine Savonius type

The main characteristics of Savonious turbine are:

- "slow" turbine
- low efficiency value
- suitability for low values of wind speed and within a limited range
- necessity of adequate speed control to keep the efficiency within acceptable values
- impossibility of reducing the aerodynamic surface in case of speed exceeding the rated one because of the fixed blades
- necessity of a mechanical break for stopping the turbine
- necessity of a robust structure to withstand extreme winds (the high exposed surface of the blades)
- suitable for small power applications only
- low noise.

[6] *The difference between "slow" and "fast" turbines is made based on the value of the peripheral tangential speed at the extremities of the blades.*

1.4.2 Vertical axis wind turbines – Darrieus type

They are vertical axis "lift-type" wind turbines since the surfaces presented to the wind have an airfoil able to generate a distribution of the pressure on the blade and therefore an available torque at the rotation axis (Figure 1.9).

Figure 1.9 - Turbine Darrieus type

In comparison with the "drag-type" Savonius turbines, Darrieus type (and lift-type turbines) offer higher efficiency since they reduce the losses due to friction.
However, Darrieus-type turbines cannot start autonomously since, independently of the wind speed, the start-up torque is null: as a consequence this type of turbine needs an auxiliary device.
For the combined type Darrieus-Savonius the starting torque is represented by the Savonius turbine coaxial and internal to the Darrieus turbine (Figure 1.10).

Figure 1.10 - Hybrid turbine Darrieus-Savonius

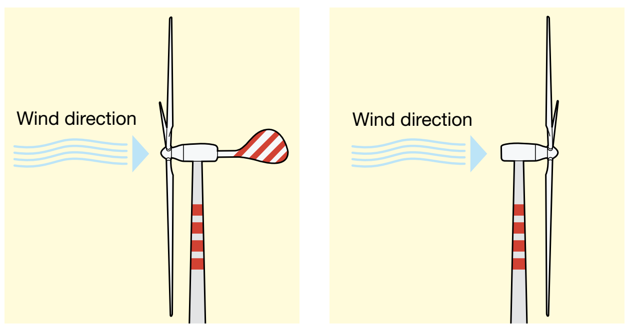
The main characteristics of the Darrieus-type turbine are:
- "fast" turbine
- reduced efficiency in comparison with horizontal axis turbines, also because a great part of the blade surface rotates very close to the axis at a low speed
- adaptability to variations in the direction of the wind
- effective for winds with an important vertical component of speed (sites on slopes or installation on the roof of the buildings "corner effect")
- suitable for low values of wind speed and for a limited range
- necessity of an adequate speed control to keep the efficiency within acceptable values
- impossibility of reducing the aerodynamic surface in case of speed exceeding the rated one because of the fixed blades
- necessity of a mechanical break for stopping the turbine
- necessity of a structure not extremely robust to withstand extreme winds (given the smaller surface of the blades exposed to the wind in comparison with Savonius turbines)
- suitable for large power applications
- low noise and with vibrations limited to the foundations, therefore suitable to be installed on buildings
- able to operate also under turbulent wind conditions
- gearbox and electric generator may be positioned at ground level
- high fluctuations of the motive mechanical torque.

[7] The world largest vertical axis wind turbine is installed in Canada with 4.2 MW rated power.

1.4.3 Horizontal axis wind turbines

Upwind horizontal axis wind turbines, called so because the wind meets first the rotor than the tower, have a higher efficiency than downwind machines, since there are no aerodynamic interference with the tower.
On the other hand they have the drawback that they are not self-aligning in the direction of the wind and therefore they need a tail vane or a yaw system.
Upwind horizontal axis turbines are affected by the negative effects of the interaction tower-rotor, but are intrinsically self-aligning and have the possibility to use a flexible rotor to withstand strong winds (Figure 1.11).

Figure 1.11



Three-blade horizontal axis wind turbines (Figure 1.12) are the most widespread model; however, there are also two-blade models (Figure 1.13), single-blade with counterweight (Figure 1.14), at present fallen into disuse, and multi-blade models, used above all in the small-wind market (Figure 1.15).

Figure 1.12 - Three-blade turbines

[8] *Free orientation through tail vanes in small wind turbines or active electrical orientation after signaling by the "flag" in higher power turbines.*

Figure 1.13 - Two-blade turbine

Figure 1.14 - Single-blade with counterweight turbine

Figure 1.15 - Multi-blade turbine

Since the rotation speed decreases when increasing the number of blades (whereas the torque rises), two-blade rotors require higher rotational speed in comparison with three-blades rotor (characteristic revolutions per minute 40 rpm with respect to 30 rpm of three-bladed ones) with a consequent louder aerodynamic noise.
Moreover, a two-blade rotor is subject to imbalance due to the wind variation caused by the height, to gyroscopic effects when the nacelle is yawed and has a lower moment of inertia when the blades are vertical compared to when they are horizontal. This is the reason why most two-blade turbines generally use a teetering hub, thus allowing the asymmetric thrust on the rotor to be balanced.
However, the two-blade rotor is lighter and therefore all the supporting structures can be less massive with a consequent reduction in costs. Moreover, the visual impact and the noise are less important in offshore installations, which, in addition to smaller costs, makes two-blade rotors desiderable for such applications.
Table 1.2 compares the main features of a two- and a three-blade turbine.

Table 1.1

TWO-BLADE	THREE-BLADE
Lower cost of the rotor (low weight)	Better balance of aerodynamic forces
Louder noise (higher peripheral speed)	Better mechanical stability (the gyroscopic forces are balanced)
Easier installation (assembly of the tower at ground level)	More uniform motive torque
More complex design (a teetering hub is necessary)	Lower visual impact

1.5 Features of wind turbines

When making a distinction based on the power of wind turbines, wind power plants can be classified as follows:

- "*small*" wind turbines for rated power lower than 20kW, consisting in plants mainly intended for the supply of household loads;
- "*medium*" wind turbines for rated power ranging from 20 to 200kW, with plants mainly intended for the generation and sale of electrical energy;
- "*large*" wind turbines for rated power exceeding 200kW, mainly constituted by wind energy power plants for the integration of the produced energy into the transmission grid.

The performance of a wind turbine is characterized by definite speed values, referred to different phases:

- *Start-up speed* - the rotor starts to rotate and the alternator generates a voltage which increases when the wind speed rises
- *Cut-in speed* (2-4 m/s) – when the voltage is high enough to be adopted in the specific application, then energy is really produced and the whole circuit becomes active and it becomes the load of the turbine
- *Rated speed* (10 - 14 m/s) – it is the wind speed at which the rated power is reached
- *Cut-off speed* (20 – 25 m/s) – it is the wind speed beyond which the rotor has to be stopped to avoid damages to the machine; it is the control system which intervenes, with suitable active or passive systems.

A wind turbine shall withstand the worst storm which may occur on the installation site, during the design lifetime. If the turbine is installed for 20 years, the extreme gust considered shall be that one having 50-year recurrence period.
Table 1.1 (CEI EN 61400-1) shows the different classes of wind turbines as function of the speed V_{ref}[9] which is the reference wind speed average over 10 min[10].

Table 1.2 - Basic parameters for wind turbine classes

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42.5	37.5	Values specified by the designer
A	I_{ref} (-)	0.16			
B	I_{ref} (-)	0.14			
C	I_{ref} (-)	0.16			

Where:

- V_{ref} is the reference wind speed average over 10 min
- A designates the category for higher turbulence characteristics
- B designates the category for medium turbulence characteristics
- C designates the category for lower turbulence characteristics
- I_{ref} is the expected value of the turbulence intensity at 15 m/s.

Besides, a wind turbine shall be designed to operate at ambient temperatures ranging from -10°C to +40°C under normal wind conditions and from -20°C to +50°C under extreme wind conditions (IEC 61400-1).

[9] *A wind turbine designed for a class with reference wind speed V_{ref} is sized to withstand climates for which the extreme value of the mean wind speed over a 10 min time, at the height of the hub of the wind turbine and a recurrence period of 50 years, is lower or equal to V_{ref}.*

[10] *The Std. IEC 61400-1 defines a further class of wind turbines, class S, to be adopted either when the designer and/or the customer signal special wind conditions or other special external conditions, or when a special safety class is required.*

The main options in a wind turbine design and construction include:

- number of blades (commonly two or three)
- rotor orientation (upwind or downwind of tower)
- blade material, construction method, and profile
- hub design: rigid, teetering or hinged
- power control via aerodynamic control (stall control) or variable-pitch blades (pitch control);
- fixed or variable rotor speed
- orientation by self-aligning action (free yaw) or direct control (active yaw)
- synchronous or asynchronous generator (with squirrel-cage rotor or wound rotor -Doubly Fed Induction Generator (DFIG))
- with gearbox or direct drive generator.

Some time ago, the size of the turbines most commonly used was in the range from 600 to 850kW, generally with three-blade rotor, diameter between 40 and 55m and 50m hub height above ground.

Over the last years, in Italy as in northern Europe, three-blade rotor turbines have begun to be installed having power from 1.5 to 3MW, diameter in the range 70 to 90m and about 100m hub height.

Small wind turbines includes also vertical axis turbines, with units from some dozens W to some kW for isolated applications or connected to the grid but for the supply of household networks.
As large wind turbines, there are already 5 to 6 MW machines, with rotor diameters from 120 to 130m, typically used in offshore plants. The maximum power of the largest single turbine currently on the market is 8 MW, but 10 MW turbines with 160m rotor diameter are being designed.
The interest in offshore plants is due to the fact that they allow the exploitation of stronger and regular winds and have a lower visual impact. Moreover, while the annual producibility of an onshore plant is in the order of 1500-2500 MWh/MW, that of an offshore plant is in the order of 3000-3500 MWh/MW[11].

Thanks to the available technologies for the wind turbines founded into the seabed, offshore areas with water depth up to 30-40m can be exploited for the installation. For deeper depths the floating wind turbines which are being tested at the moment are used. But offshore wind farms imply higher investments in comparison with onshore plants because of the costs due to underwater foundations and offshore installations. Such investment is around 2800-3000 €/kW vs 1800-2000 €/kW for large onshore plants. The investment costs for "medium" wind turbines are bigger and can reach 2500-4000 €/kW.

On average, the splitting of the investment for a wind power plant is 70% for wind turbines and 30% for the remaining part (foundations, installation, electrical substructures…).

The lifetime of wind power plants is considered to be about 30 years, even if usually after 20 years these plants are dismantled because of the progressive decrease in the energy production due to the aging of wind turbine components.

Table 1.3 – Example of features of a wind turbine

Rated power	**4.5 MW**
Number of blades	3
Rotor diameter	120 m
Control	blade inclination and variable speed
Blade length	58 m
Maximum chord of the blade	5 m
Blade mass	18 t
Mass of the nacelle with rotor and blade	220 t
Tower mass (steel tubular structure)	220 t
Tower height (depending on the local wind conditions)	90-120 m
Tower diameter at base	5.5 m
Rotation speed of the rotor	9-15 rpm
Gearbox ratio	100-1
Start-up speed of the turbine	4 m/s
Rated wind speed	12 m/s
Shut-down wind speed of the turbine	25 m/s

[11] The efficiency of the use of a turbine in a specific site is often assessed based on the ratio between total annual power output (kWh) and rated power of the turbine (kW). The quotient represents the relevant number of hours/year of production at the rated power..

1.6 Tipology of wind power plants

1.6.1 Grid connected plants

These plants can be distinguished into single wind turbine plants (connected to the grid with or without household or industrial loads in parallel) and plants structured as wind farms.
The first ones, if in the presence of loads in parallel, use the network as a "storage" where the energy produced in excess and not self-consumed by the consumer plant can be fed into and from which the energy can be drawn if the wind turbine cannot provide for the energy supply needs of the consumer plant in case of reduced wind speed.

Wind farms instead are groups of more interconnected wind turbines operating as an electrical power station connected to the grid. In this case, the turbines must be positioned on the ground at a proper distance one from the other, so that the aerodynamic interference can be avoided. Such interference would have two main consequences: the first one linked to an increase in the turbulence and the second one to power losses. The distance between wind turbines is usually expressed as turbine diameter; the best interval is about 8 to 12 times the diameter of the rotor along the wind direction and from 2 to 4 times the diameter of the rotor transversely to the wind direction.

The turbines of wind farms may be positioned either onshore (Figure 1.16) or offshore (Figure 1.17).

Figure 1.16

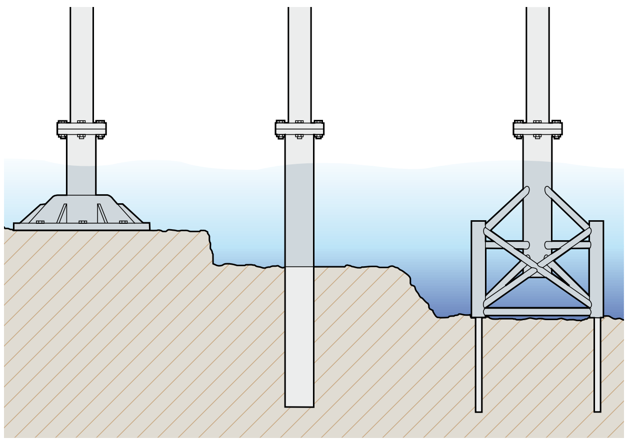
Figure 1.17

Offshore installations have higher costs but this rise in prices is compensated for by at least 30% increase in production. Moreover, offshore wind farms require a great number of large aerogenerators with power up to 5-6MW each, so that the high costs of installation, grid connection to earth and remote control and monitoring can be compensated for. The technology used at the present time for offshore installations is similar to that of onshore plants, but wind turbines in open sea must be designed taking into account also the following critical issues:

- waves cause wear and tear and additional loads on the structure being heavier than those caused by the wind
- the mechanical characteristics of the sea floor often are not extraordinary and consequently the foundations must have larger dimensions
- the moment resulting from the loads applied to the rotor on the seabed is increased by the additional length of the submerged tower.

The support structures for offshore wind turbines can be of different types (Figure 1.18).

Figure 1.18



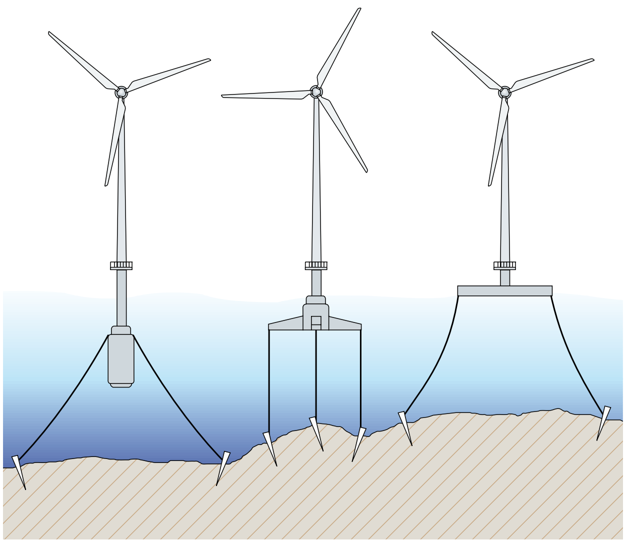
In shallow waters turbines can be fastened to concrete plates positioned on the seabed. If the depth does not exceed 20m, the structure is a steel rod hammered into the seabed up to a depth suitable to transfer loads to the floor.

This type of foundation, although it is the most economical one, it is used to a limited extent because of the risk of resonance frequencies within the interval of frequencies forced by rotor rotation and by waves. The resonance frequency decreases with the length of the structure and increases with its diameter. In deep waters the diameter of the monopile becomes unacceptable and therefore tripod structures are used, made of elements welded together and anchored to the ocean floor with poles at each corner or with suction cup anchors, according to its characteristics.

Offshore wind turbines must be very reliable so as to reduce as most as possible maintenance operations: thus, the redundancy of some components is justified and remote monitoring through sensors placed in the most critical parts is adopted by default. Besides, these turbines are designed to withstand marine environment; in fact the submerged structures are protected against corrosion through cathodic protection, whereas the parts in free air are properly painted. The insulation of the electrical equipment is reinforced and the air inside the nacelle and the tower is conditioned to avoid the accumulation of condensate.

For deep waters exceeding 50m anchoring to the sea floor is no longer efficient and passing to floating wind turbines – being studied at present – is to be considered (Figure 1.19).

Figure 1.19



1.6.2 Non-grid connected plants

These plants can be distinguished into plants for single isolated loads and plants for stand-alone grids.

As regards isolated loads, which cannot be reached or for which connection to the electrical public grid is not convenient due to the high costs or technical difficulties and where the wind resource is sufficient (indicatively with an annual average speed >6m/s), wind power energy may be a reliable and cost-effective choice to supply household loads.

Wind power plants for single loads shall be equipped with a storage system ensuring power supply even under low wind conditions.
Independent grids fed by wind power energy represent a promising application. Electric power supply to loads with high demands and far from the national distribution network is usually carried out by generators supplied by fossil fuels, but it is an expensive solution due to the high delivery and maintenance costs, in addition to the environmental issue of pollution. The case of medium-small islands is quite typical, considering also that they certainly offer good wind power potentials.

The ideal solution would be to turn to hybrid systems by using wind power energy (or other renewable sources) in addition to traditional sources, which result to be quite cost-effective in case of connection to decentralized networks with power in the order of MW.

A diesel-wind power system generally consists of medium/small-sized turbines combined with a storage system and connected to a LV or MV grid; the diesel generator is used to guarantee electric power supply continuity.

The cost per kWh is higher than for plants with large-sized turbines, but almost always lower if compared with power generation through diesel motors only, since in this last case also the costs for the fuel supply are to be considered.

1.7 Costs of wind power

Wind power can be considered, especially when produced in multi-MW wind installations, an effective type of energy in terms of costs, environmental impact and investment return times (3 to 5 years).

In fact, as it can be noticed in Table 1.4, the power output of large-size wind plants has investment and production costs (maintenance, fuel and personnel included) which can be compared to those of a traditional coal-fired thermal power station.

Besides, from Table 1.5, it can be noticed that wind power implies costs of externalities lower than those of traditional power plants.

In addition, it must be considered that for each kWh of wind power produced the emission of a certain quantity of polluting substances into the atmosphere and a "greenhouse effect" is avoided as shown in Table 1.6.

[12] *Costs which are not included in the market price and which neither producers nor consumers bear, but are overall costs incurred by society.*

Table 1.4

Energy costs		
Type of plant	Investment cost €/kWh	Cost of the power produced €/kWh
Multi-MW wind plant	1000 – 2200	0.04 – 0.08
Coal-fired thermal power station	1000 – 1350	0.05 – 0.09
Gas thermal power station	500 - 700	0.03 – 0.04

Table 1.5

Costs of externalities								
Source	Coal	Oil	Gas	Nuclear	FV	Biomasses	Hydroelettric	Wind
C€/kWh	20 - 15	3 - 11	1 - 3	0.2 – 0.7	0.6	0.08 – 0.3	0.3 - 1	0.05 – 0.25

Table 1.6

Type of substance	**kg/kWh**
Carbon dioxide (CO_2)	0.675
Nitrogen oxides (NO_x)	0.0015
Sulphur dioxide (SO_2)	0.0014

1.8 Spreading of wind energy in the world, in the European Union (EU) and in Italy

All over the world, at the end of 2009, the wind power installed had almost reached 160000 MW with a total increase of 233% since 2004, whereas, at the end of 2010, the wind power reached 194000 MW (GWEC data).
In the European Union at the end of 2009 73000 MW installed were exceeded with an increase of 114% in comparison with 2004, whereas at the end of 2010 the wind power capacity installed reached 84000 MW, of which almost 3000 MW in offshore wind power plants (EWEA data).

In Italy, at the end of 2009, 5000 MW installed power were almost reached, with an increase of 335% since 2004 (Figure 1.20), whereas, in 2010, 5800 MW were reached.
In 2010, the energy produced in Italy from wind source was about 8.3 GWh out of a total energy demand of about 326 TWh for the same year.
In particular, considering the European Union, Germany is the country having the largest number of installations with a total power capacity exceeding 25000 MW, followed by Spain with more than 19000 MW and by Italy and France. As it can be noticed in Figure 1.21, these four nations represent 74% of the over 73000 MW wind power installed in the EU.

Figure 1.20

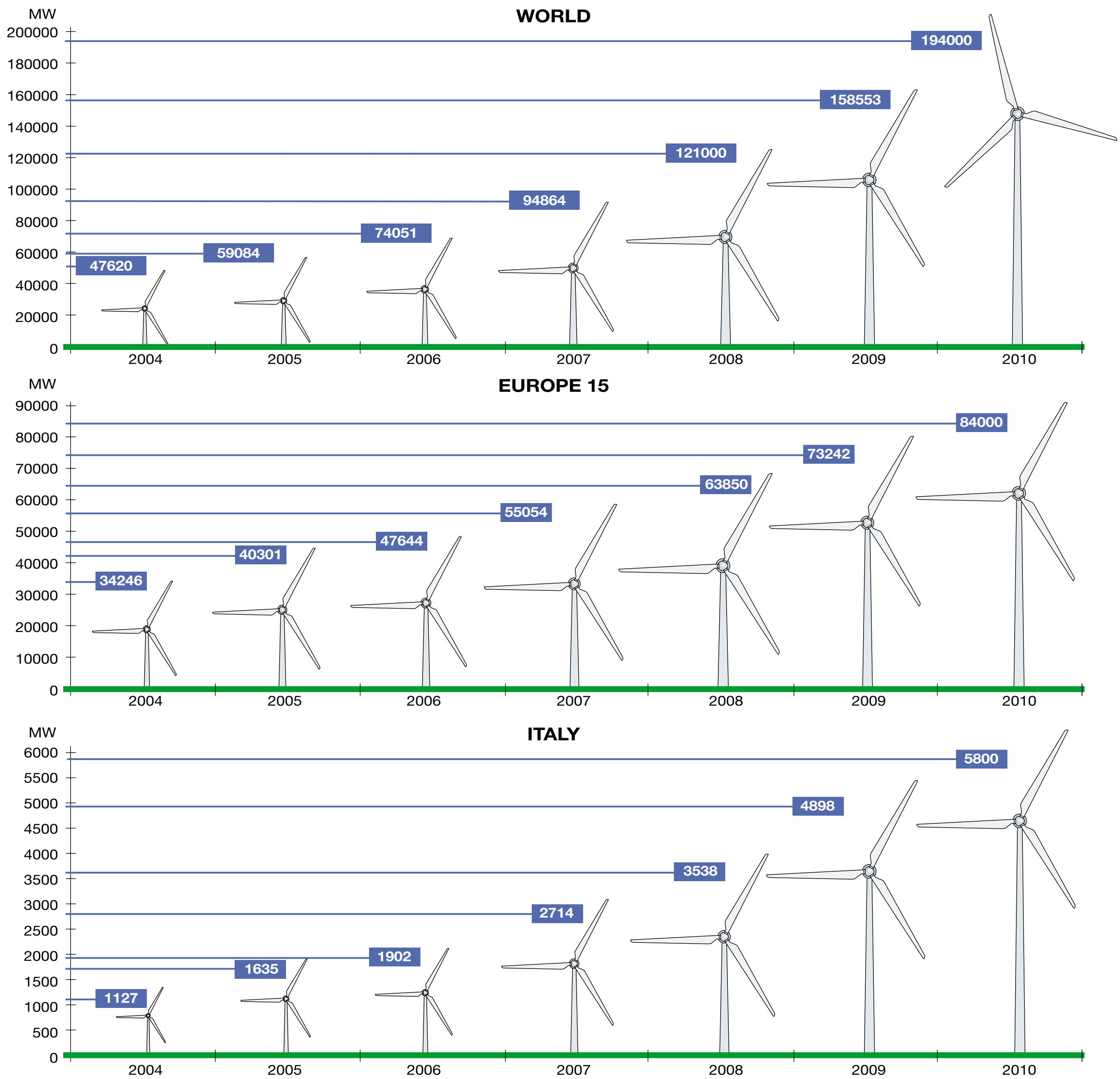
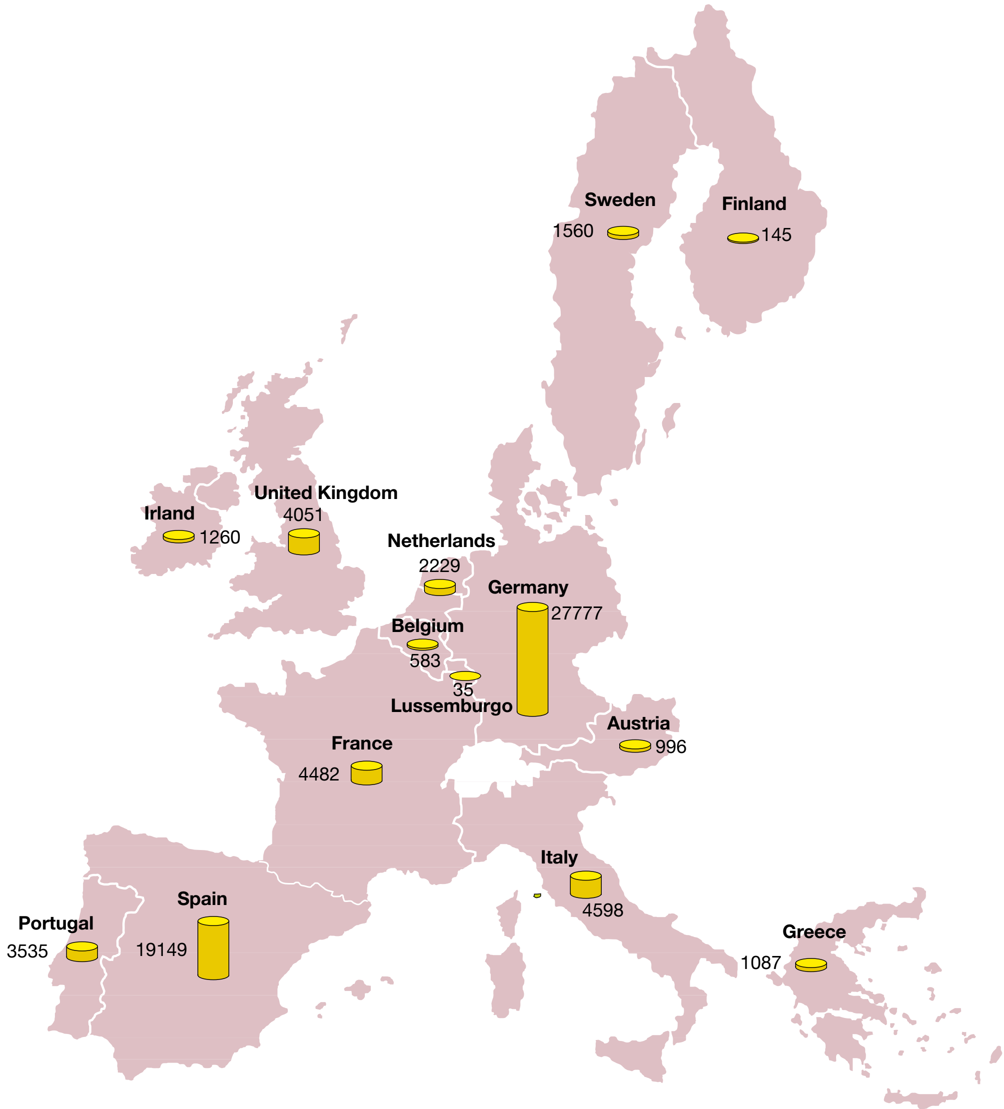


Figure 1.21



The wind power plants installed in Italy at the end of 2009 are 294 with more than 4200 wind turbines. The total power output is about 5000 MW[13], with an energy production of over 6000 GWh[14] in the same year and with a number of hours of use of the total national wind park equal to about 1300.

Taking into consideration the total of plants, 36% of them has a rated nominal power in the range from 1MW and 10MW, whereas 56% has a power exceeding 10MW. In particular, from 2000 to 2009, the medium size of power capacity for wind power plants had increased from 6.6 to 16.7MW.

[13] In Italy the average energy demand is about 38.5 GW of instantaneous gross electric power (36.4 GW instantaneous net electric power). On average, such values vary between night and day from 22 to 50 GW, with a minimum and maximum of 18.8 and 51.8 GW respectively. However, such values are affected by the reduction in the energy demand of the years 2008 and (even more) 2009 due to the international economic crisis. In fact the peak of the required power dates back to 2007, with a maximum of 56.82 GW.

[14] In 2009, in Italy, power consumption amounted to about 338 TWh. Such value is the so-called "consumption or national gross requirement" and represents the electrical energy necessary to run whatever plant or means requiring electric power supply. This datum is the sum of the values indicated at the terminals of the electrical generators of each single production plant and the balance of foreign trades. This measure is carried out before any possible deduction of the energy necessary to feed the pumping stations and without taking into consideration self-consumption in power stations.

The installed wind power plants are concentrated mainly in the regions of southern Italy: Apulia, Campania and Sicily together represent 60% of the total number of wind power plants on the national territory. In the regions of northern Italy, Liguria has the greatest number with 3.1% of the total; the regions of central Italy are at the level of the other northern regions (Figure 1.22).

Always in the southern regions 98% of the national wind power capacity is installed, where Apulia and Sicily have the leading role with 23.5% and 23.4% respectively, followed by Campania with 16.3% and Sardinia with 12.4% (Figure 1.23).

The north and central regions generally have an average dimension of wind power plants quite reduced, equal to 4.3 MW, starting from Veneto with 0.4 MW, passing through the 9 MW of Tuscany up to the 12.5 MW of the only plant installed in Piedmont. In southern Italy the average dimension is 19MW, from 9.5MW of Abruzzi to about 23MW of Sicily and Sardinia, up to 34.1MW of Calabria.

Figure 1.22

Figure 1.23

1.9 Future expectations and technologies

On a worldwide scale, by using the wind energy, by 2020 it could be possible to produce 12% of the total requirement of electrical energy and 20% of the European demand, thus reaching, thanks to this renewable source only, the targets set by the European Union.
In fact, a strong development in the wind power sector is foreseen, which could reach in 2013 a power capacity installed of more than 140 GW at European level and 343 GW (Figure 1.24) at world level, with the annual growth shown in Figure 1.25.
In many countries of northern Europe the solution of installing wind power plants offshore is well considered to make up for the lack of large areas onshore, to overcome environmental problems and to exploit higher and more regular wind speeds.
As an example, Great Britain is approving the construction of the largest wind power plant offshore with 1 GW power capacity.
The Italian government, in its "position paper" on renewable energy sources issued on 10-09-2007, with reference to the action plan of the European Union, anticipated a wind energy potential available in Italy in 2020 of 12 GW of installed power, 10 GW of which onshore and 2 GW offshore (in shallow water up to 30m depth and medium-depth water up to 60m), with an estimated total annual production of 22.6 TWh and with an increase in annual installed power equal to 800 MW. As regards offshore installations, there is a further electrical power of 2 to 4 GW in deep water beyond 60m, for which however there are no technologies available at the moment for commercial exploitation (floating wind power plants). As regards the installations onshore, the estimates have been made taking into consideration 600-850kW turbines (that is with 50m height at the hub). With the increase in wind turbine powers, which has reached 3 MW power in onshore plants (with 75-100m height at the hub), the development potential might result to be somewhat under-esteemed. As regards offshore potential instead, the available data for windiness are more uncertain and therefore only provisional evaluations are possible.

Figure 1.24 - Global wind power forecast

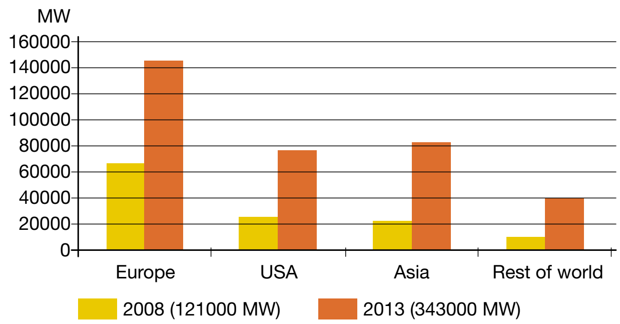
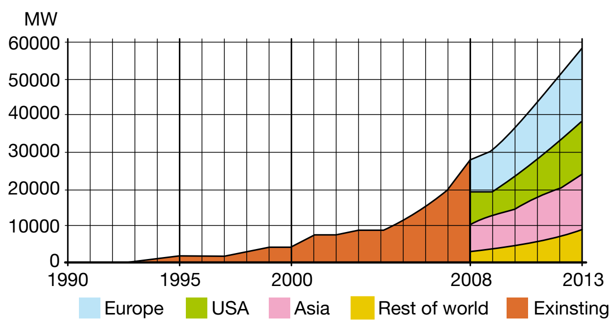
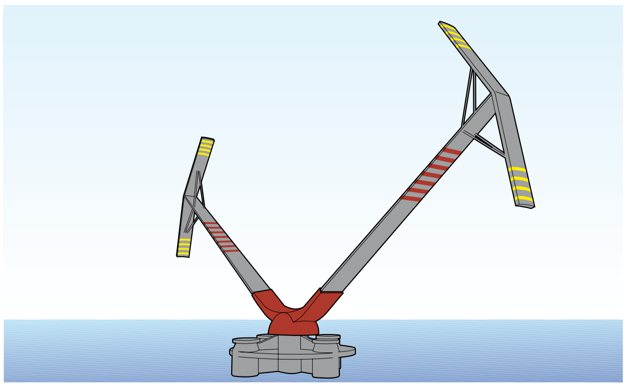


Figure 1.25 - Annual wind power development



From the point of view of the construction technology, a new model of offshore turbine named Aerogenerator X is being studied. It shall be 130m high and 275m wide, generating 10 MW of power and possibly up to 20 MW (Figure 1.26). Manufacturing shall start in 2013-2014, after testing.
Its innovative design has a V-structure and has been compared to a sycamore seed, which falls to the ground with a spiraling motion just thanks to its V-shaped "wings".

Figure 1.26



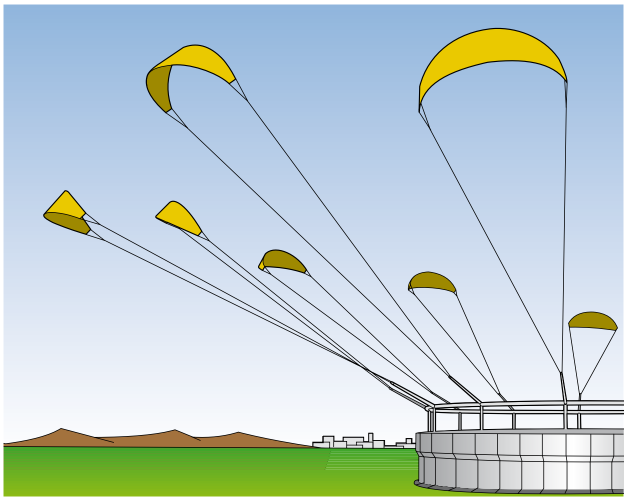
It is a vertical axis technology, which allows exploitation of the wind energy, never mind the direction from which it blows.
This model offers the advantage of concentrating most of the weight of the turbine at the base rather than at the hub as in horizontal axis turbines instead. Moreover, the blades do not experience the continuous fatigue stress due to the rotation and therefore these aerogenerators can be constructed with a form thinner than three-blade turbines of equal power.
It rotates with a speed of about 3 rpm and weights the half of an equivalent conventional turbine.

Also the total height results significantly reduced, with a consequent reduction of its visibility from a distance. It shall be installed on a semi-submersible platform, which borrows the technologies used for offshore gas and oil extraction; anchorage to the ocean floor is guaranteed by ropes up to 150m depth.

Research is also aimed at producing wind power plants of revolutionary concept in high power, even up to 1000 MW; these plants tap wind energy at high altitude through large controlled kites. The Italian project KiteGen exploits kites with surfaces of dozens of square meters able to take off also pushed by light winds; they can be manoeuvred from earth using a couple of cables to adjust their fly direction and trim to wind. The force exerted on the kite cables, at 500-600 m altitude, can be used to produce electrical energy. KiteGen (Figure 1.27) can be seen as a big carousel tied to the ground and consisting of a central structure supporting long arms at the tip of which connection cables are fixed; these cables, made of composite material, transmit traction and, at the same time, are used to control direction and angle to the wind of the kites. Even if in the considered case the projection of the area covered by the arms is equal to one square kilometers, the surface covered can still be employed for agricultural use or, in the case of offshore plants, for navigation.

Another system provides a sort of "yo-yo": a kyte is vertically lifted by fans up to an altitude at which it starts to self-sustain (about 80 m) to climb then up to 800 m. While climbing, through the control cables, the kite drives electrical generators with power up to 3MW. Once 800 m altitude has been reached, by pulling on one cable only, the kite is brought to "sideslip" condition, as it were a flag; then, by pulling again quickly the cables, almost without waste of energy, the kite is again at 400 m altitude, ready to climb and fall again cyclically.

Figure 1.27



2 Main components of a wind turbine

To exploit the kinetic energy of the wind, by converting it into electrical energy available to be fed into the network or to supply loads in parallel, a wind turbine uses different components both mechanical as well as electrical. In particular, the rotor (blades and hub) extracts energy from the wind turning it into mechanical rotation energy and constitutes the “first motor” of the wind turbine, whereas conversion of mechanical energy into electrical energy is carried out by an electric generator according to suitable configurations to be illustrated in the following chapters.

To summarize, the main components constituting horizontal axis wind turbines are (see Figure 2.1):

1. blade
2. blade support
3. Pitch angle actuator
4. hub
5. spinner
6. main support
7. main shaft
8. aircraft warning lights
9. gearbox
10. mechanical brakes
11. hydraulic cooling devices
12. generator
13. power converter and electrical control, protection and disconnection devices
14. anemometers
15. transformer
16. frame of the nacelle
17. supporting tower
18. yaw driving device

The converter and the transformer can be installed directly in the nacelle as Figure 2.1 shows, or positioned at the base of the tower. The installation of the transformer inside the nacelle allows balancing of the rotor weight, while positioning at the base allows a reduction in dimensions and weight of the nacelle.

In terms of costs, the percentage on the total cost of the different components is divided as shown in Figure 2.2.

Figure 2.2 - Wind turbine component cost (% of total)

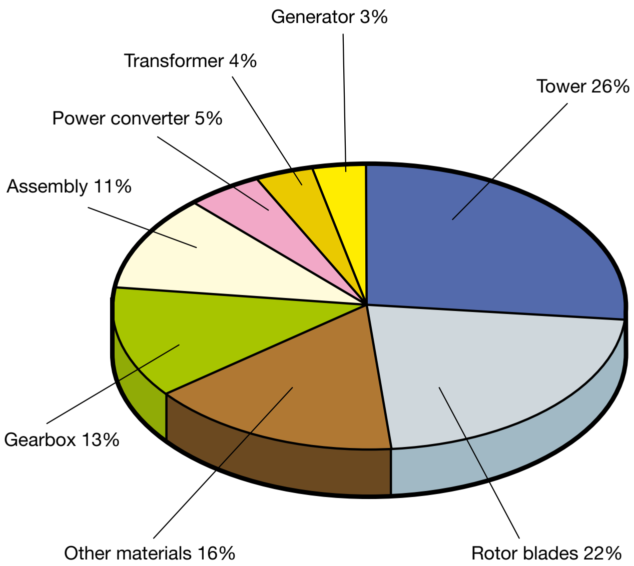
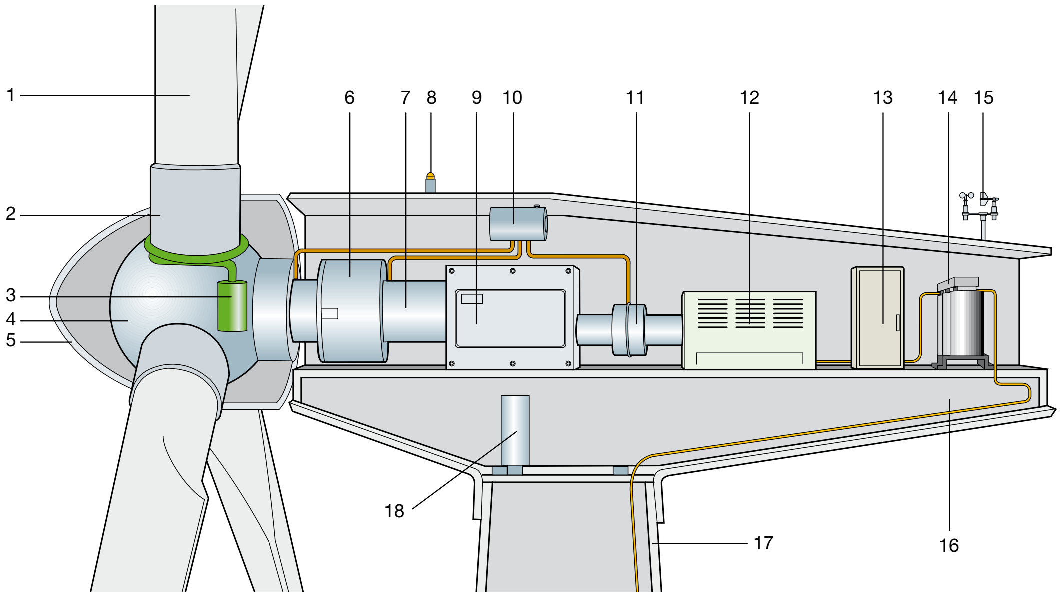


Figure 2.1



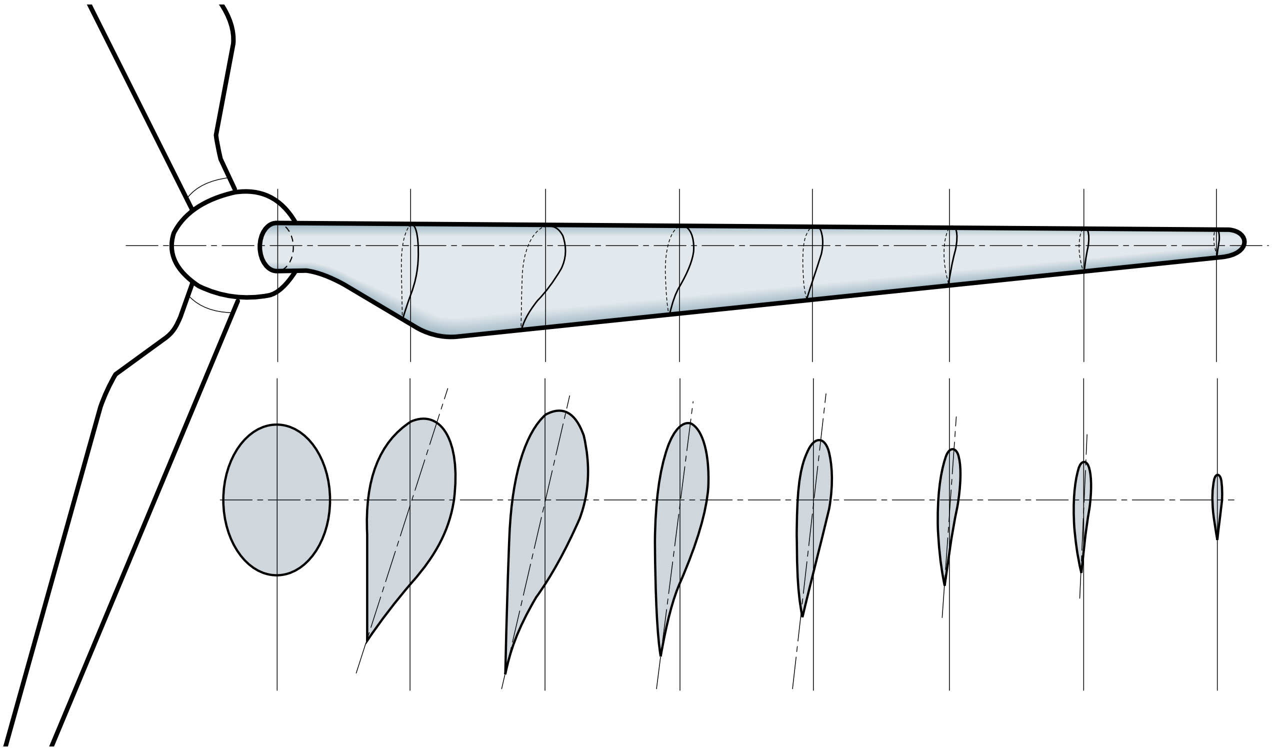
2.1 Rotor

2.1.1 Blades

The blades are the components which interact with the wind and are designed with such an airfoil to maximize the aerodynamic efficiency.
Figure 2.3 shows the typical form of a blade and its transversal sections; the blade winds up and the total angle between the root and the tip is about 25°.
Since the aerodynamic forces are proportional to the square of the relative speed, they increase rapidly with the distance from the hub; therefore it is important to design the part of the blade near the root so that there is a good lift and a low aerodynamic resistance.

The cross sectional area of the blade is quite large to get the high stiffness necessary to withstand the variable mechanical loads present under normal operation which contribute to determine the wear and tear of the blade. In fact, the wind exerts an unsteady force, both for the fluctuations due to the turbulence, as well as for the higher speed as a function of altitude.
Besides, during rotation, a blade when in the high position is subject to a stronger wind in comparison with the wind intensity when it is in the low position, with the consequent load fluctuations which recur at each rotation.
Finally, the centrifugal force due to rotation exerts traction on the different sections of the blade and the weight of the blade itself creates a bending moment on the root which alternates at each rotation.
Blades are made from light materials, such as fiber-reinforced plastic materials, which have good properties of resistance to wear and tear.
Fibers are generally made of glass or aluminum for the blades of small and medium size wind turbines, whereas for larger blades carbon fibers are used in the parts subject to more critical loads.
The fibers are incorporated in a matrix of polyester, epoxy resin or vinyl ester constituting two shells kept together and reinforced by an internal matrix.
The external surface of the blade is covered with a layer of colored gel to prevent ageing of composite material due to ultraviolet radiation.
According to the technology used by the manufacturer, blades can be equipped with additional elements, such as stall controllers to stabilize the air flux, vortex generators to increase lift or wingtip devices to reduce the lift loss and the noise.
Since the main cause of failure is represented by lightning, a protective measure is taken by installing conductors, both on the surface as well as inside the blade (see Chapter 8).
The blades and the central hub (which together constitute the rotor) are mounted on the nacelle through suitable flange bearings.

Figure 2.3

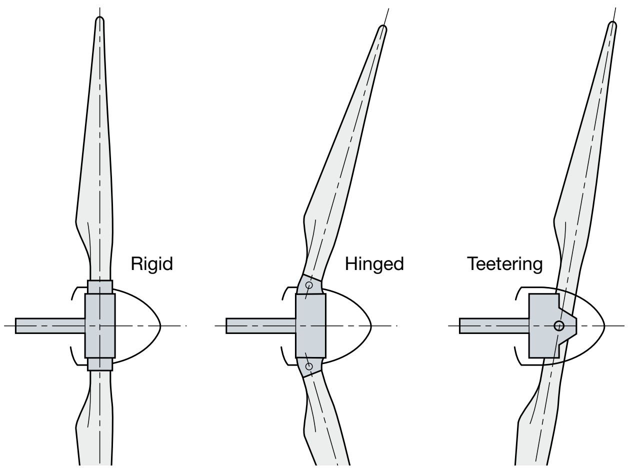


2.1.2 Hub

The hub of the wind turbine is the component that connects the blades to the main shaft, transmitting to it the power extracted from the wind; it includes pitching systems.
Hubs are generally made of steel or spheroidal graphite iron and is protected externally by an oval enclosure called spinner. There are three main types of hub (Figure 2.4):

- rigid
- teetering
- hinged

Figure 2.4



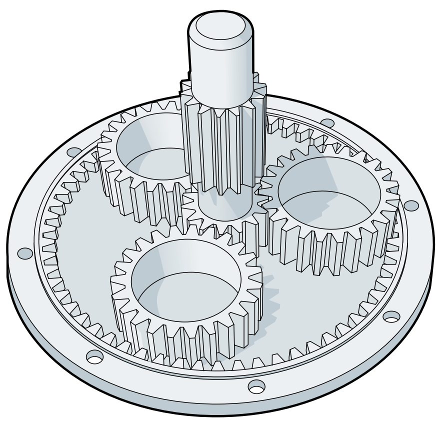
A rigid hub is designed to keep all major parts in a fixed position relative to the main shaft. The blade Pitch can be varied, but no other blade motion is allowed. It is the type mostly used for rotors with three or more blades. A rigid hub must be strong enough to withstand all the loads that can arise from any aerodynamic load on the blades as well as those due to yawing.
Teetering hubs are used on nearly all two-bladed wind turbines and are designed to reduce the aerodynamic imbalances transmitted to the shaft and typical of two-bladed rotors; thus the rotor is free to oscillate some degrees with respect to the direction perpendicular to the rotation axis of the main shaft.
Teetering hubs have been mainly coupled with turbines with fixed Pitch angle, but they can be used on variable pitched turbines as well. Also design of the pitching system is more complex since the relevant mechanisms and the switching/protection switchboards are located on the moving part with respect to the main shaft.

A hinged hub is, in some ways, a cross between a rigid hub and a teetering hub and it is basically a rigid hub with hinges for the blades. It is used by downwind turbines to reduce excessive loads in case of strong winds.

2.2 Gearbox

Most drivetrains include a one- or more-stage gearbox between the rotor, which extracts kinetic energy from the wind and converts it into mechanical rotation energy, and the electric generator, which converts the available mechanical energy into electrical energy.
The gearbox has the purpose of increasing the rotor speed to adapt it to the values required by conventional generators (in some turbines the ratio of the gearbox may exceed 1:100). The gearbox consists of one or more gears of epicycloidal or parallel axis type (Figure 2.5).
In the last few years, the development of alternators with interposed converter has made it possible the construction of some models of wind turbines without gearbox. In fact, the gearbox is a source of noise and one of the elements requiring more maintenance; furthermore it may cause efficiency losses of the wind turbine.
Therefore the lack of the gearbox implies a simplification of the mechanical part and thus allowing a reduction in the size and mass of the nacelle.

Figure 2.5



[1] For the definition of Pitch angle of a wind blade reference shall be made to the following chapter.

[2] In some cases the gearbox includes also the bearings of the transmission shaft, especially in turbines with transmission shaft of limited length.

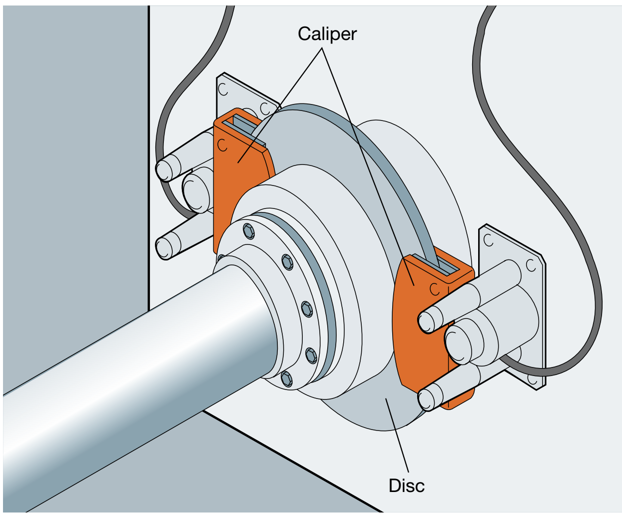
2.3 Brakes

Nearly all wind turbines employ mechanical brakes mounted on the drivetrain, in addition to an aerodynamic brake. In many cases, mechanical brakes can stop the rotor under adverse weather conditions besides being used as "parking" brakes to keep the rotor from turning when the turbine is not operating.
There are two types of mechanical brakes in common usage:

- disc brakes
- clutch brakes

The disc brake operates in a manner similar to that on cars: a metal disc is affixed to the shaft to be braked. During braking a hydraulically actuated caliper pushes brake pads against the disc, thus creating a torque opposing to the motion one (Figure 2.6).

Figure 2.6



Clutch-type brakes consist of at least one pressure plate and one fiction disc.
Actuation of this type of brakes is normally via springs applying a proper pressure; they are released either by compressed air or hydraulic fluid.
Mechanical brakes can be located on either the low-speed or high-speed side of the gearbox.
However, it is important to note that brakes on the low-speed side must be able to exert a much higher torque, while if the brakes are on the high-speed side they will act through the gearbox, possibly increasing the gearbox wear.

Furthermore, in the event of a failure in the gearbox, brakes on the high-speed side might be excluded and not able to slow the rotor.
Besides, the quality of the material of the brake discs on the high-speed shaft is a more critical issue because of the intensity of the centrifugal forces developed.
Brakes intended to stop a rotor must be able to exert a brake torque in excess of what could probably be expected to originate from the rotor, with braking times usually lower than 5s, and they must be able to function also if their external power supply fails.
Besides, they must be able to keep the rotor in the full stop position for the defined wind conditions for at least one hour after the brake is applied (CEI EN 61400-1).

2.4 Electric generator

2.4.1 Asynchronous generator

It is essentially an induction three-phase motor characterized by a synchronous speed which depends on the number of poles and on the network frequency.
If the mechanical torque acting on the rotor shaft is motive instead of resistant and makes the rotation speed increase and exceed the synchronous speed, the asynchronous machine stops working as a motor and starts working as a generator, thus putting electrical energy into the grid.
The relative difference between the synchronous speed and the effective rotation speed is called slip (s), which is negative when the machine is operated as a generator. In traditional asynchronous generators with squirrel cage rotor (short-circuit rotor), the slip is about 1% so that such devices are actually considered as having constant rotation speed.
The magnetizing current of the stator, which generates the rotating magnetic field in the air-gap, is supplied by the grid.
Besides, such generator consumes a certain amount of reactive power, which shall be supplied by compensation systems, such as capacitors.
When a gust of wind hits a wind turbine equipped with a rotor asynchronous generator under short circuit, as the rotation speed is constant, there is a sudden variation of the torque and the consequent quick variation of the power output. If the short circuit power of the grid to which the wind turbine is connected is low, voltage fluc-

[3] The rotation speed of the main shaft varies from zero to the rated dimensioning speed as a function of the speed of the incident wind, but it cannot be controlled and varied voluntarily by a control system as it occurs instead for variable speed systems.

tuations may occur on the electrical devices connected nearby and these fluctuations may cause malfunctioning of these devices.
Moreover, it is possible to notice the quick variation of the luminous flux emitted by the lamps, generating that disturbing "fluttering" known as flicker.
For this reason too, research has gone towards the development of variable speed systems which allow also the "torque pull" on the rotor to be reduced and the rotor to work at the point of maximum aerodynamic efficiency over a wide range of wind speed[4].
Variable speed solutions realized with induction generators are obtained by interposing a frequency converter between the stator of the generator with squirrel cage rotor and the grid, or by using a wound rotor asynchronous generator in which the rotor is supplied by an independent alternating current delivered by a frequency converter: thus, the synchronous speed results to be a function of the difference between the grid frequency and the frequency of the rotor current and it is possible to reach 30% speed variation.

2.4.2 Synchronous generator

In this type of generator, also called alternator, the rotor consists of a direct current electromagnet or of permanent magnets.
The frequency of the voltage induced on the stator (and consequently of the generated current) is directly proportional to the rotation speed of the rotor.
To allow functioning at variable speed, a frequency converter is interposed between alternator and grid; at first it transforms the current at variable frequency (as a function of the rotor speed and therefore of wind) coming out of the generator into direct current through an electronic rectifier, and then reconverts the direct current into alternating current at the network frequency through an inverter.
Thus the frequency of the generated current is released from the grid frequency, which may also result into the abolition of the gearbox.
Thanks to the synchronous motor and to the frequency converter, when the wind strength suddenly increases, the rotor is let free to accelerate for some seconds: the increase in the rotation speed accumulates kinetic energy in the rotor itself and allows constant power supply.
Vice versa, when the wind falls, the energy stored in the rotor is released while the rotor itself is slowing down.

[4] *For a given wind speed, the rotation speed may be varied to maximize the aerodynamic efficiency of the blades (see the following chapter).*

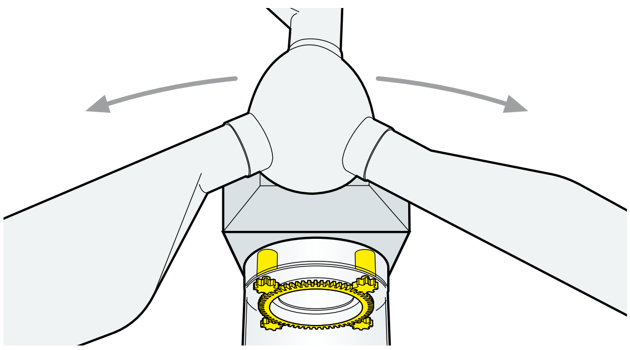
2.5 Transformer

The electric power output from generators is usually in low voltage and shall be transformed into medium voltage through a transformer to reduce transmission losses by connection to the MV distribution network.
The transformer is installed on the nacelle or at the base of the tower.
The electric cables connecting the nacelle to the base of the tower form a ring under the nacelle so that yaw movements are allowed.
These movements are controlled and, in case of excessive rotation, the nacelle is yawned in the opposite direction to prevent cables from entangling.
These cables must have such an increased length that the wind turbine shall be able to make up to three complete turns for alignment.

2.6 Yaw system

The nacelle is made to rotate on the top of the tower by an active yaw control system consisting of electrical actuators and relevant reduction gears (Figure 2.7), so that the rotor is always transversal to wind.
The direction and speed of the wind are continuously controlled by the sensors connected on the roof of the nacelle.
The rotor is generally positioned according to the average direction of the wind, calculated over a 10min period by the turbine control system.

Figure 2.7



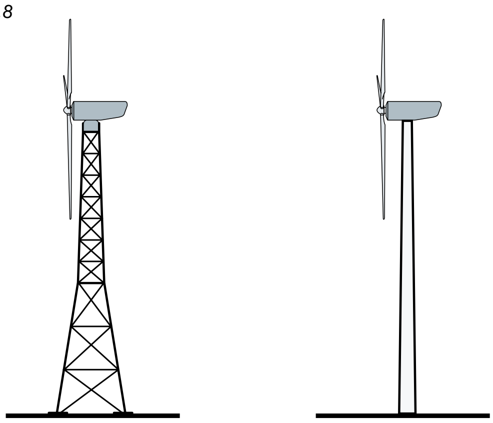
For horizontal axis turbines with downwind rotors, a yaw system is not necessary, since the turbine is intrinsically self-orienting and follows the wind direction as a wind vane.
Instead, upwind turbines have either a rear orientation tail (small and medium size wind turbines) or active yaw control; therefore, the supporting tower shall be properly dimensioned also to withstand the torsional loads resulting from the use of yaw systems.

2.7 Tower

There are two main types of towers commonly used horizontal axis wind turbines (Figure 2.8):

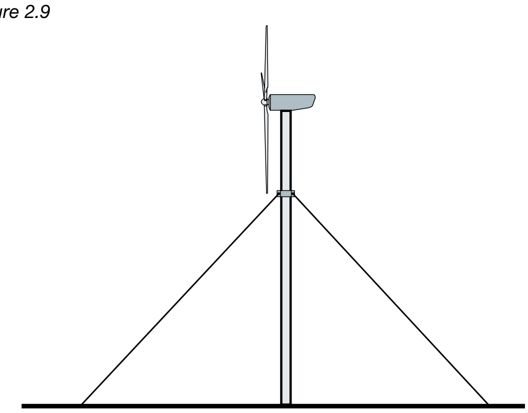
- *free-standing lattice (truss)*
- *tubular*

Figure 2.8



The first wind turbines were on free-standing lattice towers, commonly used until the mid-1980s. Nowadays wind turbines are mostly of tubular type since they offer a number of advantages in comparison with the truss one. In particular, tubular towers do not require many bolted connections which need to be periodically checked; they provide a protected area to access the turbine and climbing to the nacelle is made safer and easier thanks to internal stairway or lift in case of larger turbines.
Furthermore, they are aesthetically more acceptable in comparison with truss towers.
There is a third type of tower, *guyed lattice tower* (Figure 2.9), but they are little used for medium and large size power plants.

Figure 2.9



The tower height depends on the wind regime at the installation site.
In onshore plants the nacelle is usually at a height equal to 1 or 1.2 times the rotor diameter, whereas in offshore plants the height is equal to 0.8 times the rotor diameter.
Tubular towers are usually made of rolled steel, although sometimes reinforced concrete is used.
They are cone-shaped, with the base diameter longer than that on the top where the nacelle is positioned.
The different sections are joined and fixed together by bolted flanges.
These types of towers generate a remarkable downwind wake; that is why in most cases the rotor is positioned upwind.
Moreover, they are very visible structures and therefore they must not show signs of corrosion over many years: to this purpose, adequate coating must be chosen.
The towers are set into the ground through foundations generally consisting in reinforced concrete plinths placed at a certain depth.

2.8 Control and protection/disconnection systems

These systems are the "brain" of the wind turbine and provide the control logic to command start up and shut down procedures of the turbine and to guarantee turbine functioning in a defined range of operation parameters, by protecting the rotor, in particular, against overspeed, and the different parts of the electric circuit against overcurrents and overvoltages.
The logic of control is usually programmed in a PLC. In particular, the protection/disconnection systems disconnect the turbine from the grid in case of malfunctioning, thus allowing proper operation of the other wind turbines in the wind power plant.

2.9 Auxiliary devices

The main auxiliary circuits mounted inside the nacelle comprise a hydraulic device to lubricate the gearbox or the other mechanical parts and also heat exchangers to cool the oil and the generator, pumps and fans included.
On the top of the nacelle there are anemometers and wanes for turbine control, aircraft warning lights and a possible platform for helicopters' landing (for the access to offshore turbines). In order to improve the reliability of the wind turbine, different sensors are used to monitor the status of the various components and to signal any possible malfunctioning which needs maintenance operations.
This is particularly true for offshore wind power plants, the access to which is not easy.

3 Theory of wind turbines

3.1 Power of the fluid vein

Electric power production through wind turbines depends on the interaction between the blades of the rotor and the wind by transforming the kinetic energy of the wind into rotation mechanical energy and then by converting it into electrical energy.
The kinetic energy E_c of an air mass m moving at constant speed v_1 is given by:

$$E_c = \frac{1}{2} \cdot m \cdot v_1^2 \quad [3.1]$$

Therefore, the available specific power $P_{available}$ of an air mass with capacity $q = \frac{dm}{dt}$ is:

$$P_{available} = \frac{dE_c}{dt} = \frac{1}{2} \cdot q \cdot v_1^2 \quad [3.2]$$

The capacity can be expressed by the formula:

$$q = \frac{dm}{dt} = \dot{m} = \rho \cdot A \cdot v_1 \quad [3.3]$$

called *continuity equation*, where:
- ρ is the air density
- A is the cross-sectional area of the stream tube of the air under consideration.

Therefore, the available specific power results equal to:

$$P_{available} = \frac{1}{2} \cdot \rho \cdot A \cdot v_1^3 \quad [3.4]$$

As it can be noticed $P_{available}$ varies according to the cube of the wind speed v_1.
For example, with a standard air density at sea level $\rho = 1.225 kg/m^3$, it is:

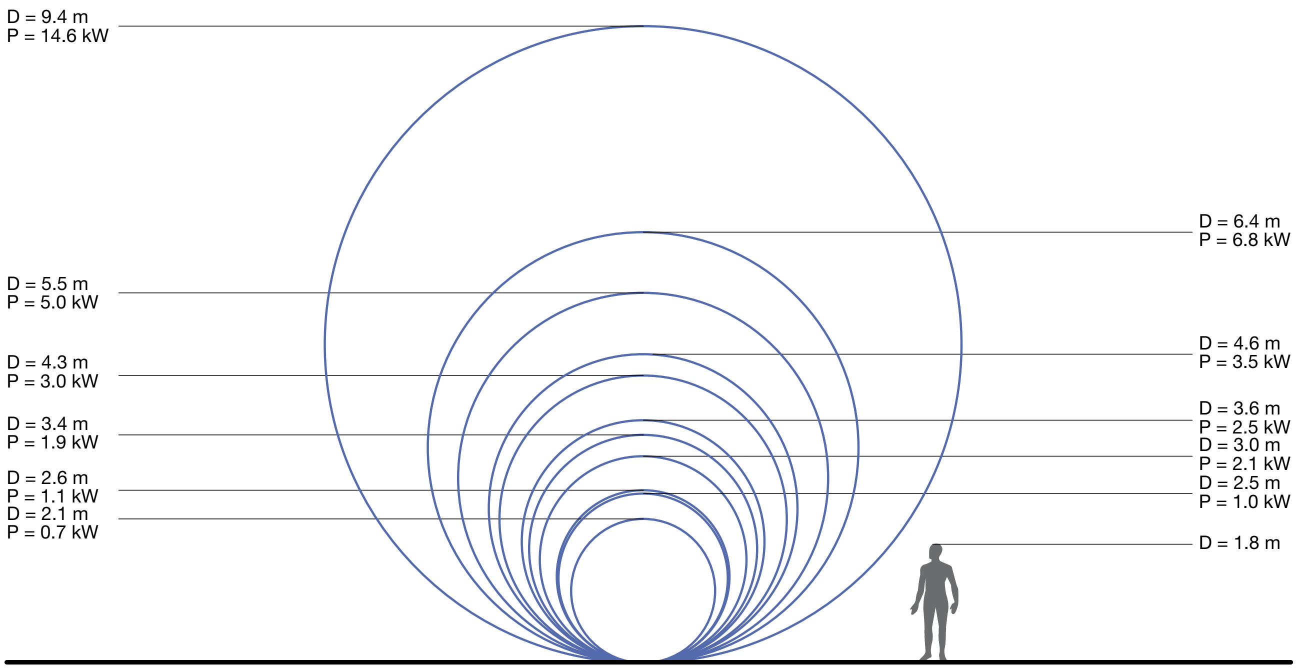
$$v_1 = 5 \ m/s \Rightarrow P_{available} = 76 \ W/m^2$$
$$v_1 = 6 \ m/s \Rightarrow P_{available} = 132 \ W/m^2$$
$$v_1 = 7 \ m/s \Rightarrow P_{available} = 210 \ W/m^2$$

Therefore, with an increase of the wind speed of about 1 m/s only, the available specific power rises of about 60-70%.
Besides, taking as reference the available specific power ($P_{available}$=210W/m²) of the fluid vein relevant to the speed v1=7 m/s, it is possible to determine the area and the diameter of such fluid vein for different values of usable power (Figure 3.1):

$$P = 1kW \Rightarrow A = 4.7m^2 \Rightarrow D = 2.5m$$
$$P = 10kW \Rightarrow A = 47.6m^2 \Rightarrow D = 7.8m$$
$$P = 20kW \Rightarrow A = 95.2m^2 \Rightarrow D = 11m$$

Figure 3.1

Fluid vein at v_1 = 7 m/s



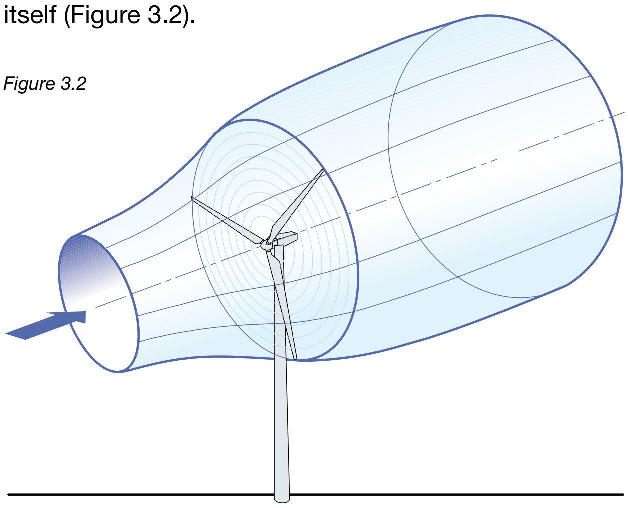
3.2 One-dimensional theory and Betz law

A simplified model, attributed to Albert Betz, is generally used to determine the power output from an ideal wind turbine having an available incident wind power expressed by [3.4]. The higher the kinetic energy which the turbine can extract from the wind, the lower the speed of the wind leaving the turbine.
As a consequence, the wind is slowed down so that the speed downstream the turbine shall range from zero to the speed value upstream (for both these limit cases the extracted power would be zero).
The assumptions on which the Betz theory is based are the following ones:

- the whole of the blades of the wind rotor is comparable to a "porous disc" with zero thickness – actuator disc with an infinite number of blades (Figure 3.2);
- the mass of air flowing over the disc remains separated from that surrounding it - stream tube (Figure 3.2);
- the mass of air flows only in longitudinal direction;
- slowing down of the air on the actuator disc is evenly distributed on the disc surface;
- the pressure in the far upstream and far downstream section is equal to the atmospheric pressure;
- the wind flow does not meet obstacles except for the turbine, neither upstream or downstream;
- the wind is steady and with constant intensity according to the altitude;
- there are no rotation effects on the air mass;
- air compressibility is disregarded, that is density is assumed to be constant.

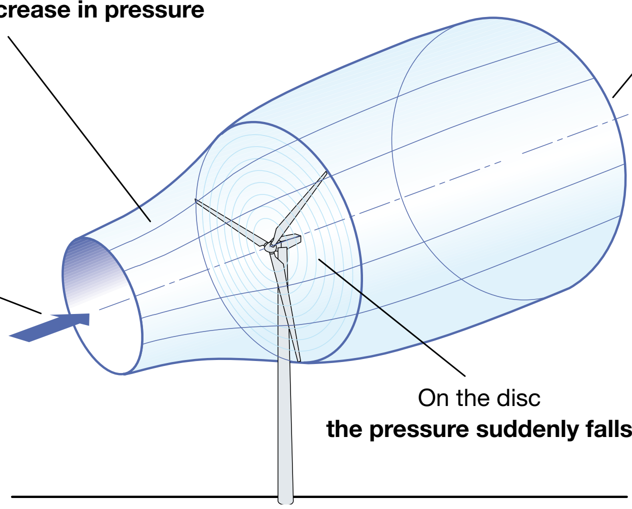
Since the air flow (continuity equation without mass accumulation) is considered as constant and also the density is assumed to be constant, from equation [3.3] it derives that a decrease in the velocity of the fluid vein incoming and outcoming from the stream tube, results in an increase of the cross-section of the stream tube itself (Figure 3.2).

Figure 3.2



Moreover, starting from the atmospheric pressure at the tube entry, the gradual decrease in velocity in the stream tube determines an increase in pressure (without work production), which suddenly sinks on the disc to return gradually to the atmospheric pressure value coming out of the stream tube (Figure 3.3).

Figure 3.3



By indicating with (see Figure 3.4):

- p_1 and v_1 the pressure and the wind velocity in the cross-sectional area A_1 coming into the stream tube and sufficiently far from the turbine;
- p_2 and v_2 the pressure and the wind velocity in the cross-sectional area A_2 coming out of the stream tube and sufficiently far from the turbine;
- p_3 and p_4 the pressure immediately before and after the cross-sectional area A;
- v the wind velocity in correspondence with the rotor plane

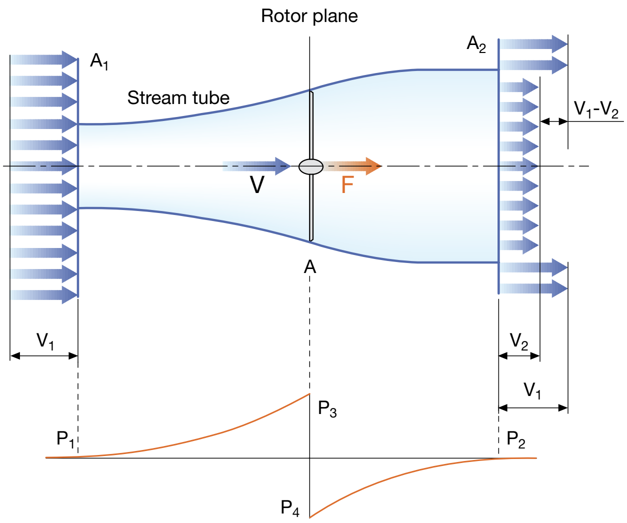
and assuming that there are no variations of potential energy and no heat exchange neither work extraction between A_1 and A, it is possible to write Bernoulli's equation as follows:

$$p_1 + \rho \cdot \frac{v_1^2}{2} = p_3 + \rho \cdot \frac{v^2}{2} \quad [3.5]$$

Analogously, between A and A_2:

$$p_4 + \rho \cdot \frac{v^2}{2} = p_2 + \rho \cdot \frac{v_2^2}{2} \quad [3.6]$$

Figure 3.4



The discontinuity of pressure on the disc, taking into account [3.5] and [3.6], can be written as[2]:

$$\Delta p = p_3 - p_4 = \rho \cdot \frac{v_1^2 - v_2^2}{2} \quad [3.7]$$

The axial force F, in the direction of the wind, on the actuator disc and with cross-section A, perpendicular to the flow is given by:

$$F = \Delta p \cdot A = \rho \cdot A \cdot \frac{v_1^2 - v_2^2}{2} \quad [3.8]$$

Such force, for the impulse-momentum theorem, is equal to the change in momentum of the air mass, that is[3]:

$$F = F_3 - F_4 = \dot{m} \cdot (v_1 - v_2) \quad [3.9]$$

Substituting [3.3] into the previous relation, it is obtained:

$$F = \rho \cdot A \cdot v \cdot (v_1 - v_2) \quad [3.10]$$

Equating the relation [3.8] with [3.10], the speed in the cross-section of the actuator disc can be obtained:

$$v = \frac{1}{2} \cdot (v_1 + v_2) \quad [3.11]$$

As it can be noticed, the slowing down of the wind occurs half in the part upstream of the actuator disc and half downstream.
The ratio between *is defined "axial induction factor" a*

$$a = \frac{v_1 - v}{v_1} = 1 - \frac{v}{v_1} \quad [3.12]$$

which represents the decrease in velocity in front of the disc. From [3.12], taking into account [3.11], the velocity v on the disc plane and the outcoming velocity v2 from the stream tube can be expressed as a function of the axial induction factor a and of the incoming velocity v_1:

$$v = v_1 - a \cdot v_1 = (1 - a) \cdot v_1 \quad [3.13]$$

$$v_2 = 2 \cdot v - v_1 = 2 \cdot (1 - a) \cdot v_1 - v_1 = (1 - 2a) \cdot v_1 \quad [3.14]$$

The power captured by the blade can be represented as the product of the force exerted by the wind F multiplied by its incident velocity v:

$$P = F \cdot v = \left(\rho \cdot A \cdot v \cdot \left(v_1 - v_2\right)\right) \cdot v \quad [3.15]$$

Taking into account [3.11], the relation above can be written as:

[1] *In fluid dynamics, the Bernoulli function represents a particular simplified form of Navier-Stokes equations, obtained in case of non-viscous fluid (that is a fluid in which viscosity can be disregarded) from the integration along a flow line and it describes the motion of a fluid along such line.*

[2] *Wind velocity decreases from section 1 at the entry of the stream tube to section 2 at the exit without discontinuity. As a consequence, on the disc there isn't a velocity gradient as it occurs for the pressure. p1 and p2 are equal in value and equate the atmospheric pressure.*

[3] $F = \frac{d(m(t) \cdot v(x,t))}{dt} = \frac{\partial m(t)}{\partial t} \cdot v(x,t) + m(t) \cdot \frac{\partial v(x,t)}{\partial t}$ *Since - by assumption - the wind is steady, the derivative of velocity with respect to time is null, from which [3.9] is obtained.*

$$P = \left(\rho \cdot A \cdot \frac{v_1 + v_2}{2}\right) \cdot \left(\frac{v_1^2 - v_2^2}{2}\right) \quad [3.16]$$

As it can be noticed, the power extracted from the wind is proportional to the mass flow across the rotor and to the difference in kinetic energy between the entry section and the exit section. Considering the expressions [3.13-3.14], the power captured can also be set as:

$$P = 2 \cdot \rho \cdot A \cdot v_1^3 \cdot a \cdot (1-a)^2 \quad [3.17]$$

from which it derives that power depends:

- proportionally, on the density ρ of the incident air mass; therefore, there is a decrease in the power extracted in hot climates or in the mountains;
- proportionally, on the area A of the rotor; therefore, increasing the length of the blades, also the area of the disc they “draw” when rotating increases;
- on the cube of the incoming velocity of the wind, which justifies the interest in the installation of wind turbines in very wind sites;
- on the outcoming wind velocity v_2 through the axial induction factor a.

In particular, there is an optimum value for the outcoming velocity v_2, in correspondence of which there is the maximum extracted power. Such value is obtained by differentiating P with respect to a and by equating to zero the derivative thus obtained. Then:

$$\frac{\partial P}{\partial a} = 2 \cdot \rho \cdot A \cdot v_1^3 \cdot \left(3 \cdot a^2 - 4 \cdot a + 1\right) \quad [3.18]$$

$$\frac{\partial P}{\partial a} = 0 \Rightarrow 3 \cdot a^2 - 4 \cdot a + 1 = 0 \quad [3.19]$$

Solving this quadratic equation, two values are obtained for a:

- 1, which cannot be accepted since from [3.14] there would be a negative outcoming wind velocity
- 1/3, to which an outcoming velocity equal to a third of the incoming one corresponds.

For a=1/3 the maximum power extracted from the wind shall be equal to (from 3.17):

$$P_{max} = \frac{8}{27} \cdot \rho \cdot A \cdot v_1^3 \quad [3.20]$$

3.2.1 Power coefficient C_p

The *power coefficient $C_p(a)$ (or efficiency coefficient)* is the ratio between the power extracted and the available power of the wind:

$$C_p(a) = \frac{P}{P_{available}} = \frac{2 \cdot \rho \cdot A \cdot v_1^3 \cdot a \cdot (1-a)^2}{\frac{1}{2} \rho \cdot A \cdot v_1^3} = 4 \cdot a \cdot (1-a)^2 \quad [3.21]$$

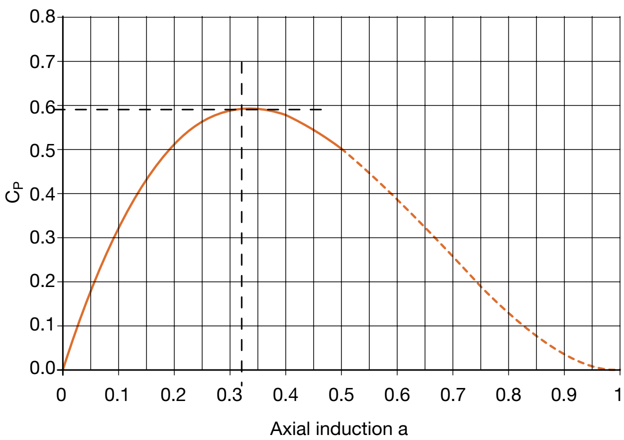
When a=1/3, the theoretical maximum

$C_{p,max} = \frac{16}{27} = 0.59$ is obtained, which is commonly called “*Betz limit*” and expresses the following fundamental concept:

“*The maximum power which can be theoretically extracted from the air flow using an ideal turbine cannot exceed 59% of the available power of the incident wind*”.

As it can be noticed from the graph in Figure 3.5, the power coefficient C_p grows at first at the increase in the axial induction factor a, reaches its maximum when a=1/3 and then it decreases; when a=1/2, the wind has slowed to zero velocity. The part of the diagram for a>1/2 has no sense from a physical point of view, since it would mean air with negative velocity in the exit section.

Figure 3.5 - Power coefficient C_p



In practice, three effects lead to a decrease in the maximum achievable power coefficient:

- rotation of the wake behind the rotor
- finite number of blades
- non-zero aerodynamic drag.

However, with modern turbines, a value $C_p \cong 0.5$ can be reached, which is not far from the Betz limit.

Since the power extracted from a wind turbine is a function of the power coefficient C_p and of the available wind power given by:

$$P = C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v_1^3 \qquad [3.22]$$

The generated electric power can be calculated as follows:

$$P_e = \eta_e \cdot \eta_m \cdot C_p \cdot \frac{1}{2} \cdot \rho \cdot A \cdot v_1^3 \qquad [3.23]$$

where:

- η_m is the overall mechanical efficiency of the drivetrain
- η_e is the efficiency of the electrical generator.

To obtain an electric power P_e, with a certain available wind power and power coefficient C_p, it is possible to estimate the rotor diameter of a horizontal axis wind turbine[4], knowing that:

$$A = \frac{\pi \cdot D^2}{4} \qquad [3.24]$$

Substituting [3.24] into [3.23] and solving it with respect to diameter D, it results:

$$D = \sqrt{\frac{8 \cdot P_e}{\eta_e \cdot \eta_m \cdot \pi \cdot C_p \cdot \rho \cdot v_1^3}} \qquad [3.25]$$

For example, a 50kW wind turbine has a diameter of about 15m, whereas a 5MW one reaches diameters of 120m as it can be seen in Figure 3.6 which illustrates the increase in the commercial dimensions of turbines from the 1980s to recent years.

Usually the C_p declared by the manufacturers does not express only the power fraction which the wind transmits to the rotor, but it includes also the efficiency for all the energetic conversions (including the self-consumes of the auxiliary services) as Figure 3.7 shows.

[4] *For Darrieus turbines, the definition of the rotor dimensions is more complex since it implies solving elliptical integrals. However, comparing the shape of blades to a parabola, the equation [3.24] can be expressed as:*

$$A = \frac{2}{3} \cdot L \cdot H$$

where:
W is the maximum width of the rotor (diameter)
H is the rotor height.

Figure 3.6

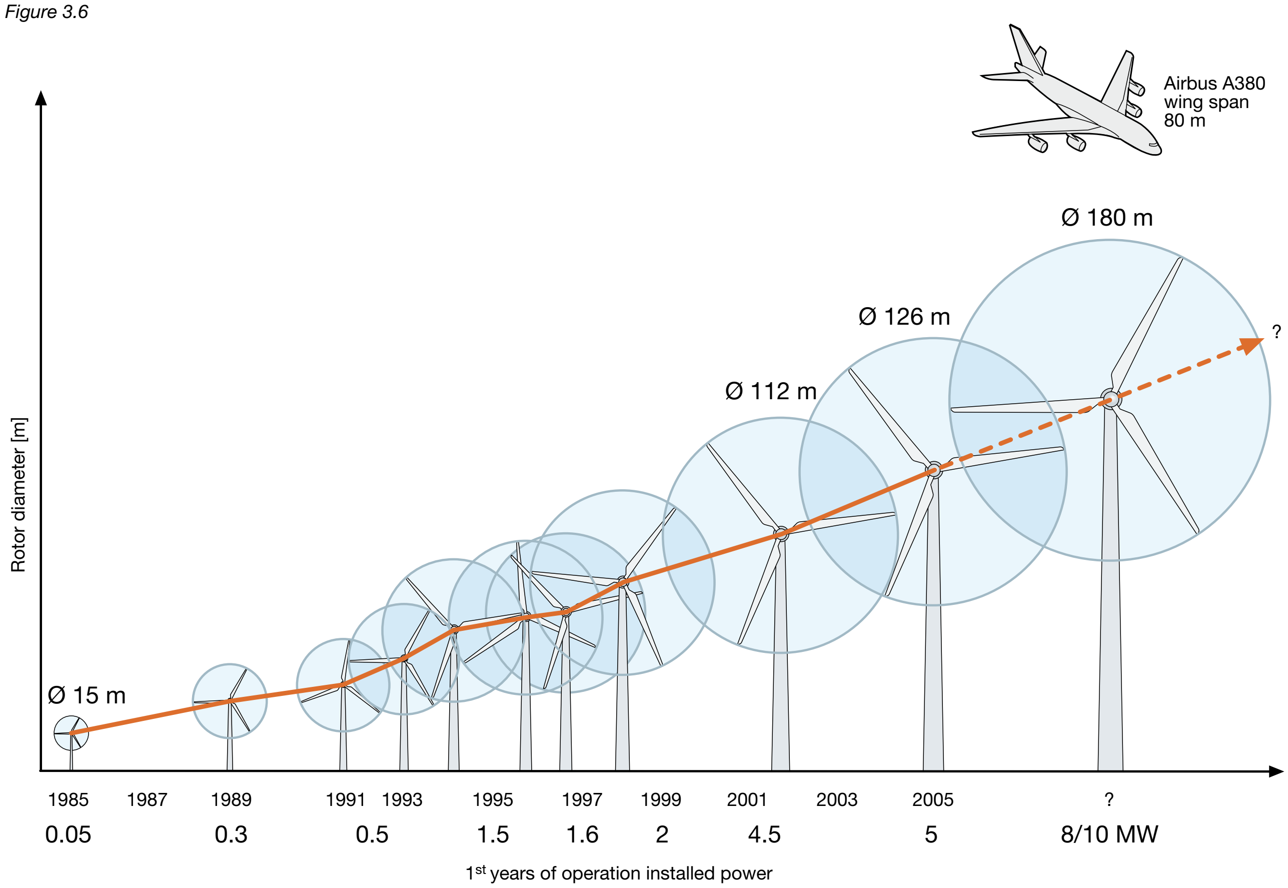
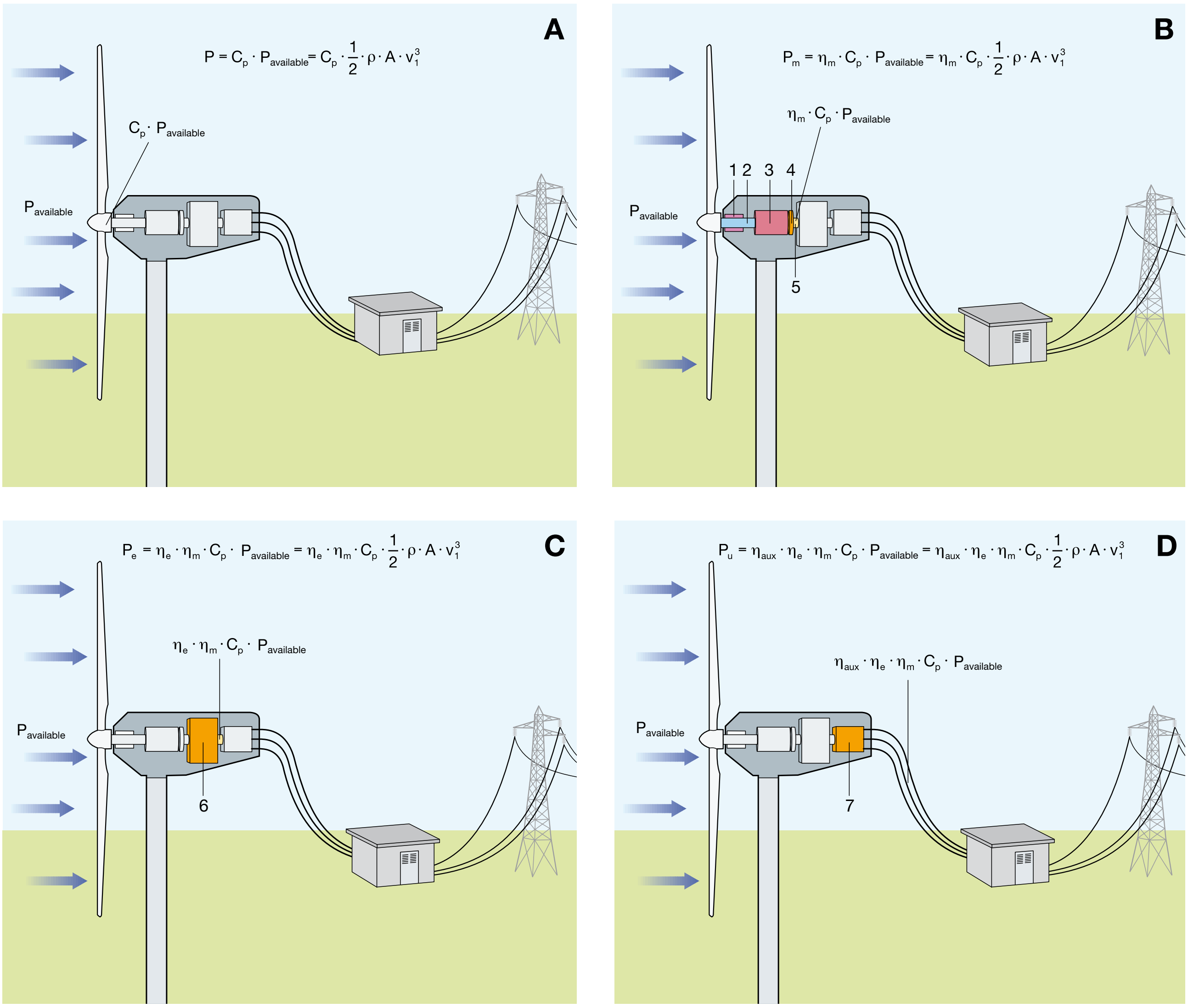


Figure 3.7 - Efficiency of a wind turbine



1. Support bearing
2. Low speed shaft
3. Gearbox
4. Brakes and yaw system
5. High speed shaft
6. Generator
7. Auxiliary circuits

The power supplied by a wind turbine and given by [3.22] can actually undergo reductions due to losses for effects "external" to the turbine itself. In particular, there may be losses due to:

- "altitude" due to pressure variation – the standard density at sea level at 15°C is assumed as reference: as the altitude rises, the density decreases of almost 1% each 100m of altitude;
- "altitude" due to temperature – when the temperature at the installation site increases, the density decreases of about 3% each 10°C;
- "wake effect" – occurring in the wind farm for aerodynamic interference between the different turbines;
- freezing and dirting of blades – they reduce the aerodynamic efficiency of the blades.

[5] *The air density varies as a function of pressure and temperatures in compliance with perfect gas law. Since pressure and temperature vary according to the altitude of the installation site, their combination affects the air density which can be derived from the simplified relation (valid up to 6000m altitude):*

$$\rho = \rho_0 - 1.194 \cdot 10^{-4} \cdot H$$

where:

ρ_0 is the standard density at sea level

H is the height of the installation site above sea level (expressed in meters).

3.2.2 Thrust coefficient C_s

In addition to the coefficient C_p, also the thrust coefficient C_s must be defined as the ratio between the force exerted on the actuator disc and the available wind force:

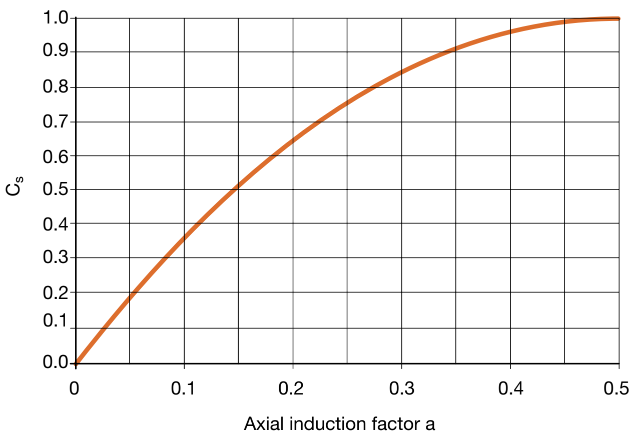
$$C_s = \frac{F}{F_{disp}} = \frac{P/v}{P_{disp}/v_1} = \frac{2 \cdot \rho \cdot A \cdot a \cdot (1-a) \cdot v_1^2}{\frac{1}{2} \cdot \rho \cdot A \cdot v_1^2} = 4 \cdot a \cdot (1-a) \quad [3.26]$$

The maximum value of the thrust coefficient is obtained by equalizing to zero the derivative with respect to a, that is:

$$\frac{dC_s}{da} = 4 \cdot (1-2a) = 0 \Rightarrow a = \frac{1}{2} \quad [3.27]$$

Therefore, as it can be noticed also in the diagram of Figure 3.8, the maximum thrust on the actuator disc would occur if the outcoming velocity fell to zero.

Figure 3.8 - Power coefficient C_p

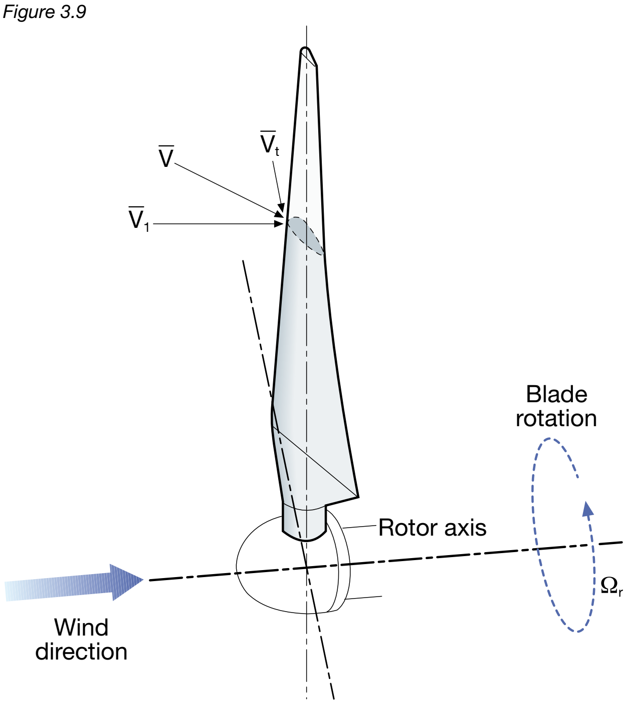


3.3 Aerodynamics analysis of blades

A blade is essentially a wing on which two air flows act depending on (Figure 3.9):

1. wind entering the stream tube with absolute velocity $\vec{v}_1$ parallel to the turbine axis;
2. rotation of the blade creating a drag velocity component $\vec{v}_t$ perpendicular to the above mentioned velocity vector.

Figure 3.9



By assuming that the component 1 is constant in the cross-section of the stream tube, at a distance r from the hub, the component 2 results:

$$\vec{v}_t = -\vec{\Omega} \cdot r \quad [3.28]$$

where $\vec{\Omega}$ is the rotation angular velocity of the rotor [rad/s]. As a consequence, the total velocity of the air flow skimming over the blade (in the reference system which is integral with the blade itself) is given by the vector sum of the two components, that is:

$$\vec{v} = \vec{v}_1 + \vec{v}_t \quad [3.29]$$

whose module is:

$$v = \sqrt{v_1^2 + v_t^2} = \sqrt{v_1^2 + (\Omega \cdot r)^2} \quad [3.30]$$

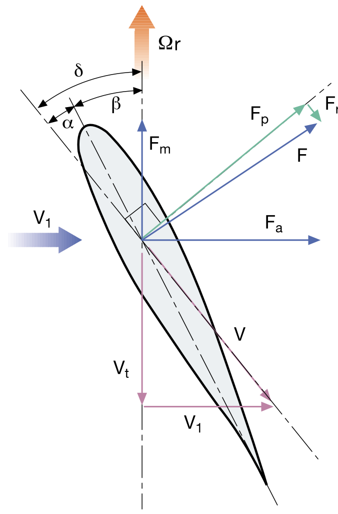
As it can be noticed, the air flow velocity over the blade increases when the rotation speed of the blade rises.

3.3.1 Lift and drag forces

The effect of the resulting air flow (v) over the airfoil of the blade is the creation of two aerodynamic forces defined as (Figure 3.10):

- *lift force*[7] F_p perpendicular to the direction of the resulting air flow
- *drag force*[8] F_r parallel to the direction of the resulting air flow

Figure 3.10



where:

α is the *angle of attack or of incidence,* which is the angular deviation between the direction of the resulting air flow and the maximum chord of the cross-section of the blade

β is the*Pitch angle,* which is the angular deviation between the rotation plane of the blade axis and the maximum chord of the cross-section of the same

$\delta = \alpha + \beta$ is the *fabrication angle*.

As for each other airfoil, also in wind blades, the lower the drag force in comparison with the lift force, the higher the efficiency E of the wing $\left(E = \frac{C_a}{C_b}\right)$.

Lift and drag can be expressed with the following formulas respectively:

$$F_p = \frac{1}{2} \cdot C_a \cdot A \cdot \rho \cdot v^2 \quad [3.31]$$

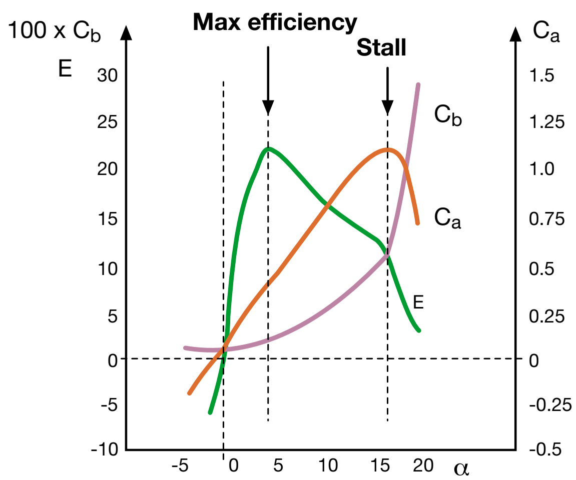
$$F_r = \frac{1}{2} \cdot C_b \cdot A \cdot \rho \cdot v^2 \quad [3.32]$$

where:

v is the apparent speed of the wind incident on the airfoil of the blade;
ρ is the air density;
A is the blade surface;
C_a is the lift coefficient;
C_b is the drag coefficient.

Figure 3.11 shows the curves of the two coefficients C_a and C_b as a function of the angle of attack. Under stall conditions, the efficiency E of the airfoil is considerably reduced and the aerodynamic behavior becomes unsteady with the formation of a turbulent wake.
As it can be noticed from Figure 3.11, the lift coefficient C_a is approximately proportional to the angle of attack for values lower than 15° and, unlike the drag coefficient C_b, the lift coefficient can become negative with the consequence that the lift force can change direction (negative lift).

Figure 3.11



Resolving the lift and drag forces, respectively perpendicular and parallel to the axis of the turbine, one obtains (Figure 3.10):

- the component of the *motive force* F_m useful for the torque generation of the main shaft[9]
  $F_m = F_p \cdot \sin\delta - F_r \cdot \cos\delta$;
- the component of the *axial force* Fa, which does not produce a useful torque but causes stresses on the rotor support
  $F_a = F_p \cdot \cos\delta + F_r \cdot \sin\delta$.

[7] In an aircraft it is the force which lifts it.
[8] In an aircraft it is the force which opposes motion in a direction contrary to the air flow.
[9] Multiplying the force F_m by the equivalent distance from the hub and by the number of blades, the torque transmitted to the shaft is obtained.

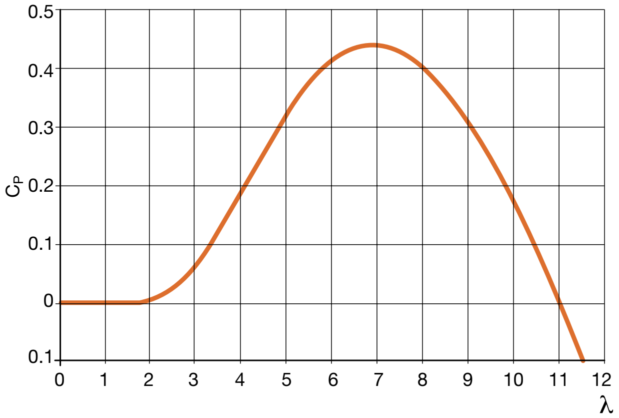
3.3.2 Tip Speed Ratio (TSR)

The aerodynamical characteristics of a blade are usually defined through the relation TSR-C_p (Figure 3.12). The TSR (Tip Speed Ratio), identified by the parameter λ, is the ratio between the tangential speed of the blade tips and the wind speed at the entry of the stream tube:

$$\lambda = \frac{v_t}{v_1} = \frac{\Omega \cdot R}{v_1} \qquad [3.33]$$

where R is the radius of the rotor.

Figure 3.12 - Relation λ - C_p (β = 1°)

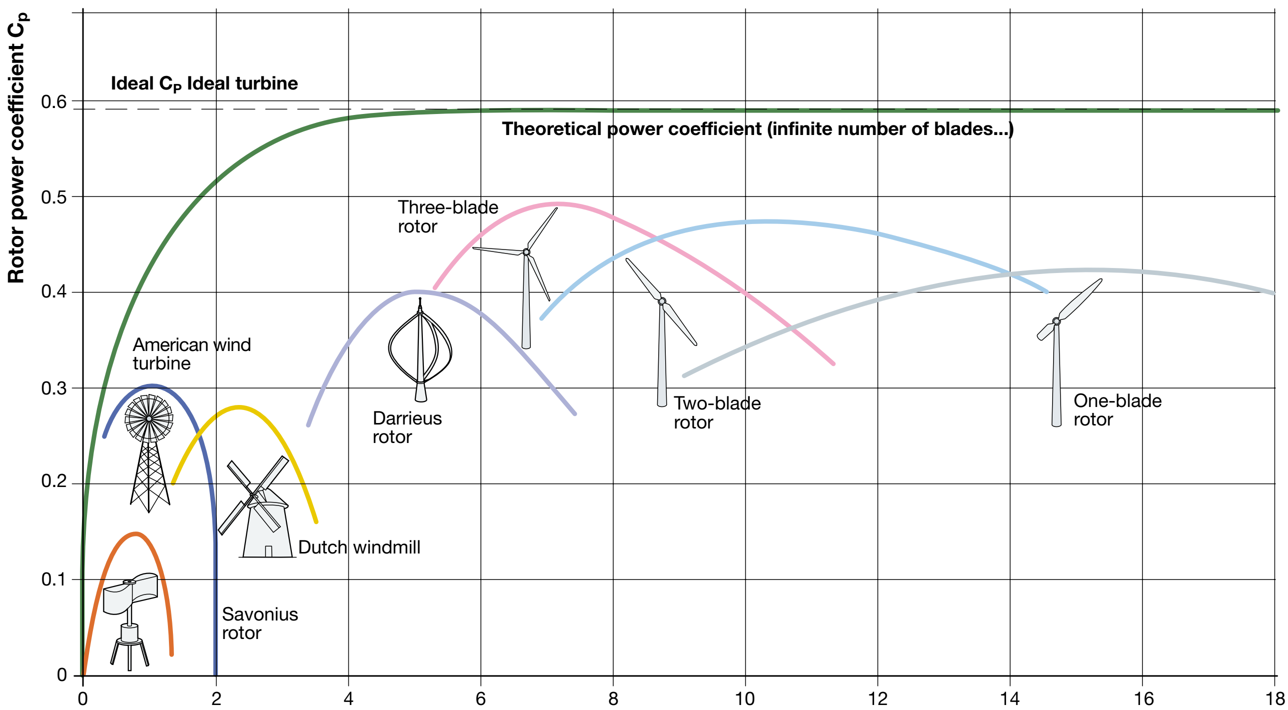


For a given blade, the relation λ-C_p depends on the Pitch angle. Keeping the Pitch angle constant, the following considerations are possible:

- there is only a TSR value for which the power conversion efficiency reaches its maximum value (C_{pmax}) depending on the type of blade;
- when the wind velocity v_1 changes, it is necessary to change deliberately the blade rotation speed (as described in the following chapters) in order to keep TSR constant and equal to the value for which C_{pmax};
- for low TSR values there is a reduction of the lift and an increase in the drag until stall condition has been reached;
- for high TSR values there is a reduction both of the lift as well as of the drag under a so-called “escape” condition ;
- the optimum TSR depends on the number of blade n and the lower the number of blades, the faster the blades have to rotate to extract the maximum power from the wind (the TSR rises)
- the shape of the curve of the relation TSR-Cp depends on the type of turbine (Figure 3.13).

[10] *In other terms, with high TSR values, the blades rotate so fast that actually they represent a wall with respect to the incident wind; therefore the wind gets over it instead of passing through it with the consequent abatement of the power extracted.*

Figure 3.13



The definition "fast turbines" refers to turbines with a high optimum value of TSR, whereas the term "slow turbine" defines the turbines with low optimum TSR. Table 3.1 shows the peripheral tangential and angular velocities (calculated with [3.33]) for different types of turbines, referred to 7m/s wind speed; these values are determined through the relevant optimum TSR reported in Figure 3.13.
As it can be noticed from the values in Table 3.1, horizontal axis turbines are fast turbines, since they have a high peripheral tangential velocity, even if they have an angular velocity reduced by the rotor radius which typically is much higher than that of vertical axis turbines.

Table 3.1

Type of turbine	Optimum TSR λ	Peripheral tangential velocity V_t [m/s]	Rotor radius R [m]	Angular velocity Ω [rpm]
Savonius VAWT	1	7	1	67
Darrieus VAWT	5	35	1.5	223
Two-blade HAWT	10	70	28	24
Three-blade HAWT	7	49	45	10

To maximize the annual energy output, the power coefficient C_p should be kept at its maximum value during operation of the wind turbine for as long as possible, also when the wind speed changes.

Therefore, the rotation speed of the rotor should vary to maintain the TSR at the value which maximizes the C_p. Figure 3.14 shows the curves of power production as a function of the rotor speed and with the wind speed as parameter: to maximize the energy production, the turbine should always rotate at the speed to which the maximum power value corresponds and this for each possible wind speed value at the installation site.

Figure 3.14

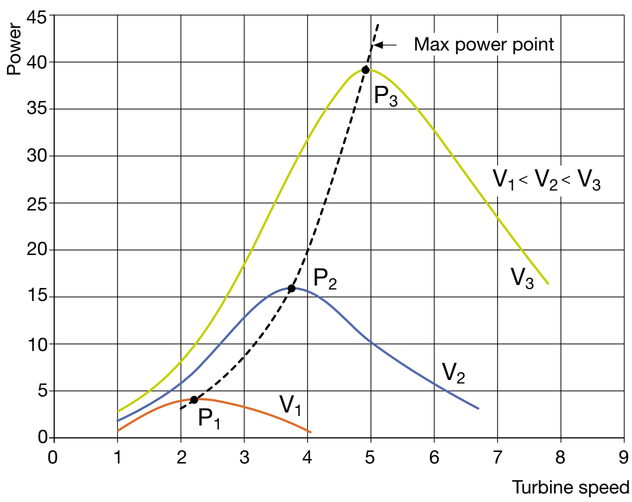
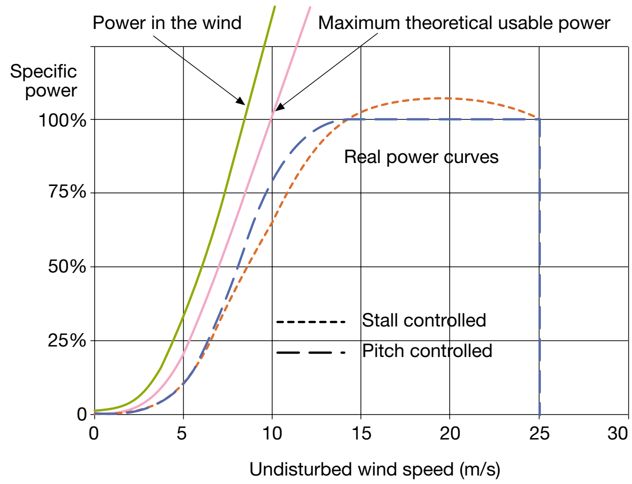


Figure 3.15 compares, as a function of the wind speed, the curve of the available power of the fluid vein, the ideal curve of the Betz limit of the maximum theoretical usable power and the real curves of the power generated in a stall controller turbine and in a pitch controller turbine.
As it can be noticed, through the control of such angle, once the rated power of the generator has been reached, it can be kept very close to such value up to the cut-off speed.

Figure 3.15



4 Energy producibility

4.1 Weibull distribution

To determine the energy producibility of a wind turbine it is not sufficient to know the mean speed of the wind at a given site. It is also important that data showing - for a defined time period (e.g. one year) - the histogram of the percentage duration of the different wind speed are available.
Such data are usually the mean value measured in 10min time by anemometers placed on anemometric towers. In particular, the histogram of Figure 4.1 shows in percentage the time for which the effective speed is higher than the reported one.

Figure 4.1 - Histogram of the velocity duration (percentage)

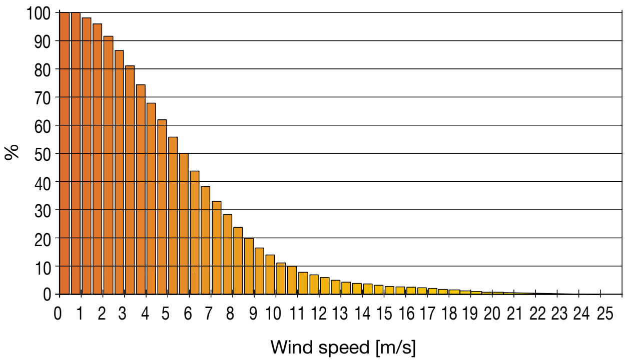


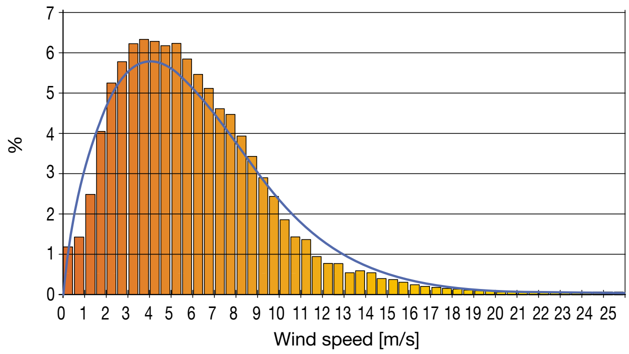
Figure 4.2
Anemometer

Installation of the anemometer on an anemometric tower

From the histogram in Figure 4.1 it is possible to obtain the histogram of the statistical frequency of occurrence of wind speed.

The time distribution of the wind speed for a given site is usually described by using the Weibull statistical distribution function since it comes nearer to the distribution frequency of the mean wind speeds in the previous histogram (Figure 4.3).

Figure 4.3 - Histogram of the occurrence frequency of speed

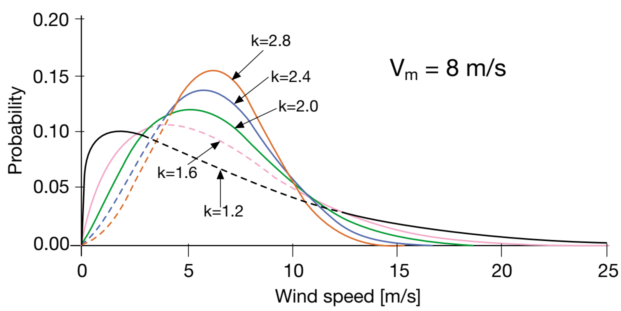


The Weibull distribution, which gives an anemological description of a site, can be totally identified by knowing two parameters only:

- the scale parameter A
- the shape parameter k.

The scale parameter (A), expressed in m/s, is univocally linked to the average speed. The adimensional shape factor (k) modifies the distribution symmetry: values very near to 1 represent very asymmetrical distributions, whereas high values (k>2-3) create symmetrical distributions similar to Gaussian functions[2] (Figure 4.4).

Figure 4.4 - Weibull curve for different values of k



[1] *It is named after the Sweden mathematician Waloddi Weibull who described it in 1951. The probability density function for a given value of scalar velocity v is:*

$$f(v) = \frac{k}{A} \cdot \left(\frac{v}{A}\right)^{k-1} \cdot \exp\left[-\left(\frac{v}{A}\right)^{k}\right]$$

[2] *When k=1 we have an exponential distribution, whereas when k=2 we have a Rayleigh distribution, which can be used for rough estimations when only the average speed is available.*

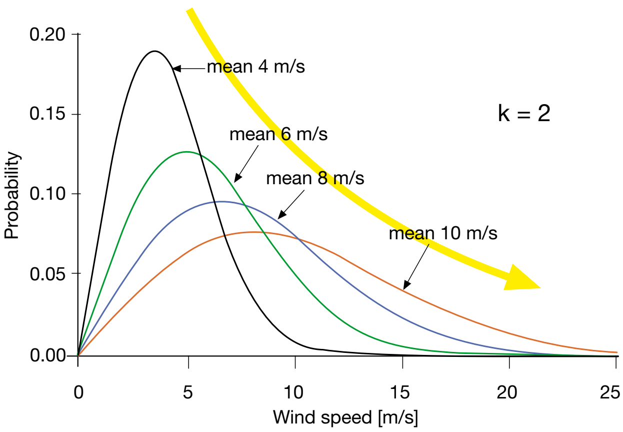
The shape parameter represents physically the “dispersion” of the speed values around the mean speed; in particular, the higher the value of k, the lower the dispersion around the average value.
The parameter k assumes different values since the ground morphology varies and depends on the wind regime present in a given region.
Typical values of k for different geographical situations are shown in Table 4.1[3].

Table 4.1

Shape parameter k	Ground morphology	Wind typology
1.2-1.7	Mountain sites	Very variable
1.8-2.5	Large plains – Hills	Variable
2.5-3.0	Open countryside	Quite regular
3.1-3.5	Sea coasts	Regular
3.5-4.0	Islands	Very regular

Availability of scale and shape factors grants the possibility of making further assessment of the energy potential output free from rough data, but at the same time characterized by high reliability.
In fact, the two parameters A and k contain effectively the statistical properties of the whole time series.
Therefore, since A is linked to the average speed, in order to assess the producibility of a wind turbine it is necessary to know the mean wind speed referred to the height of the rotor hub on the ground at the installation site and the shape factor as shown in Figure 4.5.

Figure 4.5 - Weibull curve for different mean values of wind speed



The reason why using the mean wind speed is not sufficient to calculate the energy output potential of a wind turbine can be deduced from the following example:

- **case 1**
  10 days of continuous wind at 5m/s speed (mean speed 5m/s).

- **case 2**
  10 days, of which 5 days of continuous wind at 10m/s speed and 5 days without wind (mean speed 5m/s).

By supposing to install a three-blade turbine with rotor diameter of 90m and coefficient C_p=0.43 (air density $\rho = 1.225 \frac{kg}{m^3}$)

- **case 1**

$$P_e = \frac{1}{2} \cdot C_p \cdot \rho \cdot \frac{\pi \cdot D^2}{4} \cdot v^3 = \frac{1}{2} \cdot 0.43 \cdot 1.225 \cdot \frac{\pi \cdot 90^2}{4} \cdot 5^3 = 209kW$$
$$E_e = P_e \cdot t = 209 \cdot 24 \cdot 10 = 50MWh$$

- **case 2**

$$P_e = \frac{1}{2} \cdot C_p \cdot \rho \cdot \frac{\pi \cdot D^2}{4} \cdot v^3 = \frac{1}{2} \cdot 0.43 \cdot 1.225 \cdot \frac{\pi \cdot 90^2}{4} \cdot 10^3 = 1700kW$$
$$E_e = P_e \cdot t = 1700 \cdot 24 \cdot 5 = 201MWh$$

As it can be noticed from this example, even at the same mean speed of 5 m/s, the same turbine generates 4 times more electric power in 5 days of case 2 than in 10 days of case 1.

4.2 Influence of the height from the ground level

In the previous paragraph, the wind speed frequency has been considered at a given height from the ground, typically that one which is detected by anemometric towers.
However, since the effective height of the hub of the turbines to be installed is different from that at which anemometers work, it is important to define the wind characteristics when varying the ground level.
As a matter of fact, the friction between air and ground slows down the wind near the ground, thus determining a speed profile as a function of height, also called boundary layer.
The speed curve according to height is influenced significantly by the ground nature (roughness) and by any obstacle (buildings, trees, rocks, etc.) as shown in Figure 4.6. It can be noticed how at the typical heights of installation of wind turbines there is a remarkable speed variation as a function of the installation site (in the figure a speed equal to zero is assumed at the ground level).

[3] *Italian average k=1.4 to 1.5.*

At a far distance from the ground (1500 to 2000m) the effect of it becomes almost negligible and therefore the wind speed is function of the weather conditions only.

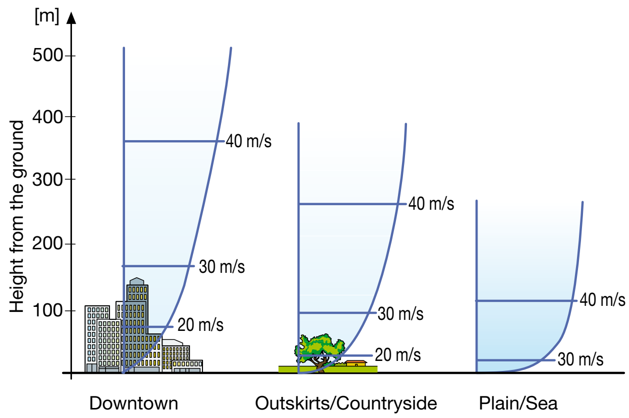


Figure 4.6 - Vertical profile of the wind

To determine the wind speed profile as a function of the height, the formula [4.1] can be used; it allows the velocity v_i at the i-th height to be calculated, once the velocity v_0 at height z_0 (from anemometric data) and the ground α are known:

$$v_i = v_0 \cdot \left(\frac{z_i}{z_0}\right)^{\alpha} \qquad [4.1]$$

During a preliminary analysis, the value reported in Table 4.2 can be assumed as indicative value of coefficient α.

Table 4.2

Coefficient α	Description
0.09	Calm sea
0.12	Open agricultural areas with limited presence of low obstacles
0.16	Open agricultural areas with limited presence of middle height obstacles (6-8)m
0.20	Agricultural areas with presence of numerous middle height obstacles (6-8)m
0.30	Urban areas, woods

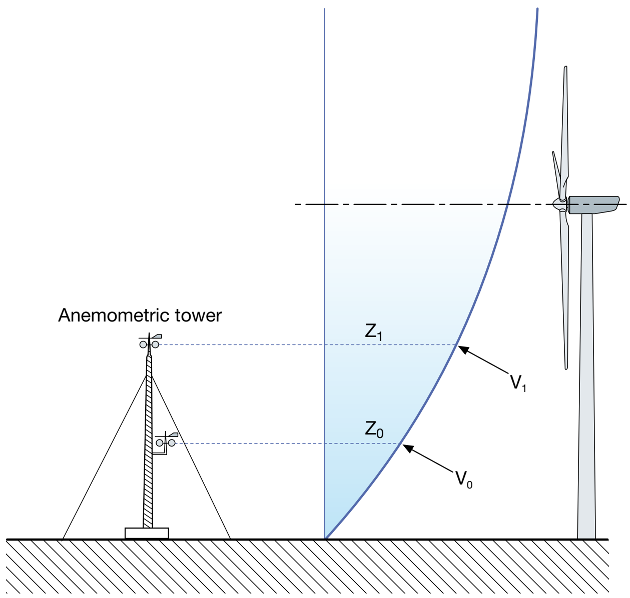
If anemometric data v_1 and v_0 for two different heights z_1 and z_0 (Figure 4.6) are available, the coefficient α for the installation site under consideration can be derived by inverting the relation [4.1] and obtaining a ratio between two common logarithms[4]:

$$\alpha = \frac{\log\left(\frac{v_1}{v_0}\right)}{\log\left(\frac{z_1}{z_0}\right)} \qquad [4.2]$$

Once determined the particular value of α, the speed can be calculated at the desired height of hub (Figure 4.7) always using the relation [4.1] and taking as reference one of the two experimental couples (v_1, z_1) or (v_0, z_0).

In this way it is possible to build the new histogram of Figure 4.3 with the various speeds of the wind at the height of the hub of the turbines to be installed reported in abscissa.

Figure 4.7 - Speed at the hub



[4] The logarithm property allowing the change of base through the following formula is applied:

$$\alpha = \log_{\frac{z_1}{z_0}}\left(\frac{z_1}{z_0}\right)^{\alpha} = \log_{\frac{z_1}{z_0}}\left(\frac{v_1}{v_0}\right) = \frac{\log\frac{v_1}{v_0}}{\log\frac{z_1}{z_0}}$$

4.3 Assessment of energy producibility

Since designing of a wind power plant is aimed at maximizing the annual production of electrical energy [kWh], this can be theoretically expressed and assessed by using Weibull distribution as regards the wind speed at the installation site and the curve of the electric power produced by the wind turbine as a function of the wind instantaneous velocity.

As a consequence, the annual producibility can be expressed through the following relation:

$$E = 8760 \cdot \int_0^{\infty} P(v) \cdot f(v) \cdot dv \qquad [4.3]$$

where:

- 8760 is the number of hours per year
- P(v) is the power output [kW] of the wind turbine at a wind velocity v [m/s] deduced from the power curve given by the manufacturer[5].
- f(v)is Weibull statistical distribution function of occurrence frequency of wind speeds at the installation site [s/m].

The total potential energy output of a wind power plant is obtained by summing the producibility of the single turbines installed and then by multiplying the result for some suitable corrective factors, so that any possible aerodynamic interference between the turbines[6] and the losses in the connection between the different units and between the plant and the grid are kept into consideration.

The annual producibility of a turbine is often expressed as "equivalent hours/year" h_{eq} according to the relation:

$$h_{eq} = \frac{E}{P_n} \qquad [4.4]$$

Theoretically and ideally, it is as if the turbine ran for a certain number of fictitious hours h_{eq} at its rated power and stood still in the remaining $(8760 - h_{eq})$ hours in order to produce the estimated power over a year period.

To compare two turbines in terms of energy producibility, it is insufficient to compare the equivalent hours/year because it is possible that a turbine with higher rated power than another one has a lower number of equivalent hours/year.

Therefore, for a correct comparison, it is necessary to refer to the *similarity criterion* according to which two wind turbines, even if with different rated power, are "*similar*" when they have close values of "*Specific rated output*" (ratio between the rated power P_n and the rotor area). In particular, two similar turbines have the same potential energy output in terms of equivalent hours/year.

[5] *In case, this curve shall be corrected to take into account the density variation of the air, due to the altitude and to the temperature at the installation site.*

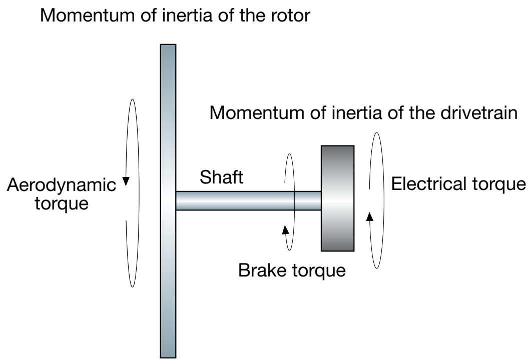
[6] *Wind turbines are arranged according to a suitable layout, leaving between the different units a distance sufficient to avoid an excessive aerodynamic interference (typically 3 to 7 times the rotor diameter).*

5 Regulation systems

5.1 Turbine mechanical model

A typical wind turbine can be simply modeled as a rotating mass with a large inertia, representing the rotor, and a rotating mass representing the generator, both connected to the rotation shaft (Figure 5.1).
To this mechanical model, the aerodynamic torques acting on the rotor apply: the electromagnetic torque acting on the generator and the possible torque applied to the shaft by mechanical brakes.
Below the rated wind speed, the control systems act to maximize the aerodynamic torque (and therefore the power output), whereas above the rated wind speed, the control systems modulate such torque to keep the rotation speed within acceptable limits.

Figure 5.1



In the turbines designed to operate at nearly constant speed, the generator torque is a function of the aerodynamic torque and the only way to control the generator torque (and consequently the power output) is by regulating the aerodynamic torque.
In variable-speed turbines instead, the generator torque and the aerodynamic torque can be independently changed, and consequently the rotor speed can be controlled both acting on the aerodynamic torque as well as on the generator torque thus affecting the acceleration or deceleration of the rotor.
Changes of the generator torque are carried out by interposing an electronic power converter (see Chapter 6) regulating phase and frequency of the current flowing through the generator windings.

5.2 Aerodynamic torque control

The aerodynamic torque can be controlled by acting on the rotor geometry, which modifies the lift and drag values and consequently the values of the aerodynamic torque.
The rotor geometry can be changed by regulating the Pitch over the length of the blade or by changing the geometry of a part of the blade only.
As explained later, full span Pitch control can be carried out both to reduce as well as to increase the angle of attack towards stall.
Pitch control can be carried out either individually, when the Pitch angle of each blade is regulated independently from all the others, or collectively, when all the blades are moved to the same Pitch angle – cyclic Pitch control – in which the Pitch of each blade is the same as the others at the same rotor Azimuth angle.

The first method has the advantage of offering more aerodynamic independent breaking systems for speed control, but has the drawback of requiring a very precise control of the mating angle of each blade so that inacceptable differences of the angle can be avoided during normal operation.
Ailerons can be used to change the blade geometry over a part of the blade; they reduce the lift coefficient and increase the drag on their surface.
Ailerons at the tip of the blade can also be used to add a negative torque to the rotor, or some spoilers can be used to “disrupt” the air flow around the blade by modifying lift and drag. Recently researches have been carried out into methods of tailoring the aerodynamics along the blade in response to local flow changes, through “smart” systems, such as the use of jets of air to improve the “attachment” of the flow to the blade surface

5.3 Control strategies

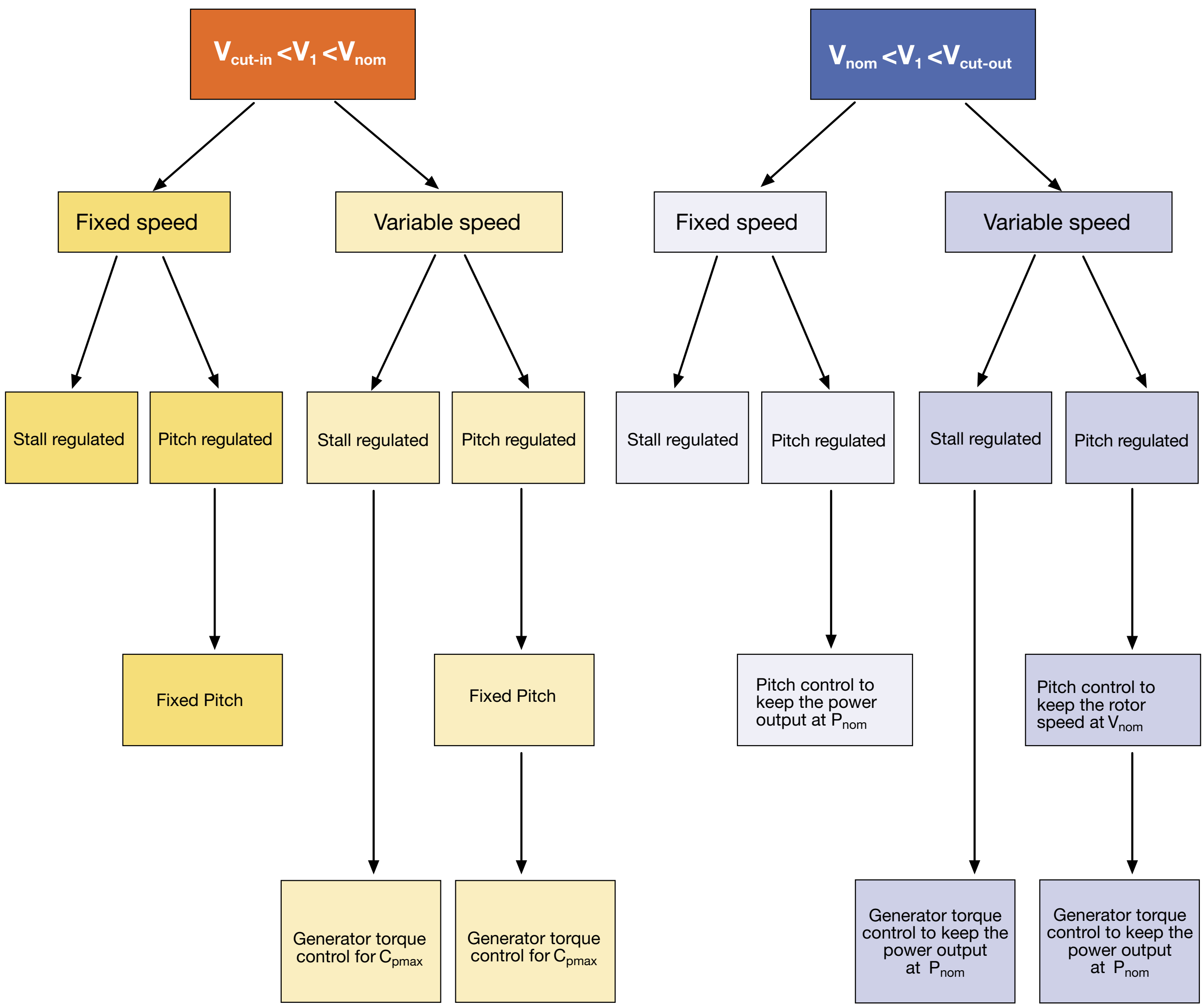
In general, the goals of wind turbine control strategies are:

- maximizing energy production while keeping operation within the speed and load constraints of the turbine components;
- preventing extreme loads, including excessive transient and resonance loads, and minimizing fatigue stresses;
- providing acceptable quality of the power put into the grid;
- ensuring safe turbine operation.

Such goals are influenced by the operating regime of the turbine: in fact, for wind speeds lower than the rated one, the main purpose is maximizing energy production by operating at the point of maximum efficiency of the blade, whereas for higher speeds the goal is limiting the produced power by keeping it close to the rated value.

Figure 5.2 shows a typical control strategy as a function of the wind speed for fixed or variable speed turbines and with passive stall or Pitch regulation.

Figure 5.2



As better described in the following clauses, passive stall-regulated fixed-speed turbines don't usually offer the possibility of active control, except when using mechanical brakes on the main shaft or when connecting and disconnecting the generator from the grid.

Pitch-regulated fixed-speed turbines use the active variation of such angle for starting up and control of the power produced above rated wind speed.

Variable-speed turbines typically use Pitch control, if available, above the rated wind speed to limit blade rotation speed, while they use generator torque control over all the operation range of the turbine.

Also the starting mode of the wind turbine depends on the available control systems. Fixed-speed, passive stall-regulated turbines cannot rely on aerodynamics to increase the rotor speed; as a consequence, starting is carried out by connecting the induction generator to the grid and starting it as a motor up to the operation speed.
Fixed-speed, Pitch-regulated turbines vary actively the Pitch angle to get an aerodynamic torque, which accelerates the rotor up to the rated operation speed and consequently the generator is connected to the grid.

Variable-speed turbines instead use the same starting modes as the fixed-speed ones, but the generator is grid-connected through a power converter.

5.4 Constant-speed turbines

At the beginning of the 90s', the installed wind turbines ran mainly at fixed speed. This means that independent of the speed of the incident wind, the rotor runs at a fixed speed determined by the grid frequency, by the gear of the gearbox and by the number of poles of the electrical generator.

As better explained in the following chapter, fixed-speed turbines are equipped with an induction motor (usually a squirrel-cage motor) directly connected to the grid, with a soft-starter to reduce the starting current and a capacitor bank to compensate the reactive power.

These types of turbines are designed to reach the maximum efficiency at a given wind speed. Nevertheless, to increase the power extracted from the fluid vein, the induction generators of some fixed-speed turbines have two stator windings, one of them with a higher number of poles to operate at low wind regimes, whereas the other with the pole number lower than the first one, so as to reach the steady state condition at medium-high wind speeds.
From the constructional point of view, these wind turbines have the advantages of being simple, robust, reliable and with contained costs for electrical equipment. But they consume reactive power, have high mechanical stresses and limited quality controls on the power fed into the grid.
Each fluctuation of the wind speed causes a change in the mechanical torque, which results in a fluctuation of the power fed into the grid. In grids with a low short-circuit power level, this causes voltage fluctuations with negative effects for the loads in parallel and can create inconvenience to persons because of the possible flicker generation (see clause 9.3.4).

5.4.1 Passive stall regulation

Taking into consideration a constant-speed wind turbine, as the wind speed increases so does the angle of attack of the blades. Above a certain speed, the air flow begins separating from the airfoil causing a condition called stall. Initially this phenomenon is close to the hub and progresses towards the blade tip as wind speed increases, thus providing an automatic passive mechanism of power regulation.
This type of regulation was largely used in the first commercialized wind turbines equipped with asynchronous generators and three fixed-Pitch blades, rigid hub and designed to have optimum TSR at low wind speeds.

In this type of turbines, when the mechanical brakes are released, the rotor reaches the operating speed; then the asynchronous generator is grid-connected, or the rotor is started through the generator itself (when it operates as asynchronous motor) up to the operating speed. However, passive-stall method caused some problems such as vibrations, instability, difficulties in foreseeing both entering stall as well as returning to laminar flow.

5.4.2 Two-speed, passive stall-regulated turbines

Some turbines were equipped with two-speed asynchronous generators through which it was possible to partially regulate entering the stall region, thus reducing the effect of wind speed fluctuations.
This control system is however to be included in fixed-speed systems since it is not a real variable-speed system even if the turbine operates as a two-established-speed fixed machine.
Energy gains are only 2 to 3%, but sometimes two-speed operation is deemed useful because of considerations linked to the total noise generated by wind turbines.

Two-speed regulation has the following disadvantages:

- additional cost of generator
- further control switchgear requiring additional maintenance
- turbine speed control required for each single speed
- loss of energy, whereas the generator is disconnected during speed changes.

5.4.3 Pitch regulation

When the wind speed becomes excessive, the rotor is stopped by increasing the Pitch angle up to feathering (thus, the aerodynamic load on the blades is reduced to the minimum).
As the wind speed rises, it is possible to reduce the Pitch angle instead of increasing it to intentionally cause stall. Thanks to this method, the amplitude of the blade rotation necessary to adjust the power is lower than that necessary to feathering (minimum variations required 0÷-4°); therefore in theory regulation takes less time, but the control of the power becomes difficult with stalled blade.
At high wind speed the average value of the extracted power is kept close to the rated power of the generator. On the contrary, below the rated power, the Pitch is generally kept constant to limit the wear of the regulation mechanism: this has the consequence of reducing the efficiency of the turbine but improves the total reliability of the system.

[1] *The aerodynamic noise produced by a wind turbine is approximately proportional to the fifth power of the peripheral speed of the blades.*

5.5 Variable-speed turbines

In the last few years variable-speed turbines have become the main type of installed turbines. They are designed to reach the maximum aerodynamic efficiency in a wide range of wind speeds. In fact, with variable-speed operation it is possible to continuously adapt (by accelerating or decelerating) the rotation speed of the blades to the wind speed, thus keeping the tip speed ratio (TSR) constant at the optimum value.

Contrary to fixed-speed systems, variable-speed systems keep the electromagnetic torque constant and the wind speed fluctuations are absorbed by the rotor speed changes. The electrical system is more complex than for fixed-speed systems and typically there are synchronous or asynchronous generators connected to the grid through a power converter which controls the rotor speed.
Variable-speed systems offer a certain number of advantages:

- increase the power extracted from the wind in terms of efficiency
- the reduced rotor speed at low wind speeds implies a reduction of the aerodynamic noise; this is quite significant at low wind speeds since the environmental noise cannot cover the turbine noise
- improvement of the quality of the power fed into the grid by smoothering fluctuations of the motive torque
- reduction in the mechanical stresses on the turbines.

However, these systems have the disadvantage of more power losses due to the presence of the converter and more costs for electrical machines, converter included.

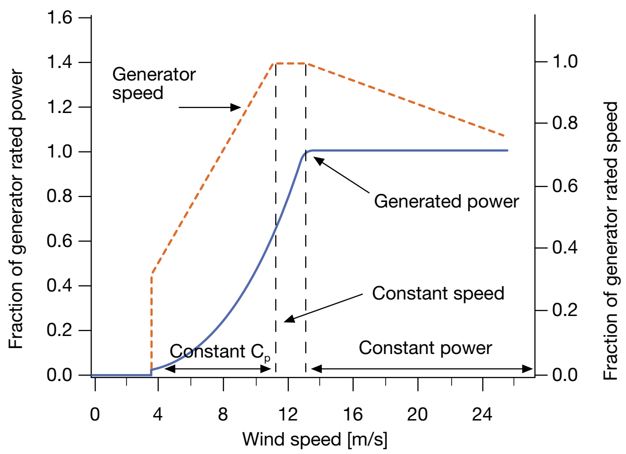
5.5.1 Passive stall regulation

Variable-speed, passive stall-regulated turbines has been a topic of research in Europe and in the United States, but they have not been commercialized and distributed. These are turbines controlled by using power electronics to regulate the generator electromagnetic torque. By using the generator torque to regulate the rotor speed, the turbine can be operated at the point with optimal tip speed ratio (TSR) within the generator and rotor design operation constraints. When the maximum design rotor speed is reached, the turbine is operated in a constant-speed mode with passive stall-regulation. As the wind speed increases and the extracted power exceeds the generator rated power, the turbine is operated in a constant-power mode and the rotor speed is regulated to limit the power extracted from the wind, thus increasing stall and consequently reducing the rotor efficiency.

5.5.2 Pitch regulation

These systems have two possibilities to control turbine operation: by controlling the generator torque and by varying Pitch.
At moderate wind speeds, these turbines are usually operated at constant Pitch with variable rotor speed, through torque control, to keep the TSR at an optimal value.
As the wind speed increases, the rotor generally reaches its rated speed before the rated power is reached; therefore the rotation speed shall be kept constant with consequent fluctuations of the power output.
Once rated power is reached, the combined action on the generator torque and on the Pitch is used to control both the electrical power output keeping it at the nominal value P_n, as well as to control the rotor speed and maintain it within acceptable limits around the rated speed (Figure 5.3).

Figure 5.3



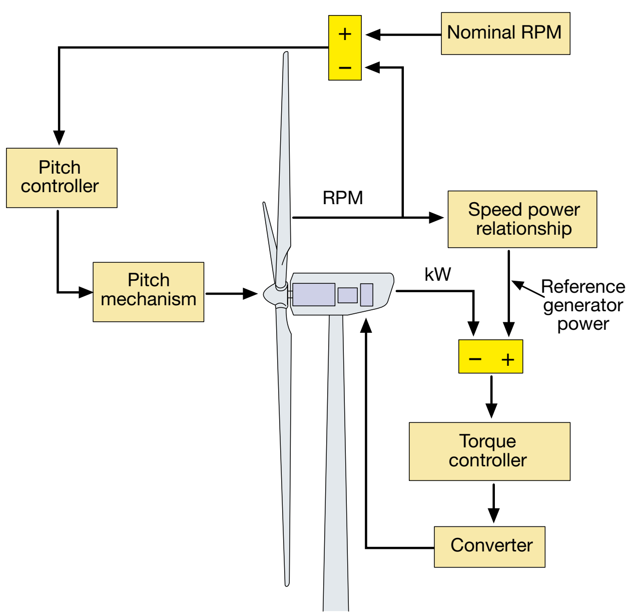
[2] For a turbine with a given diameter and for given values of available wind power and of power coefficient C_p, it is possible to have different values of rated power P_n as a function of the onerousness of sizing. For example, for a turbine currently on the market, with a rotor diameter of 90m, rated powers of 2 or 3 MW are possible.

[3] At low wind speeds with constant TSR, the variation speed $\left(\frac{dP}{d\Omega}\right)$ of the output power P as a function of the rotor speed Ω is quite small. At moderate wind speeds and with constant-speed operation, $\frac{dP}{d\Omega}$ may be quite high, whereas for high wind speeds, $\frac{dP}{d\Omega}$ is close to zero, since the output power is kept constant.

Beside, during wind gusts, the generated power is maintained at a constant level while the rotor speed increases. The transient increase of the wind energy is stored in the kinetic energy of the rotor.
On the contrary, if the wind speed suddenly drops, the reduced aerodynamic torque results in a deceleration of the rotor and the generated power is kept constant through the kinetic energy stored in the rotor.
If the wind speed remains high, the blade Pitch is changed to reduce the aerodynamic efficiency (and with it also the aerodynamic torque) thus reducing the rotor speed. In this manner the output power can be closely controlled and the Pitch mechanism can be slower than that one used in a constant-speed system.
Figure 5.4 shows the control diagram of these types of turbines.

It can be noticed that the instant speed of the rotor is compared both with the rated speed as well as with the speed-power curve of the generator at C_{pmax}.
If the instantaneous speed is higher than the rated speed, Pitch regulation is carried out to decrease the speed and kept it as close as possible to the rated speed.
By considering the curve it is possible to obtain the desired power, which, limited in the upper part by the generator rated power, is compared with the power actually delivered.
Then the converter is operated to control the generator torque to reach the required power or to limit it to the rated power.

Figure 5.4



The main characteristics of the Pitch and stall control systems are compared in Table 5.1.

5.5.3 Small-range variable-speed turbines

One approach to take advantage, even if in a limited way, of variable speed systems without all the relevant costs is the use of variable slip induction generators (see Chapter 6) by changing the rotor resistance through an external variable resistor.

At partial load, the generator operates as a regular asynchronous generator, but once the full load is reached, the rotor resistance is changed to increase the slip to allow the rotor to absorb the energy of gusts. The Pitch mechanism is used to modulate the power fluctuations.

Table 5.2 summarizes the main advantages of fixed- and variable-speed systems.

Table 5.1

Characteristics	Pitch angle	Stall
Produced work	Higher	Lower
Constant speed control	Difficult at high wind speeds	Generally satisfactory
Variable speed control	Better power quality and fewer stresses	Being studied
Safety	Safe device	Automatic brakes required
Stresses	Reduced	High
Cost of actuators	High	Null
Cost of blades	Reduced (less robust blades)	High (more robust blades)
Cost of auxiliary brakes	Null	High

Table 5.2

Fixed-speed systems	Variable-speed systems
Simple and less expensive electrical system	Higher efficiency
Lower probability of mechanical resonance	More regular motive torque
Lack of harmonics into the grid	Better quality of delivered power
Lower investment cost	No synchronism problem

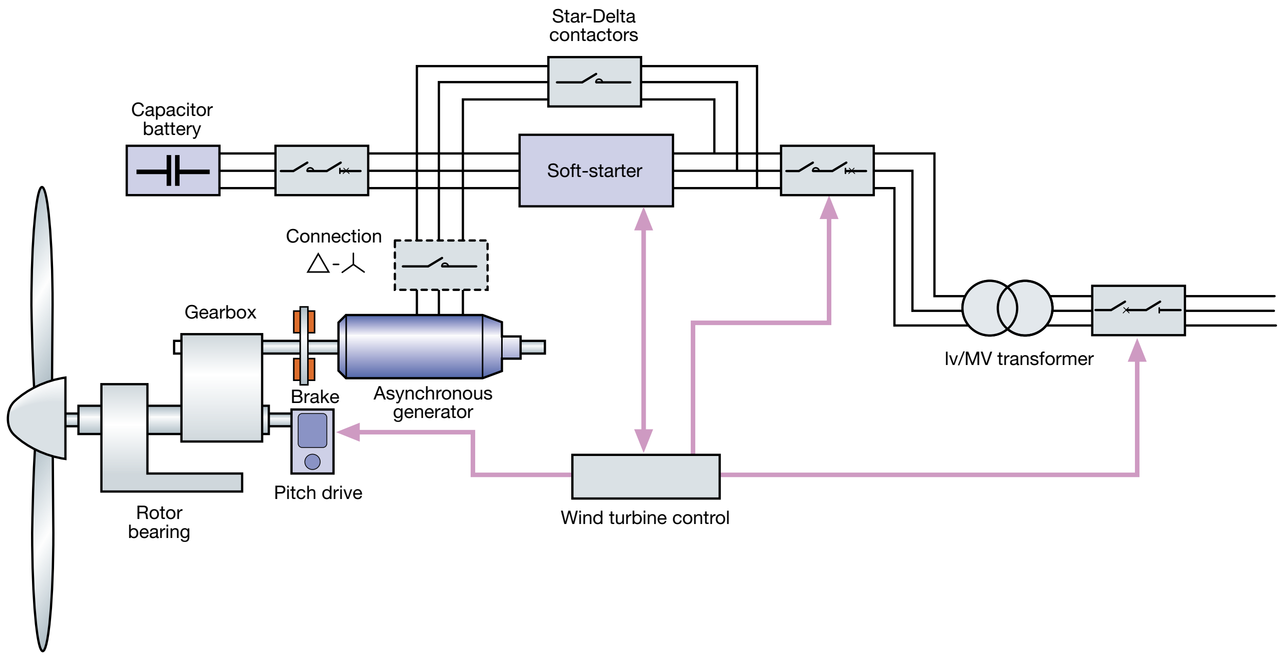
6 Power generation systems

6.1 Fixed speed wind turbines

In these types of turbines induction electrical machines (also known as asynchronous machines), generally used as motors for many industrial applications, are used for the conversion of the mechanical energy extracted from the wind into electrical energy.
In the wind turbines, on the other hand, these electrical machines are used as generators, above all because of their constructional simplicity and toughness, their relative cost-effectiveness and for the simplicity of connection and disconnection from the grid (Figure 6.1).

The stator of an induction machine consists of copper windings for each phase, as the stator of synchronous machines.
On the contrary, the rotor in squirrel-cage motors has no windings, but consists of a series of copper bars set into the grooves of the laminated magnetic core.
Some induction machines can have windings also on the rotor and in this case they are called wound rotor machines.
They are expensive and less sturdy than the previous type and are used in variable-speed wind turbines, as better explained in the following paragraphs.
Induction machines require a given quantity of reactive power to function.
This power shall be either drawn from the grid or delivered locally through a capacitor bank, which shall be properly sized so that self-excitement of the synchronous generator can be avoided in case of grid disconnection due to failure.
Besides, these machines need an external source at constant frequency to generate the rotating magnetic field and consequently they are connected to grids with high short-circuit power able to support frequency.
When working as a generator, the asynchronous machine is speeded up by the wind rotor up to the synchronous speed and then connected to the grid, or it is at first connected to the grid and started as a motor up to the steady state speed.
If the first starting method is used, the turbine clearly is self-starting and therefore the Pitch control must be present, whereas the second method is used for passive stall-regulated turbines.
In this case the control system stores the wind speed and defines the speed range within which the generator is to be started.
Once the synchronous speed has been achieved, the wind power extracted makes the rotor run in hypersynchronous operation with negative slip, thus supplying active power to the grid.
As a matter of fact, since the slip has values in the order of 2%, the deviation from the rated speed is very limited and that's why the use of these machines makes the wind turbine run at constant speed.
To reduce the starting current, a soft starter is usually interposed between the asynchronous machine and the grid.

Figure 6.1



6.2 Variable speed wind turbines

At least in principle, there are different solutions which allow the rotor to run at variable speed, also keeping constant frequency.
These solutions can be both of mechanical as well as electrical nature, even if the most used ones are of electrical type, in particular when using one of the following configurations:

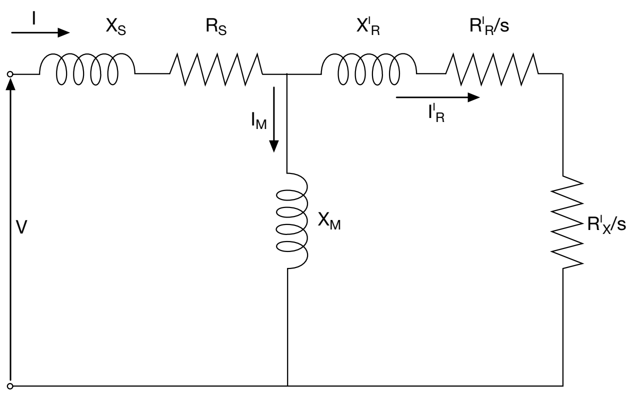
- wound rotor asynchronous generators with external variable resistor
- wound rotor asynchronous generators with a power converter interposed between rotor and grid (doubly-fed configuration)
- asynchronous generators with a power electronic converter interposed between stator and grid (full converter configuration)
- synchronous generators (alternators) with a power electronic converter interposed between stator and grid (full converter configuration).

6.2.1 Asynchronous generator with variable resistor

By adding an external variable resistor in series with the rotor windings of a wound rotor asynchronous generator it is possible to get a variation of the electromagnetic torque of the generator and of the speed at which it is delivered (Figure 6.2).

Thus, both the possibility of operating at the optimum TSR point as a function of wind as well as allowing the rotor to accelerate changing the speed due to wind gusts is guaranteed, even though the losses due to joule effect in the external resistor rise.
Besides, at high wind speeds, the total resistance of the rotor can be increased to keep constant the current flowing in the rotor (and therefore also in the stator), and with it also the power put into the grid, around the nominal power.
The excess of mechanical energy generated by the rotor is therefore dissipated as heat by the additional external resistor.
Through this resistor it is possible to achieve a variation in the speed exceeding the synchronism speed in the range 0-10%.
The equivalent electric diagram of an asynchronous generator with variable resistor R_x is shown in the Figure 6.3, in which the resistive component R'_x/s has been added to the common T circuit of the squirrel-cage asynchronous motor.

Figure 6.2



[1] *The terminals of the rotor windings are usually accessible by means of rotating rings and brushes.*

6.2.2 Doubly-fed concept

In order not to lose the power dissipated as heat in the additional resistor, this power can be put into the grid at the rated frequency by interposing an electronic power converter between the rotor of the asynchronous ring generator and the grid. This device converts the exceeding alternating power at the rotor first into direct power through a controlled rectifier and then reconverts it in alternating current at the rated frequency through an inverter (Figure 6.3).

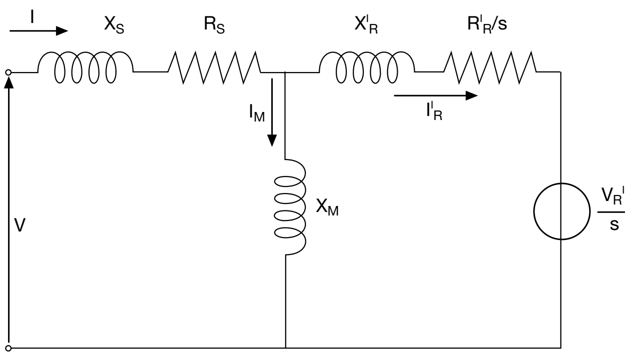
Thus it is possible to supply the rotor with voltages of the proper width and frequency supplied by the electronic converter with the purpose of compensating for the difference of frequency between the angular velocity of the stator rotating magnetic field and the effective angular velocity of the rotor.

The term “doubly-fed” reflects the fact that the stator voltage is applied by the grid, whereas the rotor voltage is applied by the electronic converter.

The equivalent electrical diagram of the DFIG is shown in Figure 6.5, where, with the purpose of representing the converter influence, the varying voltage generator (V’r/s), which is a function of slip s, has been added to the common T-circuit of the squirrel-cage asynchronous motor.

The active power shall always be going out from the stator and put into the net, independently of the operation state (either hyper- or sub-synchronous), whereas the rotor shall absorb power when operating as motor (sub-synchronism) and deliver it when operating as a generator (hyper-synchronism).

Figure 6.4



By assuming negligible both the stator as well as the rotor losses, the rotor power P_r managed by the converter, shall be linked to the stator power P_s through the slip s according to the following relation:

$$P_r = -s \cdot P_s \qquad [6.1]$$

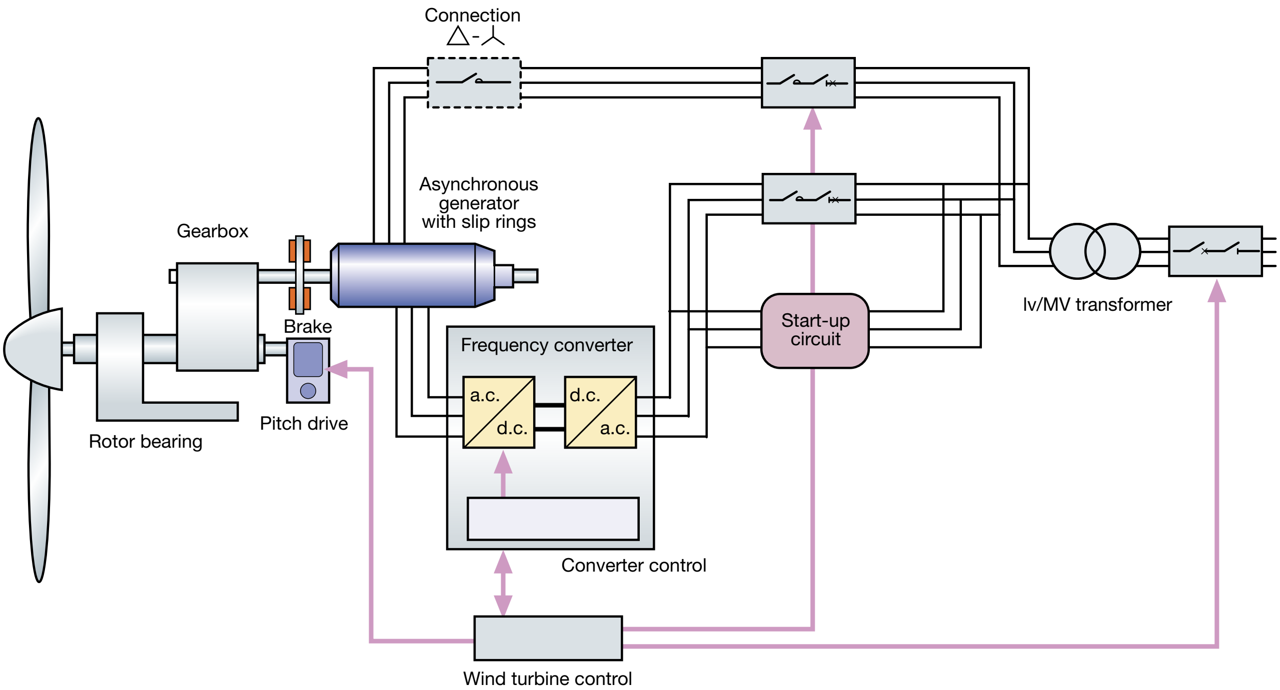
By identifying with P_{net} the power that the machine delivers to the grid on the whole, determined by the algebraic sum of the stator and rotor powers, Pnet can be expressed as:

$$P_{net} = P_s + P_r = P_s - s \cdot P_s = P_s \cdot (1 - s) \qquad [6.2]$$

with:

- negative s in hyper-synchronous operation
- positive s in sub-synchronous operation.

Figura 6.3



With this type of configuration, the electric generator supplies the network with 2/3 of the rated power through the stator directly connected and 1/3 through the rotor connected through the converter.
Therefore also the converter can be sized for power equal to 1/3 of the rated power of the generator.
Besides, it is possible to control the reactive power production; this allows voltage regulation and magnetization of the machine by the rotor regardless of the grid voltage.

By means of the doubly-fed configuration it is possible to obtain 30% speed variation above or below the synchronism speed.
The wound rotor asynchronous generator usually has a synchronism speed up to 2000 rpm and it is connected to the rotor axis through a three-stage gearbox.
The connection of the rotor windings to the converter is carried out by means of the slip-rings and relevant brushes.

6.2.3 Asynchronous generator and converter

Squirrel-cage asynchronous generators can be used in wind turbines at variable speed by interposing an electronic converter between the generator and the grid.
Such converter de-couples and releases the frequency of the rotating magnetic field from the grid frequency; then the frequency of the rotating magnetic field is modulated to control the rotating speed of the rotor.
As shown in Figure 6.6, there is an electronic power system similar to that of the doubly-fed configuration, but positioned on the generator stator.
As a consequence, the converter, unlike the previous configuration, must control the total power output.
Being an induction generator, it needs however to absorb reactive power to function; this power can be supplied by the converter itself.

6.2.4 Synchronous generator and converter

The most common constructional shape of a synchronous generator (alternator) consists of a rotor, which creates the magnetic field, and of a stator comprising the induced windings. The rotor magnetic field ($\Phi=k_r \cdot I_r$) is generated by a continuous current (Ir) circulating in the field windings.
Such continuous current is supplied by a dynamo coaxial to the alternator or it is drawn at the stator terminals and then rectified by a diode bridge.
The movement of the rotor magnetic field with respect to the stator windings due to the rotation of the main shaft induces a triad of alternating voltages in the stator windings with an r.m.s. value proportional to the magnetic flow of the rotor and to the rotation speed (n):

$$E = k_s \cdot \Phi \cdot n \qquad [6.3]$$

Since the frequency of the generated electromotive force is linked to the rotation speed by the relation:

$$n = \frac{60 \cdot f}{p} \qquad [6.4]$$

where p is the number of the pole couples of the rotor winding, the r.m.s value of the voltage induced on the stator is proportional to the value of the frequency at which it is generated:

$$E = k_s \cdot \Phi \cdot f \qquad [6.5]$$

When the generator is connected to a load (island- or grid-connection) and the current is delivered, this generates in the air gaps of the machine a rotating magnetic field synchronized with the induction field, without the relative slip. Besides, if the two magnetic fields are aligned (angle δ=0),), there is no resistive torque and consequently the active power provided to the grid is null. Otherwise, if there is a displacement due to an external motive torque, a resistive electrical torque is generated balancing the active power put into the grid (δ>0).
The higher the deviation, the higher the active power put into the grid.
By keeping the angle δ fixed, the active power put into the grid increases linearly with the r.m.s. value of the induced voltage and therefore proportionally to the rotation speed and to the voltage frequency[2]:

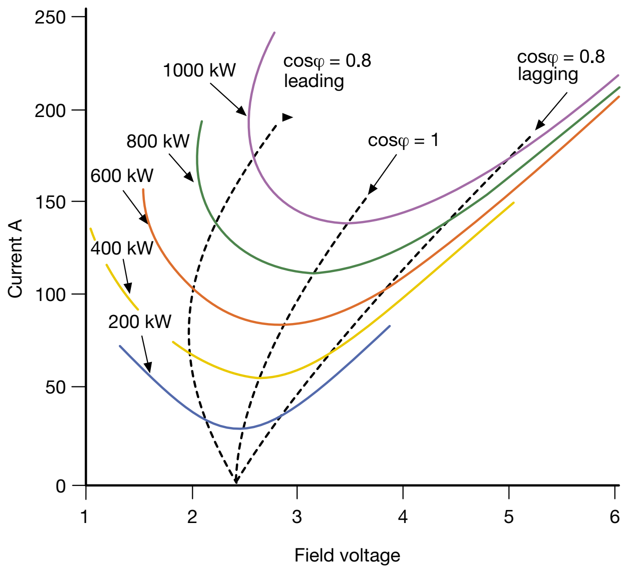
$$P = \frac{E \cdot V}{X_s} \cdot \sin\delta = \frac{V \cdot k_s \cdot \Phi \cdot f}{X_s} \cdot \sin\delta \qquad [6.6]$$

On the contrary, by keeping constant the provided active power when the rotation speed and consequently also the frequency and the induced voltage vary, the delivered current changes as shown by the curves in Figure 6.5. As it can be noticed, by assuming as parameter the delivered active power, if the induced voltage exceeds the grid voltage, the alternator provides reactive power, while, if the induced voltage is lower than the grid voltage, the alternator absorbs reactive power[3].
In particular, if the induced power has value equal to the grid voltage (cosφ=1), the current flowing through the stator takes its minimum value.

2 For this reason the power generated by a wind turbine grows as the wind speed increases and therefore as the rotation speed of the rotor increases.

3 According to generator convention.

Figure 6.5



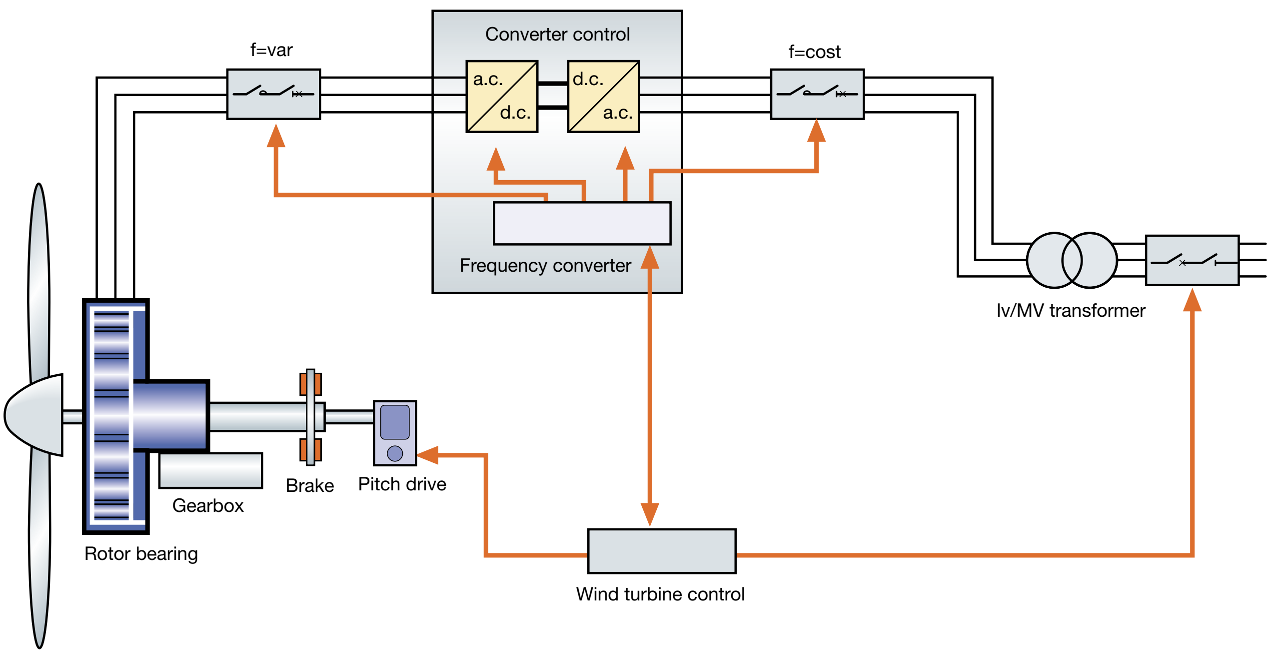
Synchronous generators are not intrinsically self-starting. The alternator generally reaches the synchronous speed by means of the prime mover and then it is connected in parallel following a proper procedure.
In applications, for which self-starting is needed, the rotor is equipped with dampening copper bars, which start the alternator as an induction machine and during operation they dampen the dynamic oscillations of the machine.
In wind applications, turbines with synchronous generators are normally started by the wind itself and a speed control system is used for the synchronization procedure.

Permanent magnet alternators are often used in wind turbines, in which the rotor is without the excitation winding and the induction magnetic field is generated directly by the permanent magnets built-in into the rotor.
As a consequence, slip-rings and brushes are not necessary for the supply of the excitation circuit.
The operating principle is analogous to that of the alternators with the induction winding, but in the permanent magnet alternators the voltage induced into the stator windings cannot be adjusted through the excitation current; therefore the voltage at the generator terminals is only a function of the rotation speed of the rotor.
Since the frequency generated by the alternator depends on the rotation speed of the rotor and on the number of pole couples, to be able to use the synchronous generator in a variable speed wind turbine keeping constant the frequency on the grid side, it is necessary to interpose a two-stage power converter controlling the whole of the generated electric power (Figure 6.6):

- in the first stage, either a diode or a thyristor-controlled bridge rectifier converts the electrical quantities generated by the alternator from variable frequency alternating quantities into direct quantities;

- in the second stage, through a DC link, supply is given to an inverter which converts the direct electrical quantities of voltage and current into alternating quantities at the grid frequency.

Figure 6.6



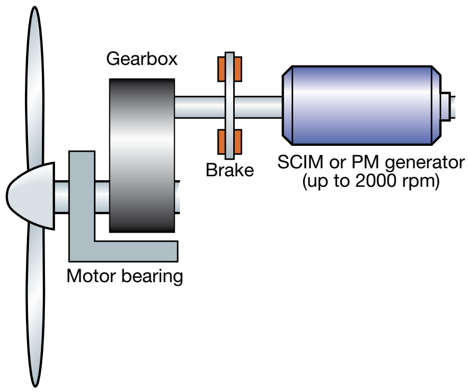
In case of a separated excitation alternator, the regulation of the r.m.s. value of the generated voltage is obtained by acting on the excitation current, while with a permanent magnet alternator the voltage can be adjusted either through a thyristor-controlled bridge rectifier or through a PWM-controlled inverter.
The PWM control of the inverter can be carried out through different modalities:

- regulation of the value of the sinusoidal modulating amplitude by comparing the voltage value of the DC-link with the optimum curve P-Vdc;
- MPPT (Maximum Power Point Tracker) by using an anemometer.
  The power on the dc side is compared with the reference power and from a comparison with the optimum curve, depending on the wind speed, the new voltage on the dc side is determined.
  The PWM (Pulse Wide Modulation) control signal varies instantaneously as the operating conditions vary;
- MPPT with wind forecast: the energy previously extracted is taken into consideration and, by statistical models, the wind speed in the following moments is forecast.
  This control system tracks the optimum points as function of the foreseen speeds.

The use of the configuration alternator-power converter allows decoupling the generator from the grid, thus reducing the mechanical shocks on turbines during grid faults. Besides, there is generation also of the desired reactive power and full control on the active power.

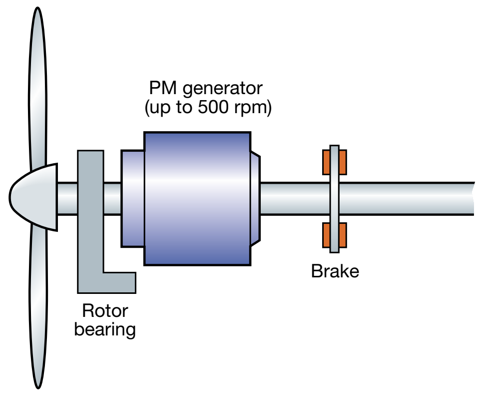
There are three full converter concepts for electromechanical conversion: high-speed, medium-speed and low-speed.
High-speed conversion is mechanically similar to the doubly-fed type and normally uses a three-stage gearbox and a turbo alternator (up to 2000 rpm) usually of permanent magnet type or an asynchronous generator (Figure 6.7).
This configuration offers the advantages of using a small-size and low weight generator and can be used to replace an existing doubly-fed configuration.

Figure 6.7



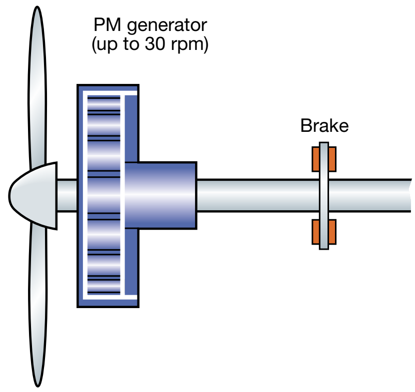
With medium-speed conversion instead either a single or a two-stage gearbox is used with a compact permanent magnet alternator (up to 500 rpm) (Figure 6.8).
This concept, with a lower size of the gearbox and lower rotation speeds in comparison with the previous configuration, allows reducing the mechanical stresses and therefore improving reliability.
The alternator diameter is larger than in the previous case.

Figure 6.8



Finally, low-speed conversion eliminates the gearbox and uses an alternator, normally a permanent magnet or a low-speed (up to 30 rpm) separately excited generator, therefore with a number of poles greater than the previous ones (Figure 6.9).
This configuration offers above all the advantages deriving from the absence of the gearbox; they imply a reduction in the mechanical losses, the elimination of total noise contribution and a further increase in the reliability of the wind turbine.

Figure 6.9



7 Protection against overcurrents and earth faults

7.1 Generalities

Since wind is a variable and uncertain source, blowing inconstantly and subject to sudden variations, the dedicated mechanical and electrical devices must guarantee high performances in order to maximize the extraction of the mechanical power and its conversion into electric power for input into the grid.
In particular, from the electrical point of view, it results in frequent operation of the control actuators (e.g. Pitch adjustment or yaw control) and in repeated connection and disconnection of the devices of the power circuit. This implies heavy stresses, in particular in onshore installations subject to wind gusts, where it is quite common to reach 10 to 20 operations per day. Besides, the turbine components, and therefore also the internal electrical components, are called to operate under heavy environmental conditions above all in terms of intervals of service temperature.
That's why the electrical equipment used for wind applications must be accurately chosen, taking into account environmental elements and thermal and mechanical stresses.
In addition to the choice of suitable switching and disconnection devices, when designing a wind power plant it is also necessary to provide for the protection of the different sections of the plant against overcurrents and earth faults.
Here are given all the necessary information for switching and protection, both on generator as well as on grid side (downstream the possible converter), for the three most common concepts of power circuit:

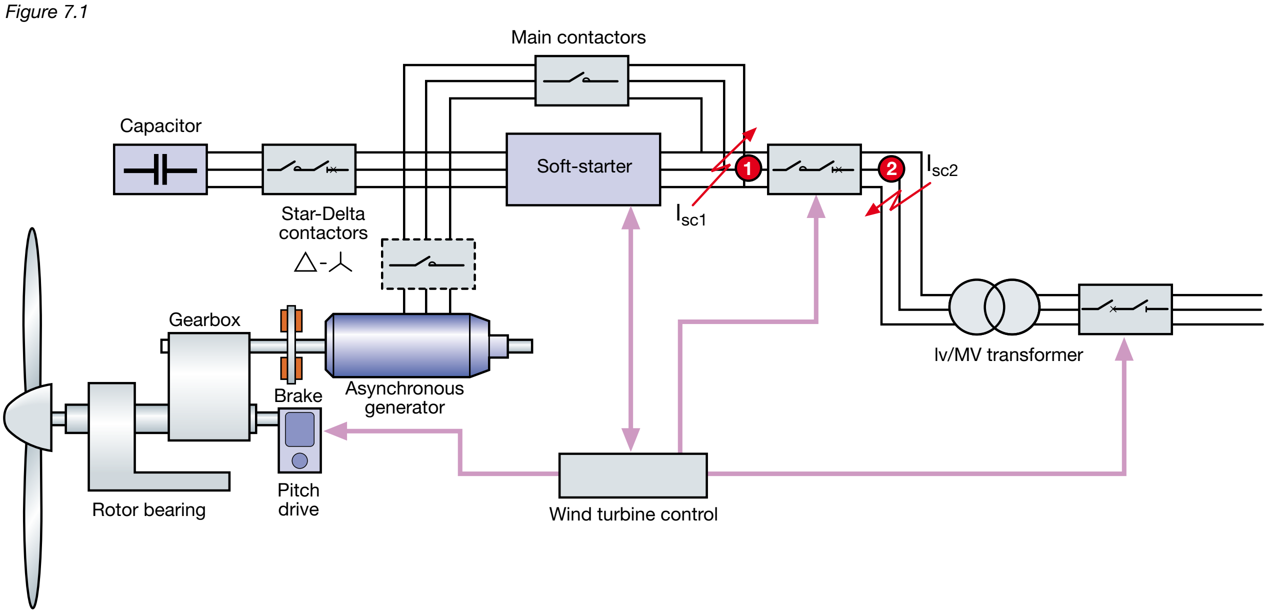
- fixed speed
- doubly-fed
- full converter.

7.2 Protection against overloads

7.2.1 Fixed speed – Aysnchronous generator

The diagram in Figure 7.1 represents the main electric power circuit (capacitor bank included) characteristic of this type of wind turbines.
As it can be noticed, the control system of the turbine operates by acting on the contactor and the main circuit-breaker, the soft starter, the MV circuit-breaker and the pitching system.
The start-up phase of the asynchronous generator is managed through a soft starter in parallel with a by-pass contactor, which is closed once the steady state condition has been reached. For the choice of the coordination soft starter-circuit-breaker-contactor and by-pass contactor reference can be made to the tables for starting/protection of ABB motors.
Besides, there is the possibility of carrying out the star-delta connection of the generator windings through contactors of suitable size so that different wind conditions can be managed.
The capacitor bank connected in parallel with the generator delivers the reactive power necessary for the operation of the asynchronous generator by reducing, and, if this is the case, by avoiding the demand of reactive power from the grid. For the capacitor bank it is necessary to provide a proper device to ensure disconnection whenever there is a loss of the network power, in order to avoid self-excitation of the rotor (EN 61400-1). As regards switching and protection of capacitors, reference shall be made to the Technical Application Paper No. 8 (QT8) *"Power factor correction and harmonic filtering in electrical plants".*

Figure 7.1



To choose the breaking capacity of the main LV circuit-breaker it is necessary to evaluate the short-circuit currents under different fault conditions:

- in case of short-circuit at point 1, the fault current I_{sc1} seen by the circuit-breaker shall have a value depending on the short-circuit power of the grid to which the wind turbine is connected and on the short-circuit impedance of the lv/MV transformer.
- in case of short-circuit at point 2, the fault current I_{sc2} seen by the circuit-breaker shall have an exponential smoothing trend and shall be supplied, for a limited time, by the asynchronous generator due to the effect of the kinetic energy stored by the rotor. The values of the tripping times of the circuit-breakers in use are generally lower than the damping times of this fault current; therefore the transient effects must be kept into consideration. To this purpose, the asynchronous generator can be represented through a longitudinal reactance (disregarding the resistances) equal to the subtransient X" of the generator itself[1]. To take into account the damped curve of the fault current, the value of X" is increased by a suitable factor k. Table 7.1 shows the values of k according to the power of the asynchronous generator and depending on the fault current contribution considered, either at the end of the first period or after four periods from the fault start. The increase of the k factor corresponds substantially to an increase of the generator reactance and consequently to a decrease of the short-circuit current supplied.
  Given a generator with rated power Sn, operating at the rated voltage Un and with a given subtransient reactance percentage X"%, the equivalent reactance is:

$$X_g = \frac{X''\% \cdot U_n^2}{100 \cdot S_n} \qquad [7.1]$$

Therefore the given fault current can be determined as:

$$I_{sc2} = \frac{U_n}{k \cdot \sqrt{3} \cdot X_g} \qquad [7.2]$$

[1] *When the value of X" is not known, the locked rotor reactance X_{cc} can be used; it is usually is lower than X" and thus a precautionary result can be achieved.*

Table 7.1

Rated power [kVA]	No. of periods from the beginning of the short-circuit	
	1	1.5 ÷ 4
≥ 40	1.2	3
< 40	1.67	∞

From the above, the current I_{sc2} indicatively results about 3 to 5 times the rated current I_n of the generator.
Since such current decreases exponentially and tends to zero in a very limited time interval, the associated specific let-through energy usually is not such as to create problems to the different electrical components.

With the purpose of protection against overload of the cables on the generator side and on the network side with current carrying capacity I_z in compliance with the Std. IEC 60364, the rated current of the protection device (or, for the adjustable trip units, the current setting for thermal protection) must satisfy the relation:

$$I_b \leq I_n \leq I_z \qquad [7.3]$$

Besides, for each value of short-circuit current likely to occur up to the maximum values at points 1 and 2, the specific let-through energy of the circuit-breaker must be carried by the connection cables according to the usual relation:

$$\left(I^2t\right) \leq K^2S^2 \qquad [7.4]$$

where:
(I^2t) is the Joule integral, that is the energy let through by the circuit-breaker during short-circuit (in A^2s);
K is a constant characteristic of the cable depending on the type of conductor and insulating material; S is the cross-sectional area of the cable (in mm^2).

The relation [7.4] must be verified for the whole length of the cables. However, given the particular trend of the curve of the let-through energy of a circuit-breaker, it is generally sufficient to verify the relation [7.4] only for the maximum and minimum value of the short-circuit current which can affect the wiring system.
The maximum value is usually the value of the three-phase short-circuit current at the beginning of line (in this case I_{sc1} and I_{sc2}), while the minimum value is the value of the short-circuit current line-to-line (neutral conductor not distributed) or line-to-earth at the end of the conductor.

The verification cannot be simplified by comparing only the value of specific energy let through by the circuit-breaker at the maximum short-circuit current with the energy withstood by the cable and by making the device trip instantaneously at the minimum short-circuit current. In practice, this means that the tripping threshold of the protection against short-circuit (taking tolerances into account) must be lower than the minimum short-circuit current at the end of line.
Besides, the main circuit-breaker allows the generator to be disconnected from the grid during normal operation and maintenance cycles.

Table 7.2 sums up the main characteristics to be taken into consideration when choosing the circuit-breakers and the contactors for the main power and auxiliary circuits. Therefore, it is necessary to verify that the circuit-breaker is able to ensure disconnection at the required voltage.

7.2.2 Variable speed – Doubly-fed concept

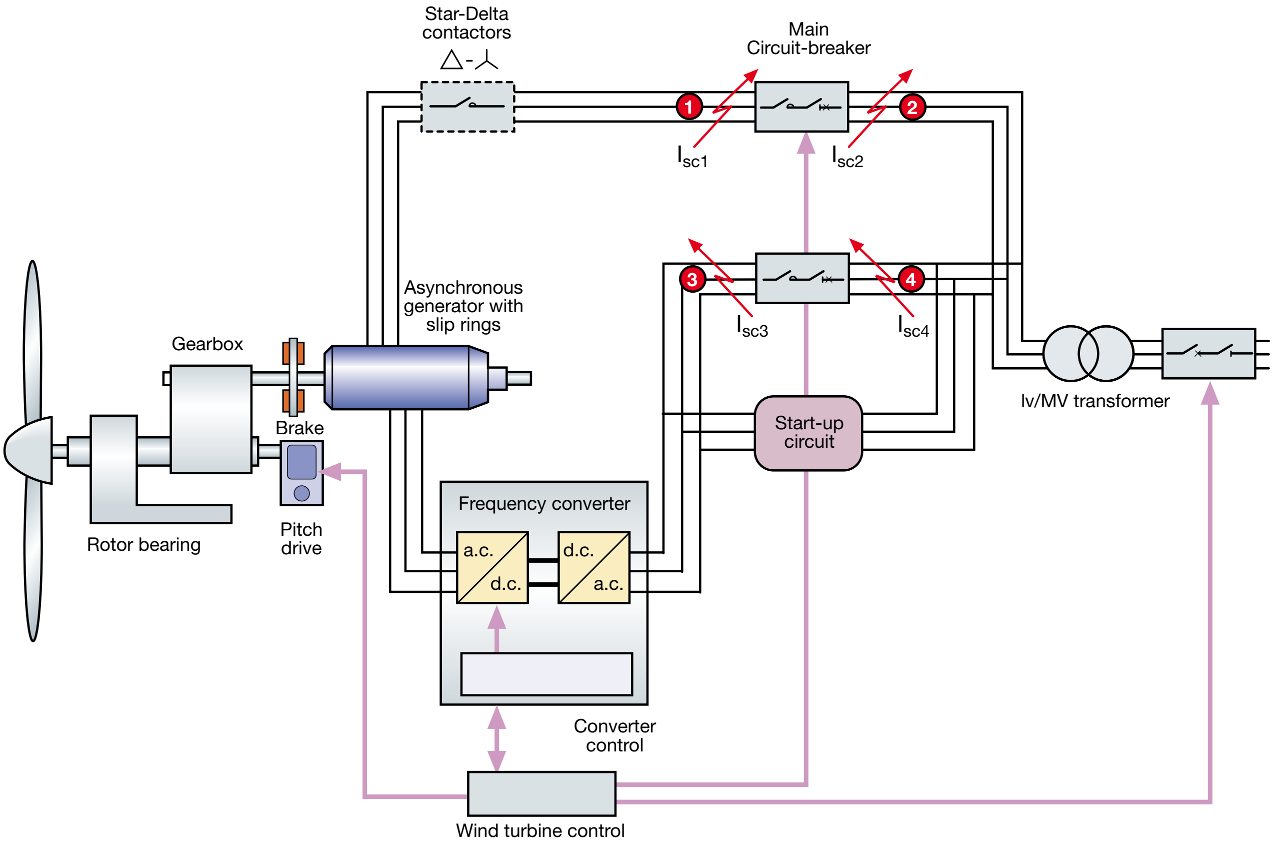
The diagram in Figure 7.2 represents the main power circuit of stator and rotor characteristic of this typology of wind turbines.

As it can be noticed, the turbine control system acts by commanding the rotor and stator contactors and circuit-breakers, the converter on the rotor, the MV circuit-breaker and the pitching system.
There is the possibility of star-delta connecting the stator windings of the generator by means of contactors properly sized in order to deal with different wind conditions. Also in this case, as regards the choice of the coordination circuit-breaker/contactor, it is possible to refer to the "motor starting/protection" tables issued by ABB.
At starting, the closing of the start-up circuit on the rotor circuit in parallel with the circuit-breaker/contactor is carried out first. The start-up circuit includes a resistance of a value suitable to limit the start-up current.
Then, closing of the contactor on the main excitation circuit of the rotor is carried out and afterwards that of the contactor on the main power circuit of the stator. Since in this case the magnetic field inside the generator is caused by the rotor supply, when the supply circuit of the stator is closed there is no inrush current (operating in AC-1).
When starting has been carried out, the start-up circuit is disconnected and therefore, under steady state conditions, the power flowing in the rotor circuit passes through the main auxiliary contactor.

Table 7.2

Characteristics	Main power circuit	Main auxiliary circuit
Load current [A]	≤ 1800	≤ 320
Voltage [V]	≤ 690	≤ 690
Frequency [Hz]	50 - 60	50 - 60
Prospective short-circuit current [kA]	≤ 35 @ 690V	
Presence of inrush current	No	Yes
Type of load	AC1	AC3 – AC6A
Life time [years]	20	20
Number of mechanical operations (or electrical operations at low current) to disconnect the system (maintenance or out of service)	100…1000	< 1000
Number of mechanical operations (or electrical operations at low current) of connection to/disconnection from the grid or of reconfiguration (production control)	10000…100000	Not applicable
Number of electrical operations	< 100 (tripping of protections or emergency stop)	< 100 (tripping of protections or emergency stop)
Protection against overcurrents	Yes	Yes
Optimum solution	Circuit-breaker + contactor	Circuit-breaker

Figure 7.2



To choose the breaking capacity of the LV circuit-breaker positioned on the main power circuit, it is necessary to assess the short-circuit currents under different fault conditions:

- in case of short-circuit at point 1, the fault current I_{sc1} seen by the circuit-breaker shall have a value depending on the short-circuit power of the grid to which the wind turbine is connected and on the short-circuit impedance of the lv/MV transformer. To this value, the rotor contribution has to be summed; such contribution is limited to about the double of the rated current of the converter due to the effect of the converter itself;
- in case of short-circuit at point 2, the fault current I_{sc2} seen by the circuit-breaker shall have an exponential smoothing trend and shall be supplied for a limited time by the asynchronous generator due to the effect of the kinetic energy stored in the rotor (what has been said about fixed speed generators is valid: see clause 7.2.1).

Analogously, as regards the choice of the breaking capacity of the LV circuit-breaker positioned on the main excitation circuit of the rotor, it is necessary to consider the short-circuit currents measured by this circuit-breaker according to the position of the fault:

- in case of short-circuit at point 3, the fault current I_{sc3} seen by the circuit-breaker shall have a value equal to the sum of the contribution of the grid and of I_{sc2};
- in case of short-circuit at point 4, the fault current I_{sc4} seen by the circuit-breaker shall be limited to about the double of the rated current of the converter.

For the protection of the cables on the generator side and on the network side with current carrying capacity Iz the same considerations of clause 7.2.1 are valid.
Besides, if the cables had a current carrying capacity Iz higher than the fault current let through by the converter, the cable protection should be verified only as regards the constant contribution to the grid.
The circuit-breakers positioned on the main power circuit

and on the main excitation circuit allow isolation from the grid of the stator of the generator and of the converter on the rotor respectively.
Therefore, it is necessary to verify that the circuit-breaker is able to ensure disconnection at the required voltage.

Generally, it is not necessary to place an automatic protection device in the connecting section between the converter and the rotor of the doubly-fed generator since, in the case (unlikely, if the connections are carried out according to the state of the art) of a short-circuit in that area, the generator would start to operate as it had the squirrel-cage rotor, whereas the converter would limit its contribution to the short-circuit to a value twice its rated current and therefore it would reach the standy-by due to the intervention of the internal protections.

Table 7.3 summarizes the main characteristics to be taken into consideration for the choice of the circuit-breakers and of the contactors for the main power circuit, for the main excitation circuit and for the start-up circuit.

7.2.3 Variable speed – Full converter concept

The diagram of Figure 7.3 represents the main power circuit characteristic of this typology of wind turbines.
The start-up phase of the asynchronous generator is managed through a soft starter in parallel with a by-pass contactor, which is closed once the steady state condition has been reached. For the choice of the coordination soft starter-circuit-breaker-contactor and by-pass contactor reference can be made to the tables for starting/protection of ABB motors.

As it can be noticed, the turbine control system operates by commanding the converter control system, the MV circuit-breaker and the pitching system. In its turn the control system of the converter, besides controlling the operation of the power electronic sections on the generator side and on the network side, controls also the two circuit-breakers interposed between converter and generator and between converter and grid.
The different designers and manufacturers of wind turbines have different design and priority criteria. As a consequence, the choice of the components can vary. Some important design criteria to be taken into consideration are:
- circuit protection
- safe disconnection
- number of connection/disconnection operations.

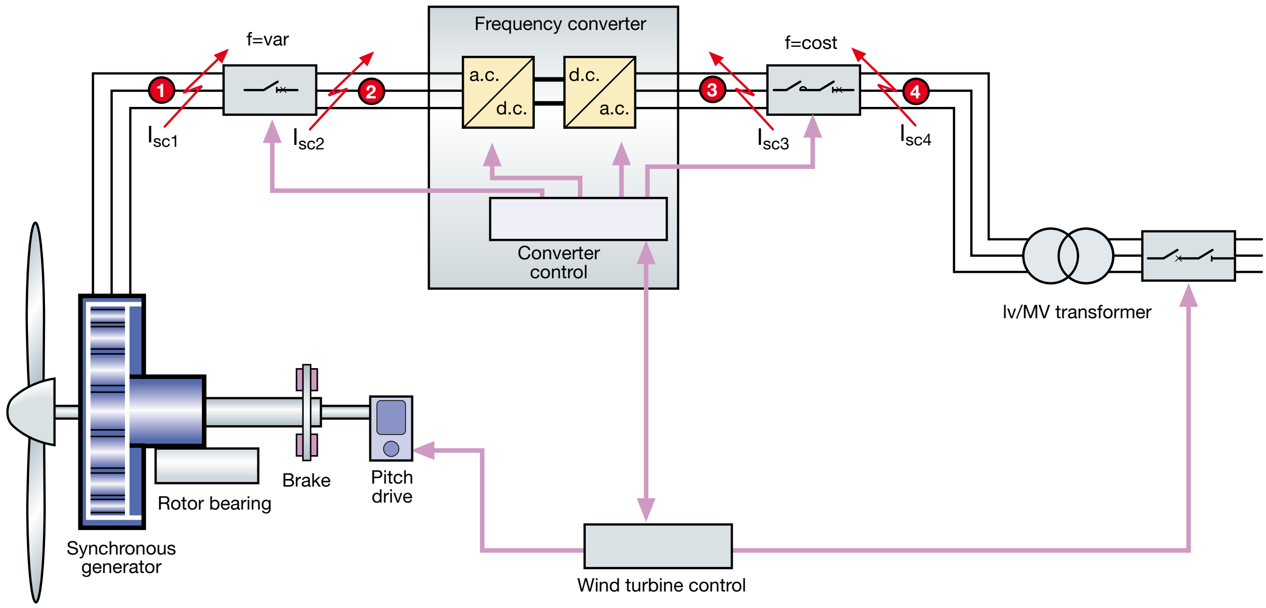
According to these criteria, the actual existing solutions are the following ones:
- grid side of the converter
  - → circuit-breaker only;
  - → coordination circuit-breaker / contactor
- generator side of the converter
  - → circuit-breaker only;
  - → coordination circuit-breaker / contactor.

ABB approach provides customers' support with any of the above mentioned solutions, by illustrating advantages and drawbacks of each concept, but usually by promoting the use of combined solutions, with converter for switching operation in coordination with circuit-breaker for protection and disconnection.

Table 7.3

Characteristics	Main power circuit	Main excitation circuit	Start-up circuit
Load current [A]	≤ 3000	≤ 630	≤ 5
Voltage [V]	≤ 1000	≤ 690	≤ 690
Frequency [Hz]	50 – 60	50 - 60	50 – 60
Prospective short-circuit current [kA]	≤ 30 @ 1000V	≤ 50 @ 690V	≤ 50 @ 690V
Presence of inrush current	No	No	Yes
Type of load	AC1	AC3	AC3
Life time [years]	20	20	20
Number of mechanical operations (or electrical operations at low current) to disconnect the system (maintenance or out of service)	100…1000	< 1000	Not applicable
Number of mechanical operations (or electrical operations at low current) of connection to/disconnection from the grid or of reconfiguration (production control)	10000…100000	Not applicable	Not applicable
Number of electrical operations	< 100 (tripping of protections or emergency stop)	< 100 (tripping of protections or emergency stop)	> 10000 (excitation circuit insertion)
Protection against overcurrents	Yes	Yes	Yes
Optimum solution	Circuit-breaker + contactor (more than one operation per day required) circuit-breaker (less than one operation per day)	Circuit-breaker + contactor	Circuit-breaker + contactor

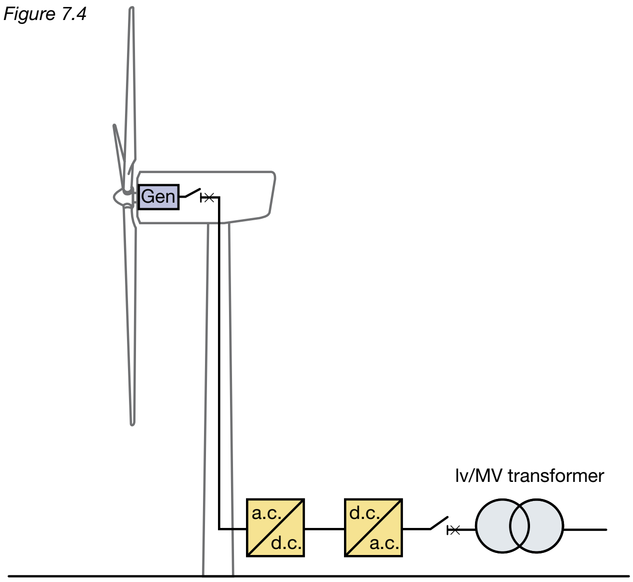
Figure 7.3



The circuit-breaker positioned between generator and converter shall be able to function at a variable frequency of electrical quantities (typically ranging from 1 to 200 Hz according to the rotation speed of the alternator) and must carry out the following functions:

- *isolation:* during normal operation or maintenance cycles the disconnection devices are controlled by the automatic system of the inverter. In this application a safe isolation is necessary to guarantee the disconnection of the source, represented by the generator, from the remaining part of the circuit, since the semiconductor devices must not be used alone as isolation devices (IEC 61400-1);
- *back-up:* certification bodies require that, during a fault, a redundancy for the protection system inside the inverter is guaranteed and acts on the generator disconnection: the circuit-breaker is exactly an effective back-up system;
- *protection:* in case of a fault involving the inverter or of a fault in the section between the generator and the inverter (e.g. in the cable connection), the circuit-breaker is the device able to detect the failure and trip by disconnecting the source and protecting the cable. Likelihood of such failure is not negligible, especially when the cable length is considerable, as when the converter is installed at the base of the tower (Figure 7.4).

Figure 7.4



Such circuit-breaker shall be able to operate and detect variable frequency currents and have a rated service voltage U_e equal to:

$$U_e = 1.3 \cdot 1.1 \cdot U_n = 1.43 \cdot U_n \quad [7.5]$$

where:

U_n is the rated voltage of the generator

1.1 takes into account the variation, under service, of the generated voltage

1.3 takes into account the increase of the generated voltage in case of a sudden load disconnection.

The most part of LV circuit-breakers are designed to operate at fixed frequency, and therefore they are not very suitable for this application. In particular, the protection units provided for these apparatus are not able to measure variable-frequency currents and therefore they cannot detect faults correctly. As a consequence, it is necessary to use circuit-breakers equipped with protection units suitably designed for variable frequencies.
Figure 7.5 shows an example of the trends – according to frequency - of the r.m.s. value of the voltage when the circuit is open, of the r.m.s. value of the steady-state component and of the peak value of the generator contribution to the short-circuit current. As it can be noticed, the voltage rises linearly with the value of frequency (as explained in the previous chapter), while the r.m.s. value of the steady-state component and the peak value of the short-circuit current tend to stabilize when the frequency increases[2].

Figure 7.5

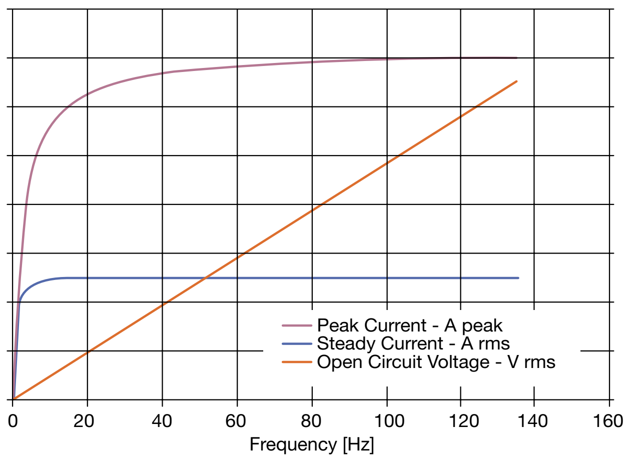
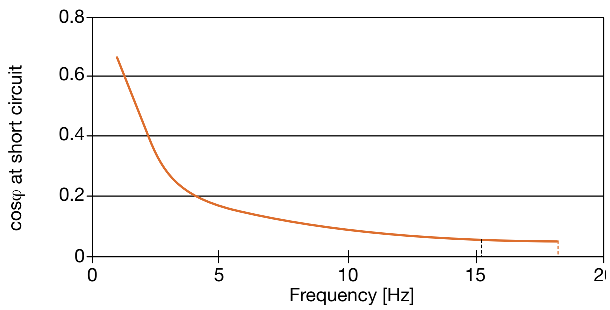


Figure 7.6 shows the trend of the short-circuit power factor on the load side of the alternator according to the operation frequency.
As it can be noticed, as the frequency rises, the power factor value decreases due to the increase of the short-circuit reactance (inductance unchanged, but increase of the pulse ω).
It is necessary to take such phenomenon into consideration since the circuit-breaker must be able to break the short-circuit current at the power factor determined according to frequency.

Figure 7.6



To choose the breaking capacity of the main LV circuit-breaker positioned on the main power circuit on the generator side, it is necessary to evaluate the short-circuit currents under different fault conditions (Figure 7.3):

- in case of short-circuit at point 1, the fault current I_{sc1} seen by the circuit-breaker shall be limited to about twice the rated current of the converter
- in case of short-circuit at point 2, the fault current I_{sc2} seen by the circuit-breaker shall be supplied by the generator. For a generator with rated power S_{ng} running at a rated voltage U_n, this current as first approximation is equal to:

$$I_{sc2} = \frac{I_{ng} \cdot 100}{X''_d \%} \qquad [7.6]$$

where:
$X''_d\%$ is the direct subtransient reactance of the alternator in percentage;
I_{ng} is the rated current of the generator:

$$I_{ng} = \frac{S_{ng}}{\sqrt{3} \cdot U_n} \qquad [7.7]$$

When the frequency varies, the voltage at the generator terminals varies, but also the reactance varies; as a consequence, the short-circuit current remains practically constant (Figure 7.5).
Analogously, to choose the breaking capacity of the LV circuit-breaker positioned on the main power circuit on the grid side it is necessary to evaluate the different fault conditions (Figure 7.3):

- in case of short-circuit at point 3, the fault current I_{sc3} seen by the circuit-breaker shall have a value depending on the short-circuit power of the grid to which the wind turbine is connected and on the short-circuit impedance of the lv/MV transformer
- in case of short-circuit at point 4, the fault current I_{sc4} seen by the circuit-breaker shall be limited to about twice the rated current of the converter.

Instead, as regards the protection of the cables on the grid side and with current carrying capacity I_z the considerations in clause 7.2.2 are valid.
The tripping threshold of the protection against short-circuit for the circuit-breaker in the main power circuit on the generator side must be such as to "intersect" the decrement curve of the short-circuit current of the

[2] *The load current of the alternator has a trend which is a function of frequency similar to that of the steady-state component of the short-circuit current.*

generator from the initial value to the steady-state one. In particular:

- for circuit-breakers with thermal-magnetic release, the magnetic threshold shall be low, with typical values such as 2.5/3 I_n, where In is the rated current of the release;
- for circuit-breakers with electronic release, the trip threshold of the instantaneous protection against short-circuit shall be usually set between 1.5 and 4 I_{ng}[3] .

Table 7.4 summarizes the main characteristics to be taken into consideration for the choice of the circuit-breakers and of the contactors for the main power circuit on the generator side and on the grid side and for the main auxiliary circuit.

[3] *If also the protection against short-circuit with intentional delay is provided, its trip threshold shall be usually set between 1.5 and 4 I_{ng}, whereas the trip threshold of the instantaneous protection against short-circuit shall be set at a value higher than the generator short-circuit current I_{cc2} to guarantee quick tripping due to a short-circuit on the CB supply side in case of parallel configurations of more generation sections (see Figure 7.8).*

With large-sized wind turbines and consequently with consistent powers involved, sometimes, instead of having a single converter, it is preferred to divide the whole generated power into more converters connected in parallel (Figure 7.7).

Figure 7.7

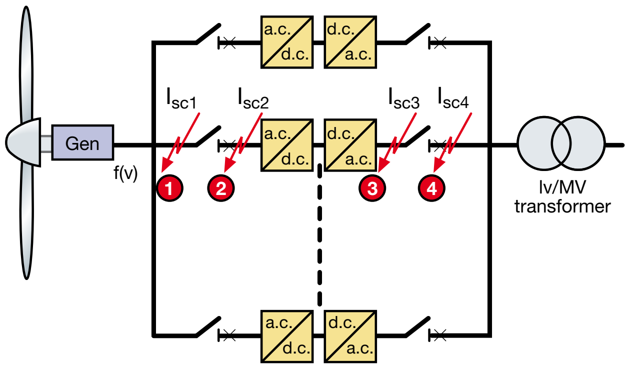


Table 7.4

Characteristics	Main power circuit on the generator side	Main power circuit on the grid side	Main auxiliary circuit
Load current [A]	≤ 5000 or nx700…1600	≤ 5000 or nx700…1600	< 250
Voltage [V]	≤ 1000	≤ 690	≤ 690
Frequency [Hz]	1…16	50 - 60	50 - 60
	30…80		
	40…140		
Prospective-short circuit current [kA]	≤ 15 @ 1000V*	35 @ 690V	
Presence of inrush current	No	No	Yes
Type of load	AC1	AC1	AC3
Life time [years]	20	20	20
Number of mechanical operations (or electrical operations at low current) to disconnect the system (maintenance or out of service)	100…1000	< 1000	< 1000
Number of mechanical operations (or electrical operations at low current) of connection to/disconnection from the grid or of reconfiguration (production control)	Not available (generally the generator remains connected to the converter)	1000…100000 (according to the control strategy)	Not applicable
Number of electrical operations	< 500 (tripping of protections or emergency stop)	< 500 (tripping of protections or emergency stop)	> 500 (tripping of protections or emergency stop)
Protection against overcurrents	Yes	Yes	Yes
Optimum solution	Circuit-breaker (if protection is required for the connection cable or the inverter input)	Circuit-breaker + contactor (more than one operation per day required)	Circuit-breaker
	Switch-disconnector (if an external protection system is present)	circuit-breaker (less than one operation per day)	

* According to the plant power and configuration

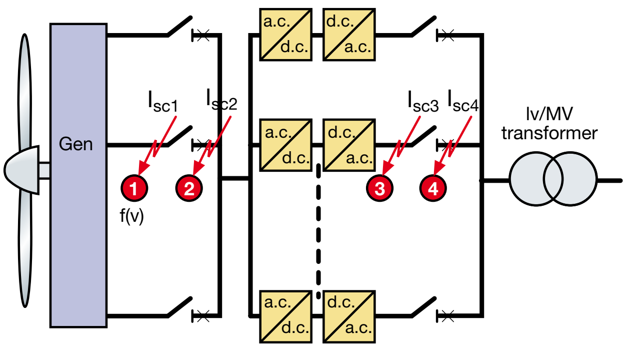
In the presence of n converters in parallel, to choose the breaking capacity of every circuit-breaker positioned on the main power circuit, generator side, it is necessary to evaluate the following fault conditions:

- in case of short-circuit at point 1, the fault current I_{sc1} shall be limited to about twice the rated current of the single converter;
- in case of short-circuit at point 2, the fault current I_{sc2} shall be the sum of the short-circuit current delivered by the generator and about 2 · (n–1) times the rated current of the single converter (assuming that all the n converters are of the same size).

Instead, for the choice of the breaking capacity of each circuit-breaker on the main power, grid side, it is necessary to evaluate the short-circuit currents under the following conditions:

- in case of short-circuit at point 3, the fault current I_{sc3} shall be the sum of the short-circuit current delivered by the grid and about 2 · (n–1) times the rated current of the single converter (assuming that the n converters are all of the same size).
- in case of short-circuit at point 4, the fault current I_{sc4} shall be limited to about twice the rated current of the single converter

Figure 7.8



Sometimes the generator set can be divided into more sections in parallel as shown in Figure 7.8.

In this configuration, with m sections of the generator in parallel in addition to the n converters in parallel, for the choice of the breaking capacity of each circuit-breaker on the main power circuit, generator side, it is necessary to consider the following situations:

- in case of short-circuit at point 1, the fault current I_{sc1} shall be the sum of the short-circuit current supplied be the other m-1 sections in parallel plus 2n times the rated current of the single converter (assuming that the n converters are all of the same size)
- in case of short-circuit at point 2, the fault current I_{sc2} shall be that supplied by the single m-th section of the afferent generator.

Instead, with the purpose of choosing the breaking capacity of each circuit-breaker on the main power circuit, grid side, it is necessary to consider the following situations:

- in case of short-circuit at point 3, the fault current I_{sc3} shall be the sum of the short-circuit current delivered by the grid and about 2 · (n–1) times the rated current of the single converter (assuming that the n converters are all of the same size);
- in case of short-circuit at point 4, the fault current I_{sc4} shall be limited to about twice the rated current of the single converter.

7.3 Protection against earth faults

When an earth fault occurs in a section of the power circuit, the fault current shall be generally formed by the component fed by the generator (especially in the configuration full converter) and by the component supplied by the grid.

7.3.1 Generator component

In the three previous configurations, the generators usually have their live parts earth insulated, whereas their exposed conductive parts are connected to earth.
Therefore, in this case, we are in the presence of an IT system and the earthing resistance of the exposed conductive parts shall satisfy the relation (IEC 60364):

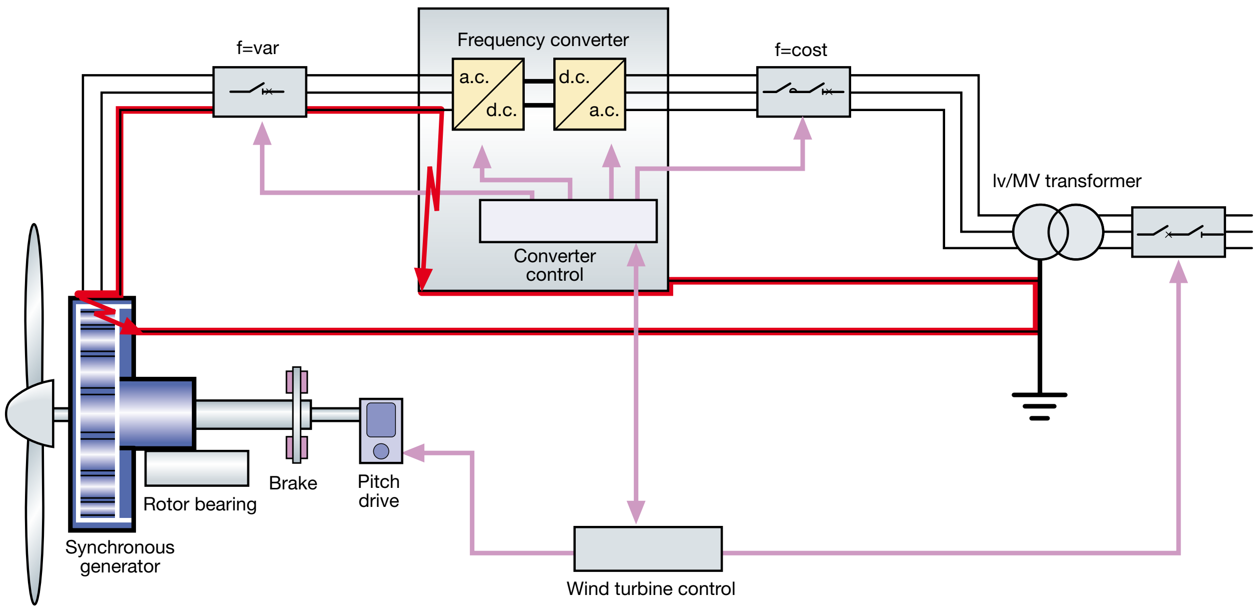
$$R_e \leq \frac{U_L}{I_d} \quad [7.8]$$

where I_d is the current of the first fault to earth supplied by the generator, unknown in advance, but generally very small given the limited extension of the main circuit[4].

As a consequence, the earthing resistance R_e of Annex C, defined for a grid fault ride, usually satisfies the relation [7.8]. Besides, the modest value of the current I_d limits the consequences of an earth fault, above all thanks to the lack of arcing dangerous for people and things.
When the first fault persists, the system is no more IT and becomes, in the common case of a single earthing plant, a system TN. If the first fault is not removed in a reasonably short time, a second fault to earth may occur on another phase of the circuit.
In the configuration with fixed speed, doubly-fed variable speed or full converter with double fault on the generator side of the converter (Figure 7.9), a configuration is established with double earth fault supplied by the line-to-line voltage and it has to be interrupted by the protection device of the circuit, which in the example of Figure 7.9 is the circuit-breaker positioned between the alternator and the converter.
However, in this case, the advantage of service continuity of the IT system would fails and therefore a control system of earth insulation is necessary to guarantee quick detection and elimination of the first fault to earth.
If the converter is present, such control system is usually inside the converter itself.

[4] In an IT system, the current of first fault to earth I_d is prevailingly capacitive. In the case of a plant of limited size, the capacitive susceptance to earth is small and therefore the current of first fault to earth is limited.

Figure 7.9



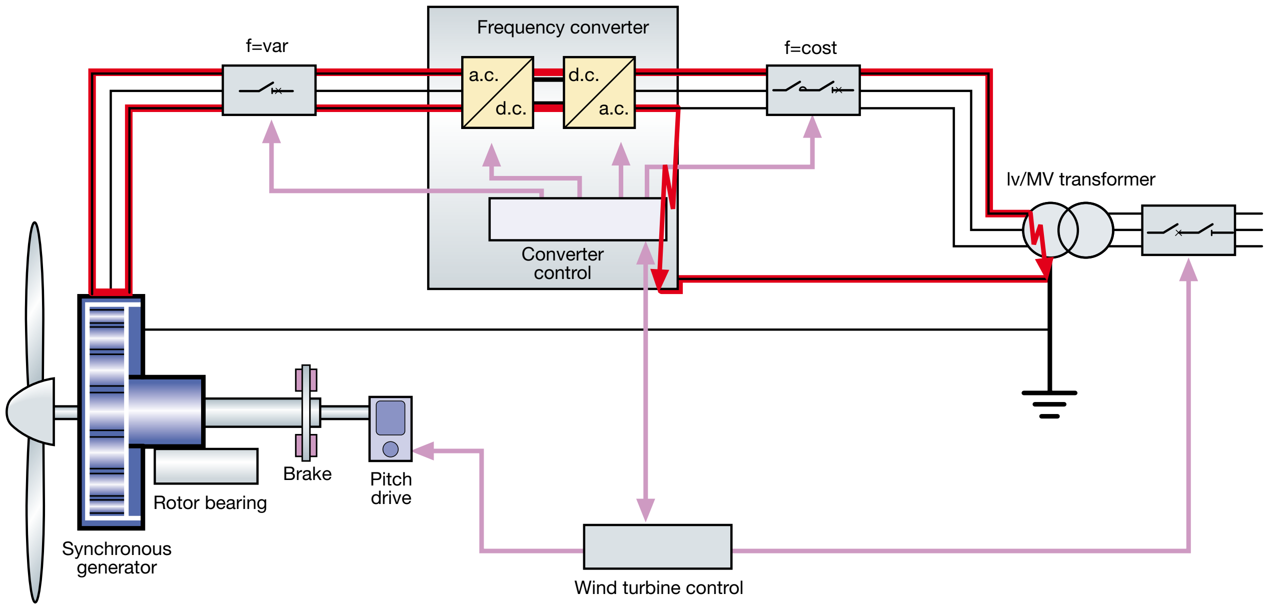
In variable speed configurations, in case of a double fault on the grid side of the converter, the contribution of the generator to the fault current is limited by the converter itself, which then goes into stand-by due to the tripping of the internal protections (Figure 7.10).
Having a trip threshold for the short-circuit protection set at low values (see above considerations), the circuit-breaker positioned between the alternator and the converter might detect this limited fault current, but usually the trip times of the internal protections of the converter are lower and therefore tripping is guaranteed by them.

In case of a second fault to earth, the fault circuit is supplied by the line-to-line voltage, but the fault ring and the relevant impedance are not known in advance. As a consequence, the Std. IEC 60364 conventionally imposes to reduce the impedance of the fault ring of each circuit formed by the phase conductor and by the protection conductor of each circuit to the half of that allowed for a TN system and consequently, for each circuit, the following relation (neutral conductor not distributed) must be satisfied:

$$Z_s \leq \frac{U}{2 \cdot I_a} \quad [7.9]$$

where:
I_a is the current which causes tripping of the protection device within the limits define for TN systems.

Figure 7.10



7.3.2 Grid component

Now, taking into consideration the component of the earth fault current from the grid, in the presence of a lv/MV transformer typical for medium/large-size wind turbines, the situation is the same as a traditional TN plant with the star centre of the lv transformer directly connected to the common earthing plant.
Therefore, in the configuration with fixed speed, doubly-fed variable speed or full converter and fault on the grid side of the converter (Figure 7.11), the protection function can be carried out by the protective devices against overcurrents provided that the fault current causes tripping of such devices within the terms prescribed by the Std. IEC 60364.

In case of fault on the generator side of the converter, in variable speed configurations, the grid component of the fault current is limited by the converter itself which then goes into stand-by due to the tripping of the internal protections (Figure 7.12). The circuit-breaker positioned between converter and transformer usually has a trip threshold for the protection against short-circuits set at a value exceeding the current limited by the converter; as a consequence it does not detect such current value and does not trip.

In medium-power wind installations connected to the grid and in parallel to the user's plant, as regards the exposed conductive parts on the load side of the transformer and in plants without transformer, please refer to the indications for protection against earth faults given in clauses 5.2.2 and 5.3 of the Technical Application Paper No. 10 (QT10) about *Photovoltaic plants*.

Figure 7.11

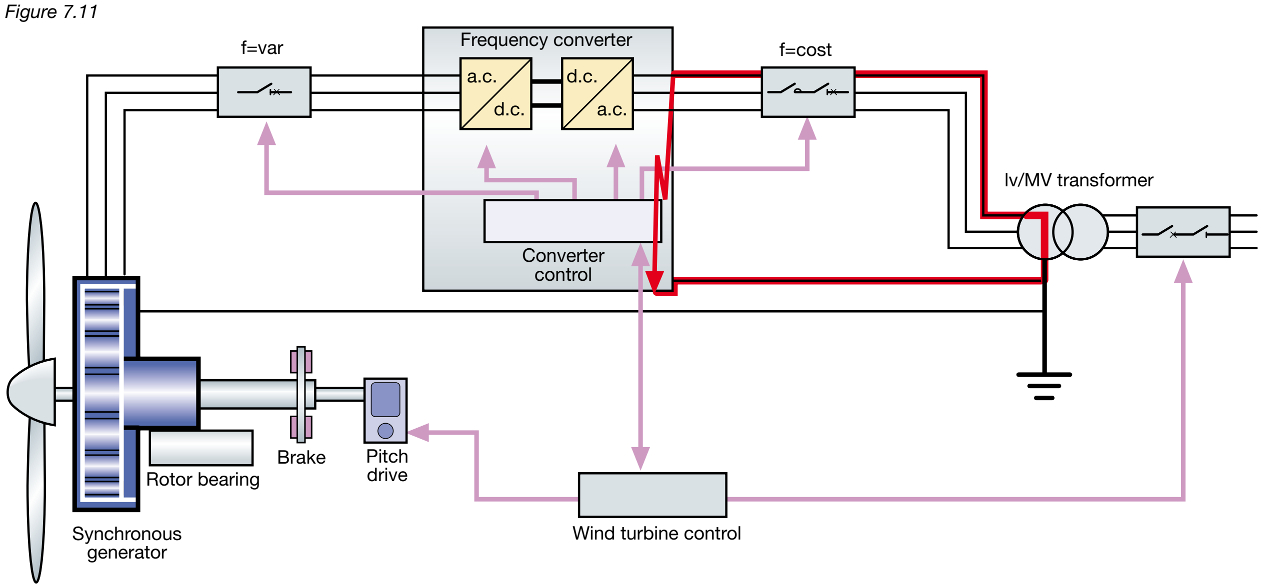
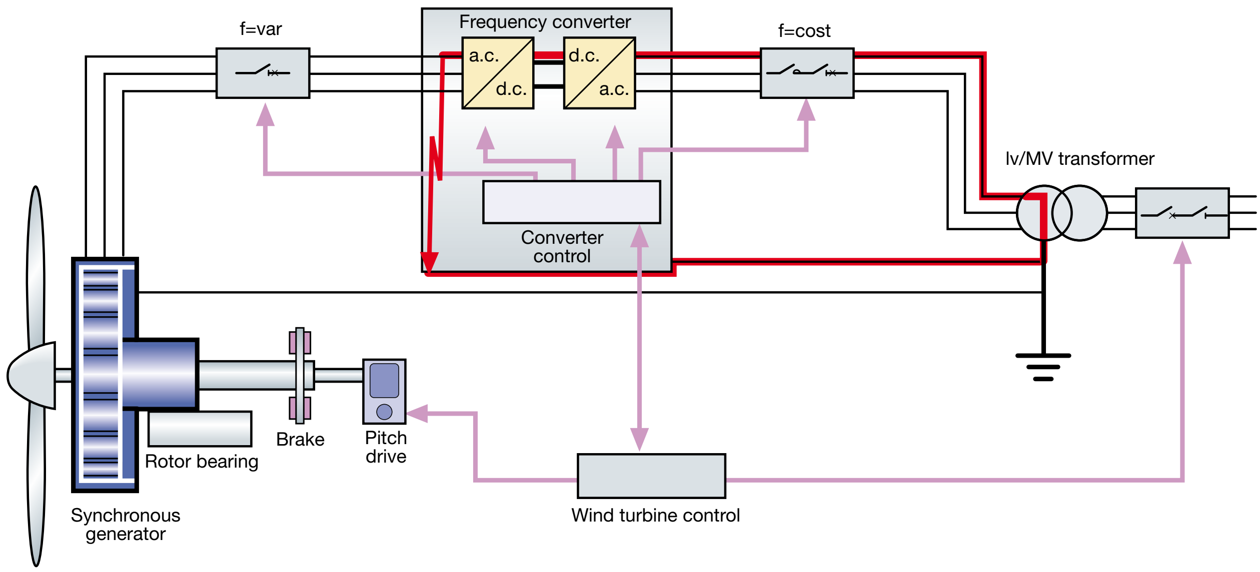


Figure 7.12



8 Protection against overvoltages

8.1 Generalities

Wind power plants, being installed outdoor, may be subject to direct and indirect overvoltages of atmospheric origin, besides being subject to switching overvoltages.

Lightning protection allows risks for people (mainly the personnel in charge) and maintenance operations due to damages on structure and on the internal components to be reduced and measures against economical losses because of drop of energy production due to the plant failure to be taken.

If the wind turbine is installed on a building (Figure 8.1) and significantly modifies the outline of the same, a new assessment of the lightning risk is necessary to verify whether installation of an LPS (Lightning Protection System) or modification of that already present are needed.

Figure 8.1

If the wind turbine is installed on the ground, stand-alone or in a wind power plant, due to its height and being often the highest structure in the surrounding area, it represents an “ideal target” for atmospheric discharges (Figure 8.2).

In particular, the height of the wind towers (especially for those ones exceeding 100m) facilitates the formation of upward atmospheric discharges from the structure to the cloud[3].

Figure 8.2

If not otherwise indicated by the risk assessment, the components of a wind turbine must be protected according to a Lightning Protection Level (LPL-I). Such level takes into account the highest lightning parameters.

A more accurate risk assessment could let us think favorable from an economic point of view making a difference in the protection levels: for example the blades shall be protected by the highest LPL, whereas other parts, which can be repaired or replaced at a lower cost, shall be protected by a lower LPL.

[1] For a definition of direct and indirect overvoltage see clause 6.4 of the Technical Application Paper No. 10 “Photovoltaic plants”.

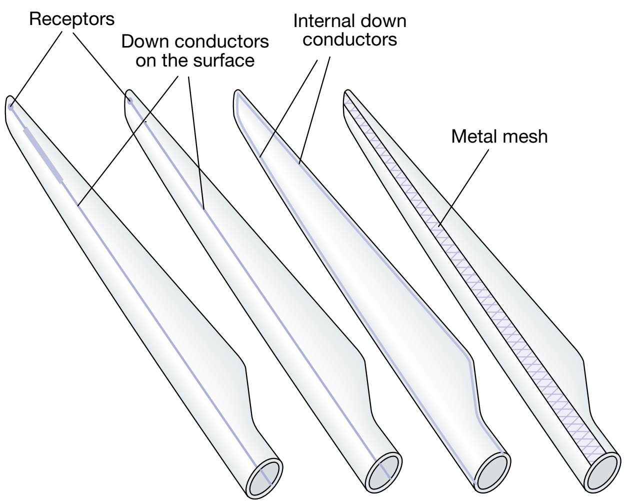
[2] The goal of any LPS is essentially to reduce the hazards to a tolerable level R_T. A representative value of tolerable risk R_T, where lightning flashes involve loss of human life or permanent injuries is 10-5 years-1.

[3] The electric charge accumulated in thunderstorm clouds induces on the surface of the ground below opposite polarity charges, but usually the consequent electric field is not sufficient to strike the upward discharge. As a consequence, most lightning flashes head from the thundercloud towards the earth. However, the induced electrical field increases in the presence of pointed surfaces, for example mountains, or high structures, such as towers or wind turbines. In this case the electric field may have such an intensity to strike an upward discharge.

8.2 Protection of blades

Blades are the most exposed part of the whole structure and the lightning protection system must guarantee that the damages caused by an atmospheric discharge is tolerated till the next inspection and scheduled maintenance.
The experience has shown that the points where lightning attaches are near the tip of the blades (IEC 61400-24 Annex C).
The phenomenon responsible for the severe structural damage to wind turbine blades is the formation of a pressure shock wave around internal arcs caused by the path of lightning across the blade and due to the presence of air-filled cavities or arcs between the different layers of composite material.
Damage may range from surface cracking to complete disintegration of the blade. Minor damage may occur when a lightning arc is formed on the outside surface of the blade or when the lightning current is conducted by metallic components with insufficient cross section.
As a consequence, the purpose of the blade protection against lightning is conducting the lightning current from the attachment point to the hub, in such a way that the formation of a lightning arc inside the blade is avoided.
This can be achieved by diverting the lightning current using metallic conductors of appropriate cross-section either fixed to the blade surface[4] or inside the blade, or by adding a metal mesh inside the blade surface[5] (Figure 8.3).

Figure 8.3



[4] *However such choice may compromise the aerodynamics of the blade or increase the generated noise.*
[5] *The main advantage by adding a metal mesh is represented by shielding of the electromagnetic field induced by any possible conducting element in the blade (e.g. carbon fibres).*

8.3 Protection of hub/spinner

The hub for large wind turbines is a hollow cast iron sphere of 2m to 3m in diameter. Hence the material thickness ensures that the hub structure itself is immune to lightning.
Typically the hub has a glass fiber cover, called the spinner, which rotates with the hub.
Since there is the possibility that lightning directly attaches the spinner, an adequate protection shall be considered and realized through a metal structure connected to the hub.
This even more so for the turbines with electrical and mechanical control systems and actuators (e.g. Pitch control systems) placed between the hub and the spinner.

8.4 Protection of supports and hydraulic and cooling systems

Inside the nacelle, the various supports (of the main shaft, of the gearbox, of the generator, etc.) and the actuating systems have moving parts directly or indirectly in contact with the turbine parts in which the lightning current flows; therefore they must be protected so that any lightning passing through the component is kept at an acceptable level.
In particular, with hydraulic systems, it is necessary to consider the risk of fluid leaks due to damage at fittings and ignition of hydraulic oil.
Protection can be achieved through spark gaps and sliding contacts (Figure 8.4) having less impedance than the direct natural current path through the equipment to be protected.

Figure 8.4

8.5 Earth electrodes

The lightning current which discharges to earth through the metal structure of the tower shall be dispersed in the ground through an earthing system; this shall conduct high intensity and frequency currents into the earth without any dangerous thermal or electrodynamic effects.
It is generally recommended (IEC 61400-24) that the earthing system for the protection against atmospheric discharges and the ordinary earthing for the operation/protection of the electrical plant are put together in a single leakage system.
Furthermore, it is recommended to include metal parts in the foundation structures in the earthing system, so that the earthing resistance is reduced as much as possible and the arrangement shall possibly comprise a ring earth electrode in contact with the soil for at least 80% of its total length.
In the particular case of rocky areas (therefore with high resistivity) it is recommended to use at least two concentric ring electrodes which may be combined with vertical electrodes drilled into the rock. Instead, in case of wind turbines offshore, since the resistivity of seawater is considerably lower than most soils, ring earth electrodes are usually not required, being sufficient the metal parts in the foundation structures.
Finally, in wind power plants, each turbine shall have its own earthing system, each connected to the earthing system of the transfomer sub-station through suitable earthing conductors, thus obtaining benefits in terms of equipotential bonding and reduction in the total earthing resistance (especially when an adequate earthing resistance is difficult to obtain at each individual wind turbine position).

8.6 Application of lightning protection zones (LPZ) concept

A wind turbine can be physically divided into zones, which approximately define the influence level of lightning on the components of such zone. Therefore, the division into LPZs is a method to ensure a sufficient and systematic protection for the various components of a wind turbine. LPZs are defined according to the possibility of direct lightning and of associated induced electricomagnetic fields in that zone. Additional methods of protection against lightning are applied to guarantee that the various equipment of a given zone can withstand the intensity of the lightning current and of the associated electromagnetic phenomena. LPZs are shown in Table 8.1 (IEC 61400-24 Annex E).
The boundary between LPZ 0_A and LPZ 0_B can be determined by means of the “rolling sphere” model (Figure 8.5).

Table 8.1

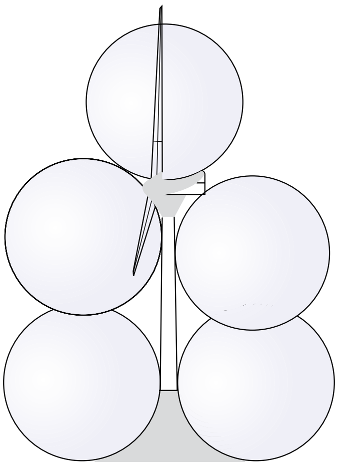
	Outer zones
LPZ 0	Zone where the threat is due to the unattenuated lightning electromagnetic field and where the internal systems may be subjected to full or partial lightning surge current. LPZ 0 can be subdivided into two subzones 0_A and 0_B.
LPZ 0_A	Zone where the threat is due to the direct litghtning flash and the full lightning electromagnetic field. The internal systems may be subjected to full or partial lightning surge current.
LPZ 0_B	Zone protected against direct lightning flashes but where the threat is due to the full lightning electromagnetic field. The internal systems may be subjected to partial lightning surge current.

	Inner zones
LPZ 1	Zone where the surge current is limited by current sharing[6] and by SPDs at the boundary. Spatial shielding may attenuate the lightning electromagnetic field.
LPZ 2..N[7]	Zone where the surge current may be further limited by current sharing and by additional SPDs at the boundary. Additional spatial shielding may be used to further attenuate the ligntning electromagnetic field.

[6] *It is the reduction in the current of each LPS conductor for the distribution of the original lightning current in the different conductors constituting the LPS.*
[7] *Generally, the higher is the number of the zone, the lower are the values induced by lightning.*

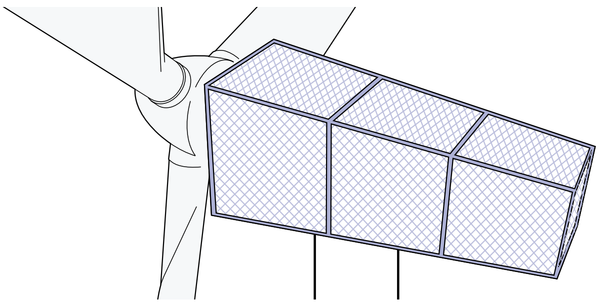
The areas against which the sphere cannot roll are protected against direct lightning attachment. Therefore the areas marked in grey are LPZ 0_B where lightning cannot strike, and the rest of the surface of the wind turbine is LPZ 0_A.

Figure 8.5



The boundary between LPZ 0_A or LPZ 0_B and LPZ1 can be put at the tower or at the top cover of the nacelle if there is a metal cover or sufficient metal shielding mesh (Figure 8.6) to protect the components inside (Faraday cage functioning).

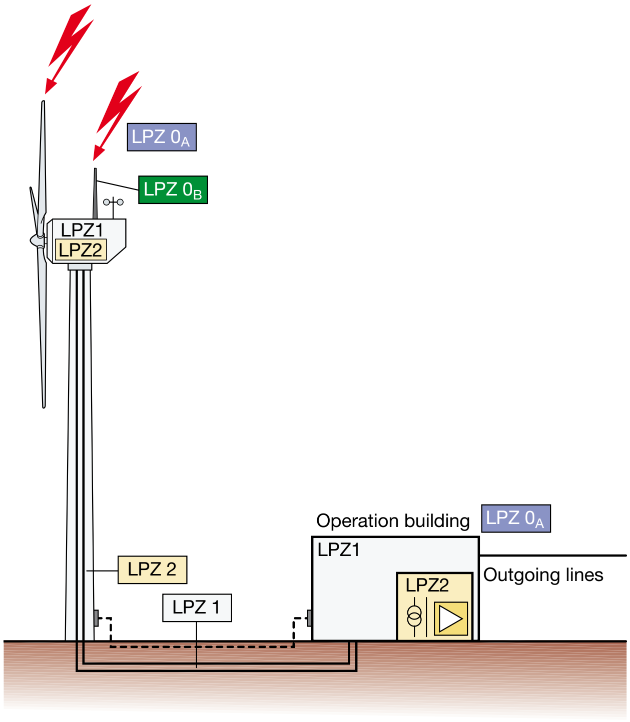
Figure 8.6



The nacelle (with some mesh in the cover), the tower and the transformer kiosk are protection zones LPZ1 (Figure 8.7).

The devices inside metal cabinets in LPZ1 areas are in protection zone LPZ2. If the tower is made of a metal tube and there is good electrical connection between the parts of the tower, the tower is a very effective Faraday cage, which satisfactorily conduct to earth the lightning current and the zone inside can be defined as LPZ2 (Figure 8.7).

Figure 8.7



[8] *If the tower is of lattice type, it protects the space inside against direct lightning and provides a reduction in the induced electromagnetic field, so that its internal space can be considered as a zone LPZ 0_B.*

Figures 8.8-8.9 show the subdivision of the rotor-nacelle areas in the configuration Doubly-fed and Full Converter respectively.

Figure 8.8

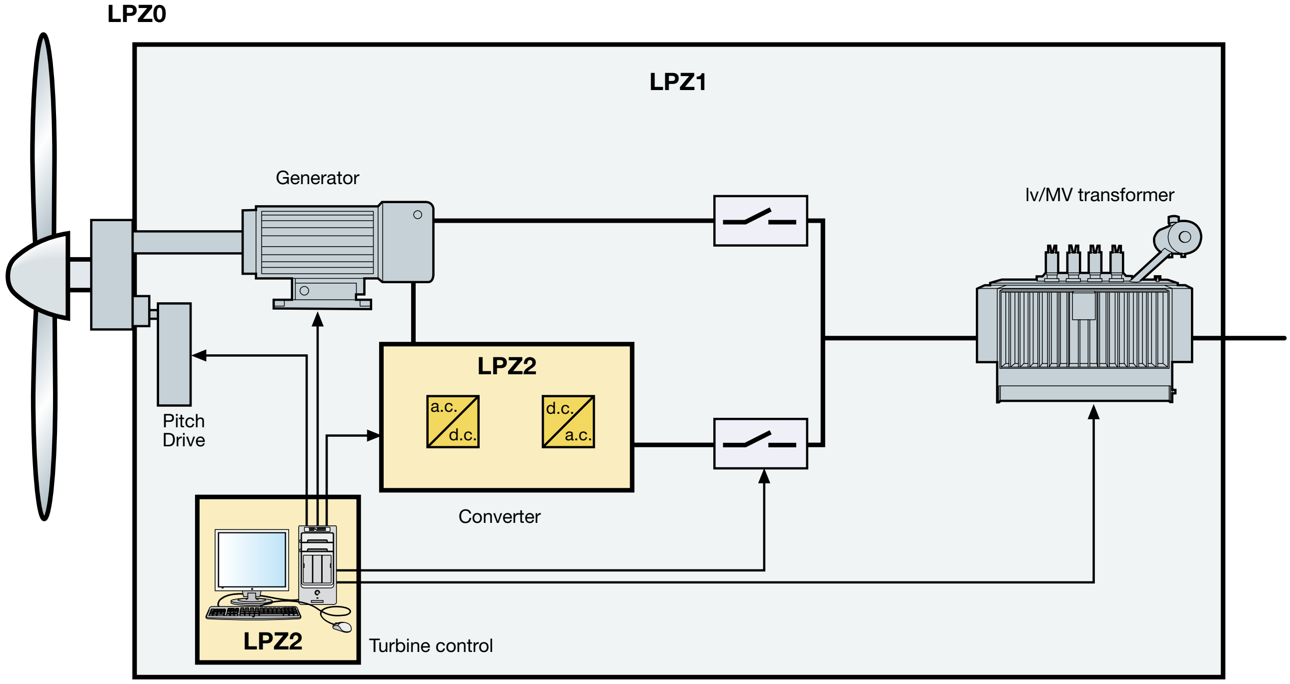
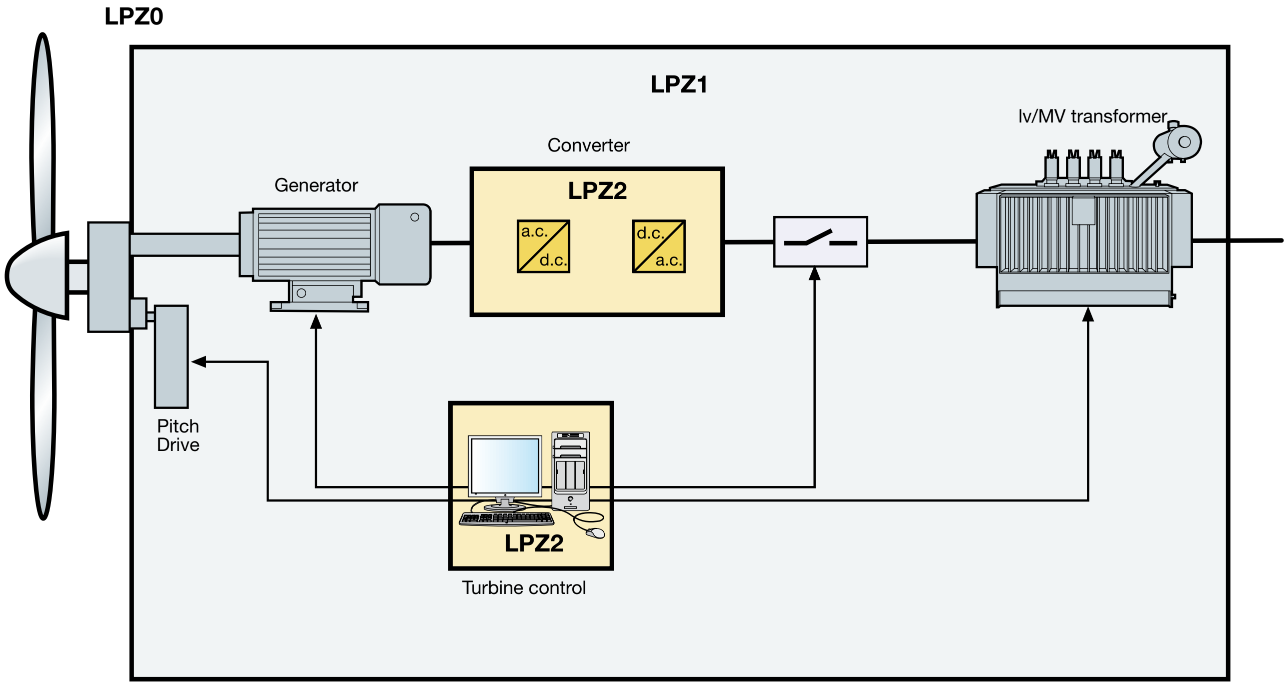


Figure 8.9



8.7 Use of Surge Protective Devices (SPDs)

In order to avoid heavy damages due to lightening, which can cause the failure of the various components, it should be guaranteed that each device within a given zone is not exposed to lightning currents and to induced electromagnetic fields (with the consequent overvoltages of atmospheric origin) exceeding their own withstand levels. Protection can be obtained by using shielded cables, reducing the loop produced by them and using SPDs.
In particular, the installation of suitable SPDs protects also against switching overvoltages for operations inside the wind turbine or outside in the electrical grid to which it is connected. Such overvoltages within wind turbines are mainly caused by:

- grid short-circuits
- energy stored in static converters in the event of disconnection
- load disconnection in LV switchgear.

In addition to the lightning parameters, various electrical parameters shall be taken into consideration for the choice of a suitable SPD:

- maximum voltage (line and phase), included the tolerances due to the settings;
- maximum frequency;
- short-circuit current level;
- transient voltages superimposed on the operating voltage.

Besides, SPDs shall withstand the environmental stresses characterizing the installation place, such as:

- ambient temperature
- humidity
- corrosive atmosphere
- vibration and mechanical shock.

The type of SPDs to be installed at the line entrance into each LPZ is the following (IEC 61400-24):

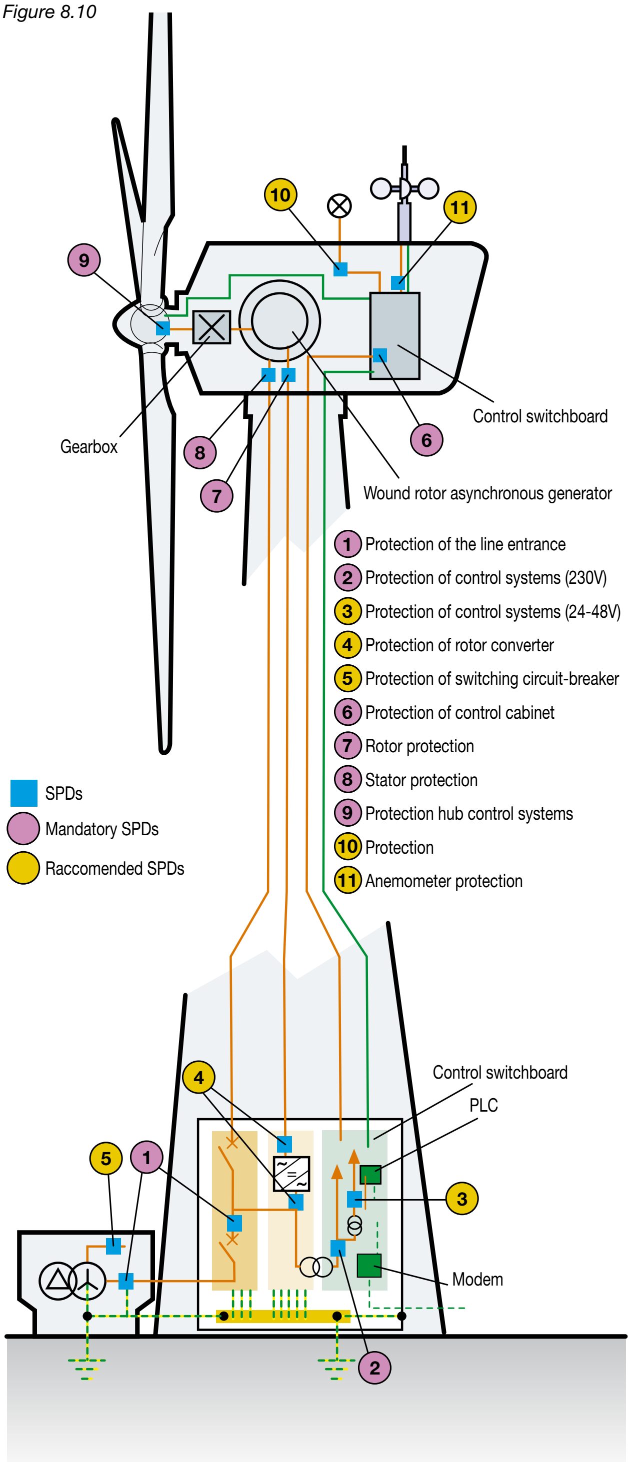
- Type I – as close as possible to the boundary of LPZ 1;
- Type II – as close as possible to the boundary of LPZ 2 or higher, and if necessary as close as possible to the equipment to be protected.

According to the above criteria, SPDs are mainly installed:

- in the generation system, on the power and excitation circuit
- in the Pitch control system
- in the yaw control system
- in the turbine control system
- in the auxiliary systems.

Figure 8.10 shows in detail the installation places of SPDs in a Doubly-fed system, in which the devices downstream the generator are located at the base of the tower.

Figure 8.10

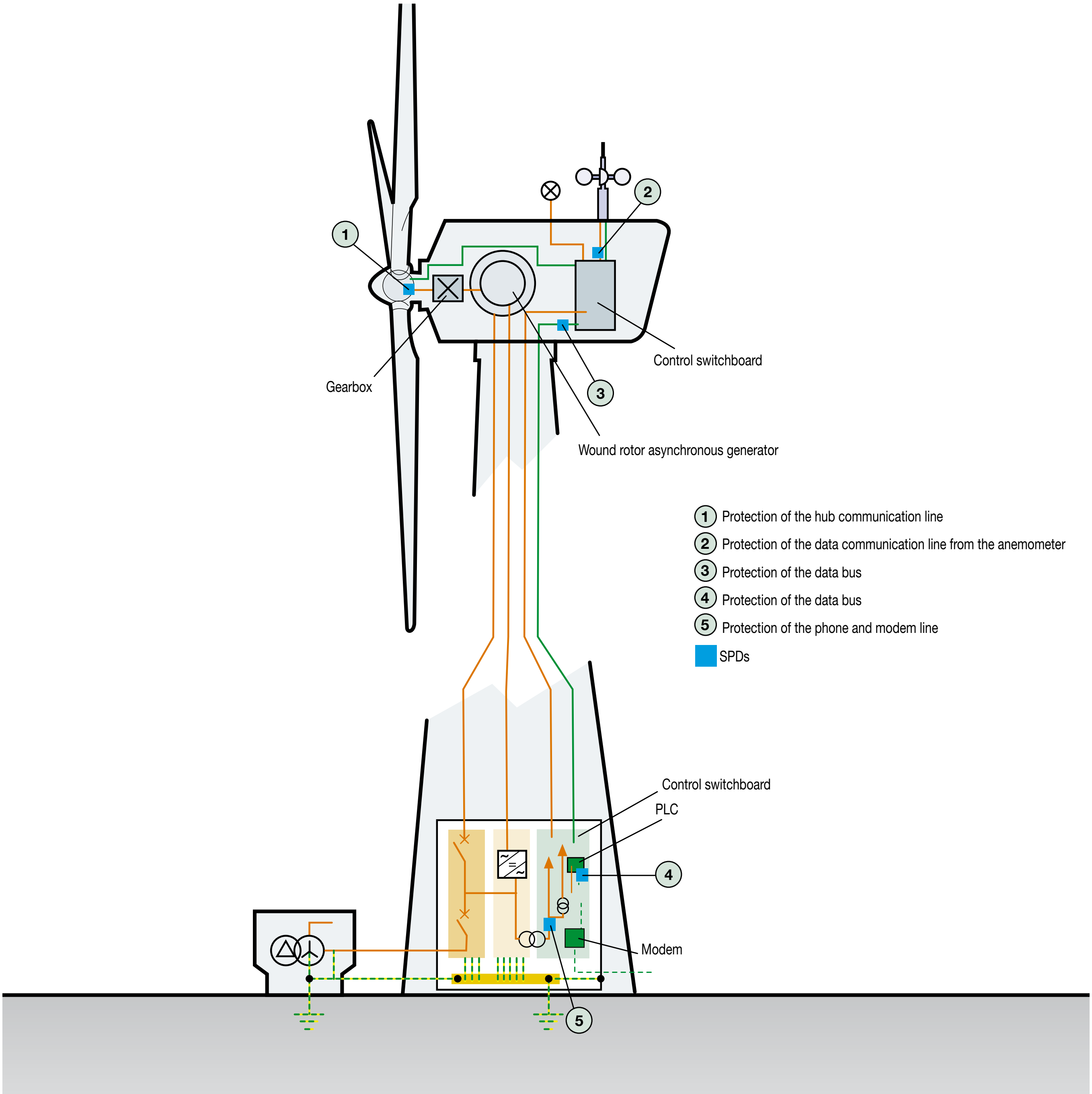


The data relevant to wind direction and speed (measured by the anemometer) are transmitted to the hub and to the yaw system for a better alignment of the blades and of the nacelle.
Therefore, it is important that the communication lines between the automatic systems are protected against overvoltages by positioning suitable SPDs as shown in Figure 8.11.

For the protection of the Pitch control system, of the yaw control system and of the auxiliary systems against indirect lightning, SPDs type II are usually sufficient.
But here are some general indications about the type of SPD to be used in the main power circuit of the three configurations:

- fixed speed – asynchronous generator
- variable speed – Doubly-fed
- variable speed – Full Converter.

Figure 8.11

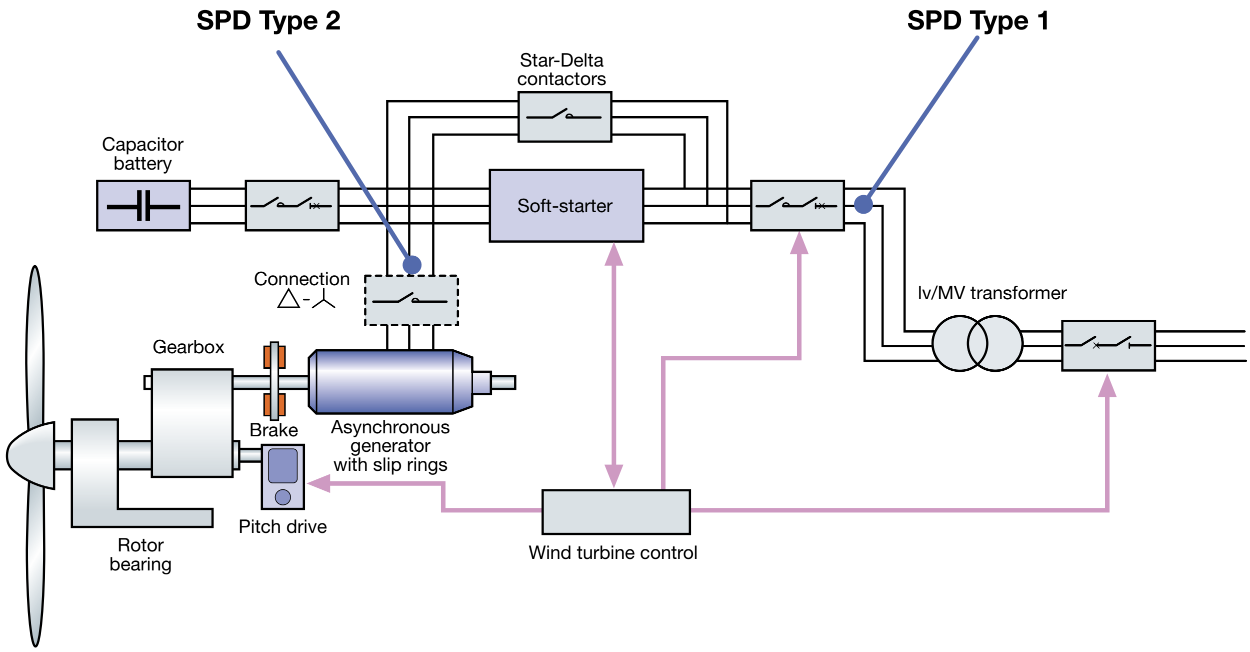


8.7.1 Fixed speed – Asynchronous generator

In this configuration, according to the scheme in Figure 8.12, it is appropriate to position an SPD of type I in the main switchboard at the entrance to the turbine for the protection against the overvoltages of atmospheric origin and against the overvoltages from the grid.
If the SPD type I does not reach autonomously the effective protection level U_{prot}[9] lower than the maximum withstand voltage of the equipment to be protected or the distance from the equipment to be protected is longer than 10m, it is advisable to install an SPD type II close to the generator for the additional protection of the stator windings.

[9] U_{prot} *is the sum of the protection level of the surge protective device* U_p *and of the voltage drop of the connections, which can be assumed equal to 1kV/m.*

Figure 8.12



8.7.2 Variable speed – Doubly-fed concept

In this configuration, according to the scheme of Figure 8.13, it is advisable to place an SPD type I into the main switchboard at the entrance to the turbine for the protection against the overvoltages of atmospheric origin and against the overvoltages from the grid. If the SPD type I does not reach autonomously the effective protection level U_{prot} lower than the maximum withstand voltage of the equipment to be protected or the distance from the equipment to be protected is longer than 10m, it is advisable to install an SPD type II near the generator for the additional protection of the stator windings and another one near the converter on the grid side for a better additional protection.
Besides, it is advisable to put, between the converter and the rotor windings, SPDs type II suitable for protection in the presence of transient overvoltages superimposed on the PWM control voltage (Figure 8.14).

8.7.3 Variable speed – Full converter concept

In this configuration, according to the scheme of Figure 8.15, it is advisable to place an SPD type I into the main switchboard at the entrance to the turbine for the protection against the overvoltages of atmospheric origin and against the overvoltages from the network.
If the SPD type I does not reach autonomously the effective protection level U_{prot} lower than the maximum withstand voltage of the devices to be protected or the distance from the devices to be protected is longer than 10m, it is advisable to install an SPD type II near the converter on the grid side for a better additional protection.
Besides, it is advisable to place between the converter and the synchronous generator SPDs type II suitable for protection in the presence of transient overvoltages superimposed on the PWM control voltage (Figure 8.14).

Figure 8.13

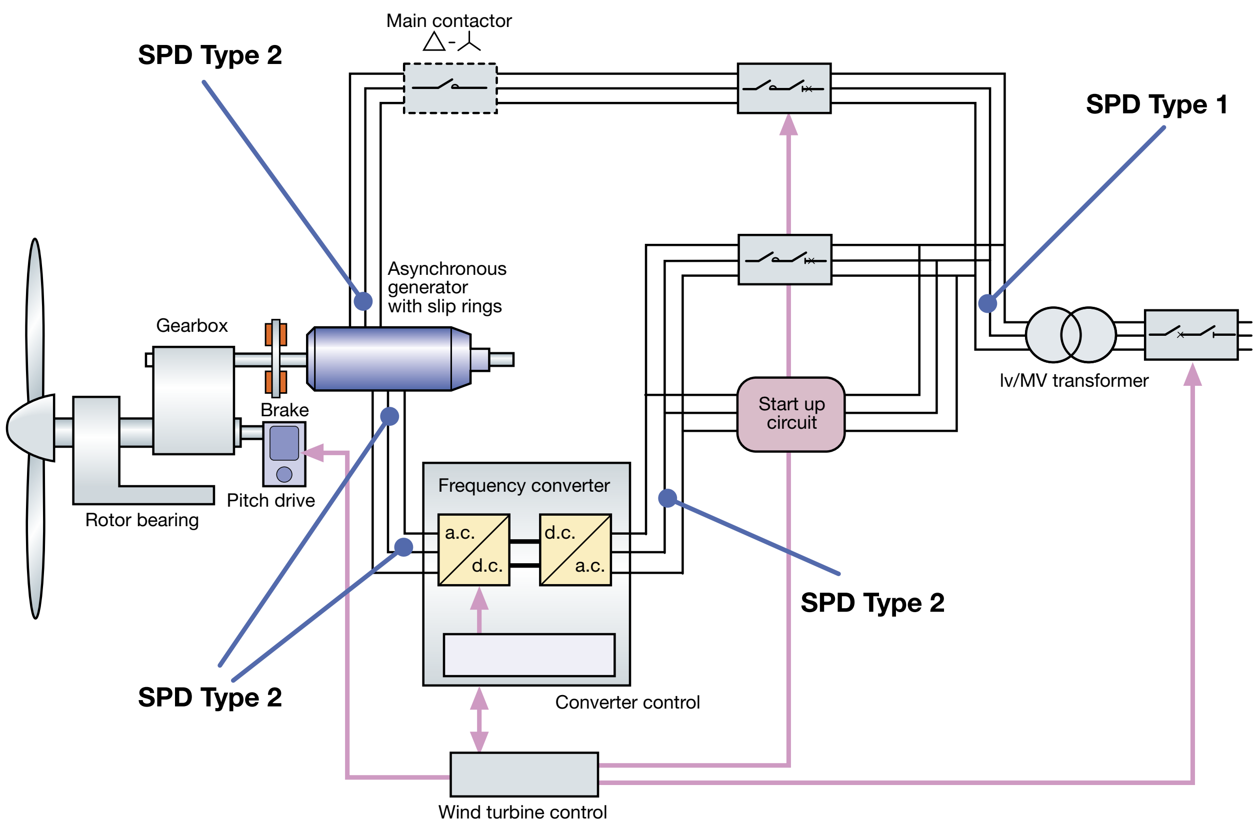


Figure 8.14

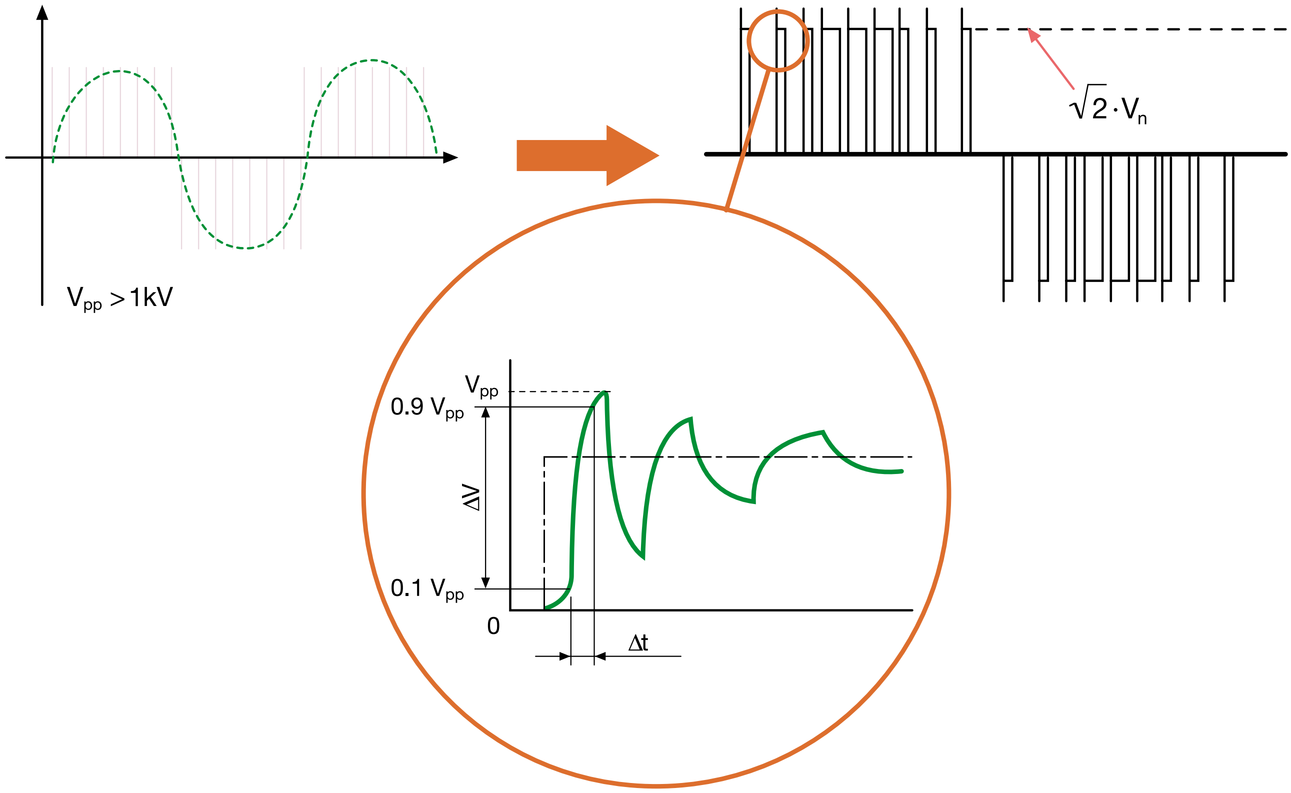
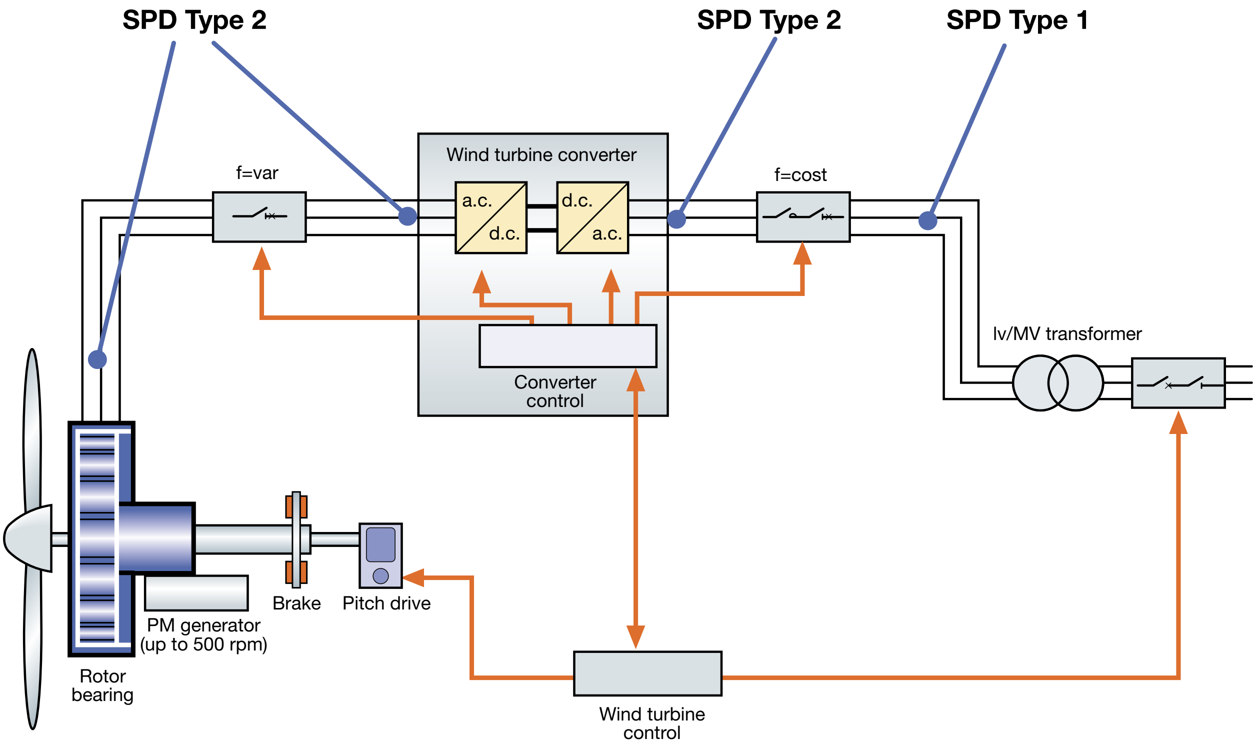


Figure 8.15

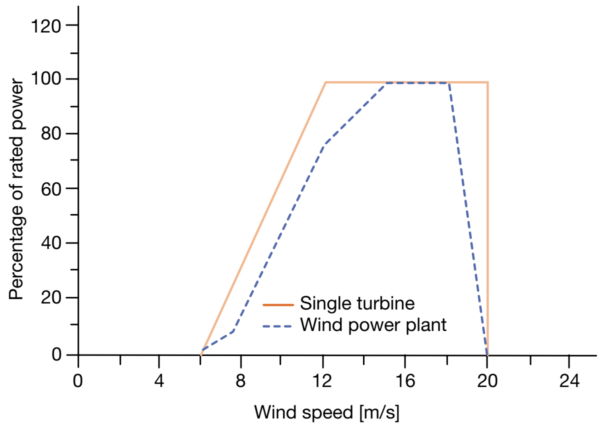


9 Wind power in electric power systems

9.1 Wind power plants

As mentioned in the first chapter, wind turbines can operate as power generation plants connected to the grid, to isolated electric systems or also individually to supply a specific load. In particular, the integration process of wind installations into power systems includes first of all the correct choice of the installation site and then, once the construction and the connection to the grid have been carried out, the subsequent management of the injected power taking into account the power demand of the network loads and the randomness and variability of the wind source.
In fact, the connection of the turbines to the electrical power systems can have local effects on the network in terms of power-quality and, if the fraction of the wind energy injected into the electrical system becomes not negligible, its effects can involve all the network.
Wind turbines can be installed as individual units or grouped in wind power stations, also known as "wind power plants".
As regards the choice of the installation site, usually the main target is maximizing the economic payback of the investment trying to minimize those effects such as noise pollution and visual-environmental impact.
Once the site has been chosen, the exact position and direction of the individual turbine or the disposition of the different wind turbines in the wind power plants are generally defined by computer simulation programmes aimed at maximizing the extraction of energy from the wind, always keeping in mind the previous limits and the morphological configuration of the installation site.
In particular, when installing wind turbines in wind power plants, one of the main technical problem is how much space has to be left between the single turbines to keep within acceptable limits the mutual aerodynamic interference.
In fact, the extraction of wind energy from the windward turbines causes a reduction in the speed of the wind available for the leeward turbines and a possible increase in turbulence.
The consequence is not only a reduction in the total energy produced by the wind power plant[1], but also a remarkable fluctuation of the electric power injected into the grid.
Besides reducing the wind energy captured, a high turbulence increases the speeds of the wind gusts with the consequence that the control systems intervene more frequently to stop the turbine, by reducing further the energy production.
Moreover, turbulence increases the fatigue stress of the materials constituting the leeward turbines thus reducing their expected life.
By analyzing the power curve of a wind power plant (Figure 9.1), the difference from the curve of the single turbine can be noticed.

Figure 9.1



When the incoming wind into the wind power plant reaches the cut-in speed, the first line of turbines starts to generate electric power.
Such extraction of energy from the wind outgoing from the first line reduces the speed of the wind itself and consequently the turbines at the back cannot work.
By increasing the speed of the incoming wind, the number of the lines of turbines working till all the turbines generate power rise, even if the turbines in the first line produce more power per unit.
Moreover, when the incoming wind reaches the speed at which the first line of turbines generates the rated electric power, the other lines produce less power.
This means that, in order to make all the turbines produce the rated power, the speed of the incoming wind should be the higher, the bigger the number of turbine lines of turbines.
Thus, not only the total energy generated by a wind power plant is lower than the sum of the energy produced by the single turbines installed separately, but also the total power curve of a wind power plant as a function of the wind speed is different from that of a turbine considered separately[2].
In short, in particular when the area of the installation site is limited, a preliminary optimization study shall be carried out to determine the number of turbines, their size and the mutual space with the aim of maximizing the energy production of the wind power plant.

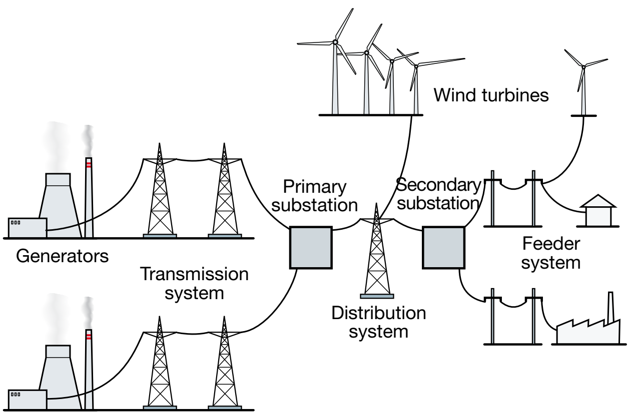
[1] *The wind energy produced in total is lower than the sum of the energy produced by the single turbines when installed separately.*

[2] *In the example in the Figure, it is assumed that all the turbines run correctly; if some turbines were out of service due to fault or ordinary maintenance, the effective power curve of the wind station should be shifted to the bottom.*

9.2 Effects of wind turbines on the network

In the study of wind turbines injecting power into the grid, the last is often considered ideally with infinite short-circuit power; therefore it cannot be influenced by the connection of additional loads or generators.
As a matter of fact, each deviation of the generated power from the absorbed one causes a variation of the network voltage frequency and, through the impedance of the different lines, it causes also a variation of the voltage with respect to the rated value.
As a consequence, the higher the ratio between the rated power of the wind plant and the fault level of the system at the connection point, the more the network is influenced by the connection of the wind turbines.
By schematizing and by simplifying, a power grid can be divided into four main sections: generation, transmission and primary and secondary distribution (Figure 9.2).

Figure 9.2



Power generation is historically carried out by large synchronous generators installed in big power stations supplied by “traditional[3]” energy sources.
These generators can meet also load variations, keeping constant the network frequency and adjusting, if necessary, the supply voltage. The electric energy in these large power plants is produced in medium voltage and then transformed in high voltage and very high voltage to be injected into the grid.
Energy transmission is carried out through big overhead lines or in cable at a high voltage so that the power losses are reduced.
MV primary distribution and LV secondary distribution are used respectively for the supply of loads (multi- or single user) of decreasing power.
The distribution networks are often near the delivery points of electric energy and far from the generation power plants, have a fault level which progressively decreases and therefore are more influenced by the low or fast load fluctuations.
Wind power generation plants are usually inserted in the electric power system by connection to the primary distribution section or, in case of small plants, to the secondary distribution section.

Onshore and offshore large-size wind power plants are usually connected to high voltage or very high voltage grids. Figure 9.3 shows a typical connection scheme to a high voltage grid for a wind power plant onshore, whereas Figure 9.4 shows the scheme of connection to the electric grid of a wind power plant offshore through a HVDC electric cable.

Figure 9.3

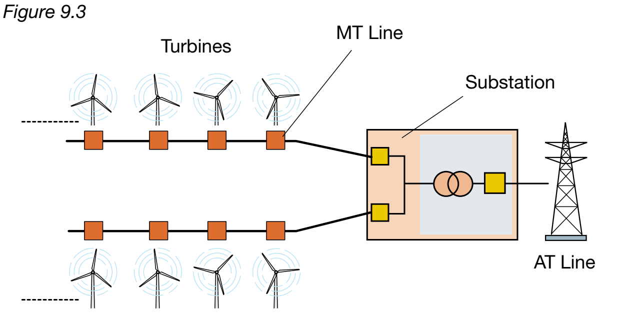
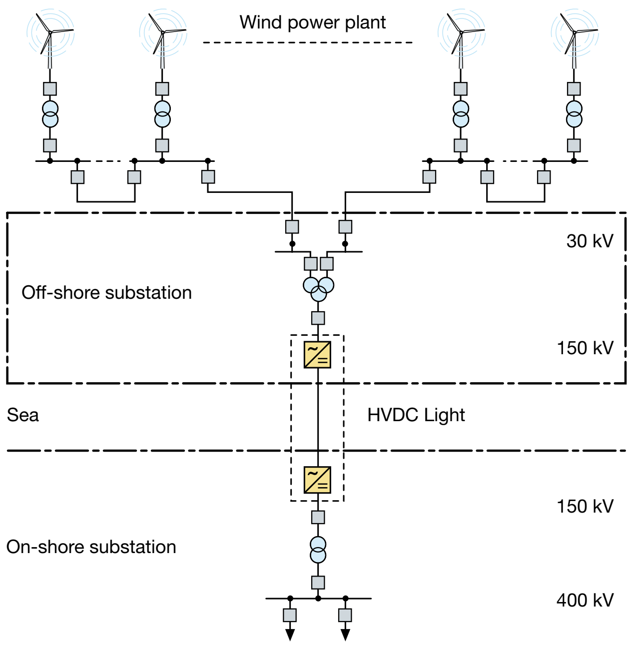


Figure 9.4



[3] *Usually thermoelectric power stations supplied by fossil or nuclear fuels and hydroelectric generating stations.*

9.2.1 Frequency variation

The frequency of the grid is controlled by the flow of the active power in the electric system. For every generator connected to the grid the following relation is valid:

$$J \cdot \frac{d\Omega}{dt} = C_m - C_e \qquad [9.1]$$

where:
- J is the moment of inertia of the rotor;
- Ω is the angle speed of the rotor;
- C_m is the mechanical driving torque applied to the rotor;
- C_e is the load resistance electromagnetic torque.

Therefore, in case of imbalance between the two torques, the rotor shall tend to increase or decrease the speed, proportional to the difference of the torques and inversely proportional to its own moment of inertia. Since the power can be expressed as the product of the torque by the angle speed, the foregoing expression, in terms of powers, becomes:

$$J \cdot \frac{d\Omega}{dt} = \frac{P_m - P_e}{\Omega} \qquad [9.2]$$

Since each generator is connected to the grid in synchronism with the others, the above equation may represent the operation of the whole system. Therefore, since the grid frequency can be directly correlated to the angle speed of the rotor through the relationship

$$\Omega = \frac{\omega}{p} = \frac{2 \cdot \pi \cdot f}{p} \qquad [9.3]$$

where:
- ω is the pulsation of the generated electrical quantities;
- p is the number of the couples of poles of the generator

the imbalance between the driving power introduced into the grid as total power output and the sum of the power of the connected loads causes a variation of the network frequency.
As a consequence of the load variation, the power outputs of the power stations are changed to keep the frequency as constant as possible and within established limits.
In particular, the higher the fraction of power produced by a power plant in comparison with the total power injected into the grid, the better such power plant is able to influence the network frequency.

9.2.2 Voltage variation

When considering the voltage instead, one of the regulation methods is the variation of the generator excitation. With reference to the alternators, by varying the excitation magnetic flux, also the r.m.s. value of the voltage and the reactive power output vary and consequently also the power factor of the energy inserted into the network varies. In particular, in wind power plants, since the connection line of a power plant at the net presents an ohmic-inductive impedance to the current flow , there shall be a variation of voltage between the terminals of the wind generator and the voltage at the point of connection with the grid, which is expressed by the formula:

$$\Delta V = \frac{P \cdot r + Q \cdot x}{V_r} \qquad [9.4]$$

where:

- P is the total active power generated by the wind power plant
- Q is the total reactive power generated by the wind power plant[5]
- r is the resistance of the connection line
- x is the inductive reactance of the connection line
- V_r is the grid voltage at the connection point.

As it can be noticed in the foregoing relation, injection of active as well as reactive power into the grid causes a voltage variation between the generation point and the connection point to the grid. Ideally, if V_r would always stay constant at the rated value (network at infinite short-circuit power), by increasing the power insertion, there would be an overvoltage at the terminals of the generators of the wind power plant, the higher the higher is the impedance of the connection line.
In reality, the lower the fault level of the connection point, the more frequently the voltage V_r may change (as a function of the power flowing through the connection node), which involves the loads connected to the node itself.
The Standard EN 50160 defines the maximum levels of the almost-steady variation of the network voltage measured in a 10min span:
- ±10% of the rated voltage U_n during 95% of the week
- for the LV grids, between -15% and +10% U_n.

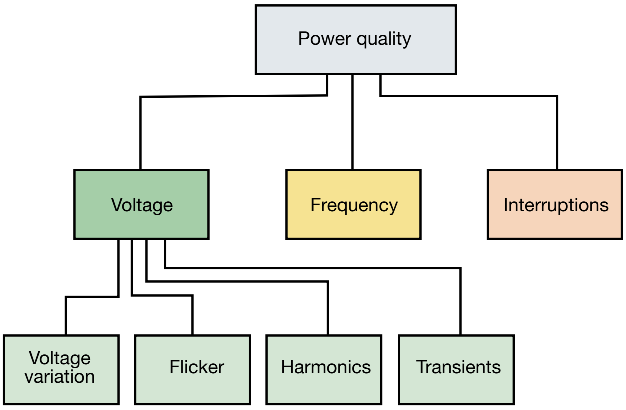
In case of wind turbines, the voltage variation can be limited by varying the power factor.
In fact, a modest reduction in the power factor from the unit value to 0.98 inductive causes a decrease of the maximum voltage variation of about 1.5%.

[4] *Transversal parameters are ignored as it is custom in the modeling of LV short electric lines.*
[5] *In case of fixed speed turbines with asynchronous generator, the reactive power would be absorbed and therefore would have a negative value.*

9.3 Power quality

Therefore, injection of electric power into the grid may affect the voltage quality.
As the voltage quality must be within certain limits, to ensure the supply of electrical energy to the consumers, the Std. IEC 61400-21 prescribes procedures for determining the *"power quality"* characteristics of wind turbines (Figure 9.5).

Figure 9.5



In compliance with the above mentioned Standard, the following parameters are fundamental for characterization of the quality of the power supplied by wind turbines:

- rated data (P_n, Q_n, U_n and I_n);
- maximum permitted power Pmc (10-minute average);
- maximum measured power P600 (600-second average), P60 (60-second average) and P0.2 (0.2-second average);
- reactive power Q (10-minute average);
- flicker coefficient $c(\Psi_k,v_a)$ for continuous operation as a function of the line impedance phase angle Ψ_k and annual average wind speed v_a
- maximum number of operations on turbines over a 10min-period (N10) and a 2hour-period (N120);
- flicker step factor k_f (Ψ_k) and voltage change factor k_u (Ψ_k) for specified switching operations of the turbine as a function of the network impedance phase angle Ψ_k;
- maximum value of the current harmonic Ik, up to the 50th harmonic over a period of 10min, of the interharmonics up to 2kHz and of the high frequency components ranging from 2kHz to 9kHz[6].

Table 9.1 sums up the main influences exerted on the grid by a wind turbine or by a wind power plant and the relevant causes.

[6] *For values of generated active power equal to 0,10,20…,100% of the rated power P_n.*

Table 9.1

Parameter	Cause
Voltage value	Produced power
Voltage variations and flicker	Operations Tower shadow effect Blade pitching error Yaw error Sudden wind variation
Harmonics	Inverter
	Rectifiers
Voltage peaks or dips	Inductive components or asynchronous generators
Reactive power consumption	Operations

9.3.1 Maximum permitted power

It is the maximum 10-minute average output power of the wind turbine, depending on its design. Wind turbines with active control (Pitch angle, variable speed) of output power typically provide $P_{mc}=P_n$; wind turbines with passive control (stall, fixed speed) of output power are commonly set up with P_{mc} 20% higher than the nominal power P_n.

9.3.2 Maximum measured power

The maximum measured powers are to be considered when choosing the relay protection settings and are of particular relevance for the operation of wind turbines on isolated grids. Variable speed turbines may typically provide P0.2=P60=P600=P_n, whereas for fixed speed turbines the power will commonly be larger than the rated power P_n.

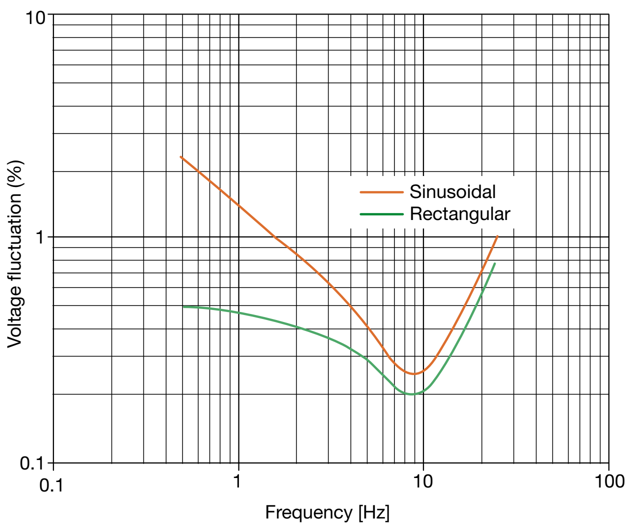
9.3.3 Reactive power

The reactive power of the wind turbine is to be specified as 10-minute average value as a function of the 10-minute average output power for 0.10%, ..., 90%, 100% of the rated power P_n and as a function of P_{mc}, P60 and P0.2.
Wind turbines with asynchronous motor connected directly to the grid consume reactive power as a function of the output power.
The consumption is usually compensated by capacitors connected in steps.
Wind turbines employing frequency converters are usually capable of controlling the reactive power by reducing it to zero, or consuming it or supplying it according to the needs of grid, although this is limited by the size of the converter.

9.3.4 Flicker coefficient

The fluctuation of the power output from wind turbines causes a corresponding voltage fluctuation at the connection point of the grid.
The amplitude of the voltage fluctuations will depend not only on the amplitude of the power fluctuations, but also on the network impedance (and therefore on the fault level).
Voltage fluctuations may cause annoying changes in the luminance from lamps, thus causing the flicker phenomenon. As Figure 9.6 shows, also a small percentage voltage fluctuation may cause annoying flickers[7].

Figure 9.6



The flicker coefficient is a normalized measure of the maximum flicker emission (99th percentile) produced from a turbine during continuous operation and it is expressed as:

$$c(\psi_k, v_a) = P_{st} \cdot \frac{S_k}{S_n} \qquad [9.5]$$

where:
- P_{st} is the flicker emission from the wind turbine on a fictitious grid;
- S_n is the rated apparent power of the wind turbine;
- S_k is the short-circuit apparent power of the grid.

The flicker coefficient must be given for specified values of the network impedance phase angle (30°, 50°, 70°, 85°) and of the annual average wind speed (6m/s, 7.5m/s, 8.5m/s, 10m/s). Variable-speed turbines usually have low flicker coefficients, fixed-speed turbines (stall-controlled) have average values, whereas fixed-speed turbines (pitch-controlled) have higher coefficient.
In fixed speed turbines, flicker emission is mainly caused by the wake due to the tower.
Everytime a rotor blade passes in front of the tower, the power output of the turbine is reduced. This effect determines a periodic variation in the power with a frequency of the order of 1Hz and the subsequent voltage fluctuation.
On the contrary the power fluctuations due to wind speed variations have a lower frequency and therefore are less important for the flicker.
Variable speed turbines have lower flicker coefficient since the periodic power fluctuations due to the wake of the tower are damped by the wind turbine itself. In wind power plants the periodic fluctuations of the total power output are damped because the power fluctuations of the single turbines are not correlated together.
As a consequence the flicker emission from a wind power plant formed by n turbines of the same type is $\sqrt{n}$ times the flicker emission of the single turbine.

9.3.5 Flicker step factor

It is a normalized measure of the flicker emission due to a single switching operation of a wind turbine and it is expressed as:

$$k_f(\psi_k) = \frac{1}{130} \cdot \frac{S_k}{S_n} \cdot P_{st} \cdot T_p^{0.31} \qquad [9.6]$$

where:
- T_p is the duration of the voltage variation due to the switching operation;
- P_{st} is the flicker emission from the wind turbine on a fictitious grid.

The flicker step factor has to be given for specified values of the network impedance phase angle (30°, 50°,70° and 85°) and for the specified types of switching operations. Variable speed wind turbines commonly have low flicker step factors, whereas fixed speed wind turbines range from average (pitch-controlled) to high (stall-controlled) factors.

[7] *The human eye is more sensitive to voltage variations at 8-10Hz.*

9.3.6 Voltage change factor

It is an index of the voltage change caused by a single operation of the wind turbine and it is expressed as:

$$k_u(\psi_k) = \sqrt{3} \cdot \frac{V_{max} - V_{min}}{U_n} \cdot \frac{S_k}{S_n} \quad [9.7]$$

V_{max} and V_{min} are the maximum and minimum phase voltage in a fictitious grid during switching operations;

U_n is the rated line-to-line voltage of the system.

The voltage change factor shall be given for specific values of the network impedance angle (30°, 50°,70°,85°) and for specific types of switching (see clause 6.2.1). Variable speed turbines usually have low values for this coefficient, whereas fixed speed wind turbines range from average (pitch-controlled) to higher (stall-controlled) values.

9.3.7 Switching operations

As regards the influence on voltage variations, the following typologies of switching operations are to be considered:

- startup of wind turbine at the cut-in speed of the wind
- startup of wind turbine at the rated speed of the wind
- the worst case of switching between generators (configuration with turbines with more than one generator or one generator with multiple windings).

The influence on the power quality depends not only on the number of switching operations, but also on their frequency. In particular, voltage variations during switching operations are due to the inrush currents and the relevant variations of active and reactive power.
For fixed speed turbines, the soft-starter limits the inrush current of the asynchronous generators.
During startup, the generator requires reactive power for the magnetization of the stator.
Few seconds after the connection of the generator, the insertion of the capacitor banks limits the reactive power consumption during normal functioning.
Moreover, swift power variations during switching operations cause flickers.
This effect is limited in variable speed turbines, which, due to their structure, damp the effects on the delivered power quality caused by switching operations.

In wind power plants, there are usually one or few turbines starting up or shutting down at the same time; therefore for the calculation of switching voltage variation it is sufficient to consider either a turbine or a limited number of turbines.

9.3.8 Harmonics

Actual variable-speed wind turbines are equipped with PWM (Pulse Wide Modulation) controlled inverters using[9] IGBT (Insulated Gate Bipolar Transistor) or IGCT (Integrated Gate Commutate Thyristor) static circuit-breakers. In particular, two types of PWM inverters are used:

- fixed clock frequency
- variable clock frequency.

The first type, with fixed frequency, produces individual inter-harmonics in the range of the clock frequency and multiple harmonics with such frequency. The second type instead, with variable frequency, present a wide band of inter-harmonics and multiple harmonics which reach their peak at the resonance frequency with the grid.

9.3.9 Frequency control

In an electric power system, frequency is an indicator of the balance or imbalance between the generated and absorbed[9] active power, including transmission and distribution losses. During normal operation of the grid, the frequency should be very close to the rated value: for example, in the European countries it usually varies in the range 50±0.1Hz and rarely it is outside the range 49-50.3Hz.
If there is lack of balance between production and consumption (due to the outage of a power plant or to a load increase), the primary and secondary controls of the frequency shall be used to re-balance the system and to restore the frequency to the established values.
If, by assumption, the network loads absorb more power than the produced one, the kinetics energy stored in the large alternators of the conventional power plants is used to keep as close as possible the power generated and the power absorbed.
This implies a reduction in the rotation speed of the alternators and consequently a reduction in frequency.
During normal functioning, the power output from a wind power plant can vary up to 15% of the installed capacity in a 15min span, above all during and immediately after extreme windy conditions.

---

[8] *It belongs to GTO family.*

[9] *Since electric energy cannot be stored on a large scale.*

This can cause an additional unbalance between the power generated and consumed in the electrical system.
In power systems there are some generation units[10], named primary control units, equipped with devices for the frequency control.
Such units increase their production as long as balancing with the total power consumption is restored and the frequency stabilized.
The time interval for such adjustment is 1 to 30s.
In order to restore frequency to its rated value and release from use the primary control reserves, secondary control is carried out in a 10 to 15min time up to one hour, with a gradual increase or decrease of the total output.
This implies that some generation units of the electric system (gas-turbine or hydro power plants, which can be started up quickly) are used as secondary reserve plants[11], to be started up when the frequency is too low.
Besides, there is a long-term reserve (tertiary reserve or unit commitment) which breaks within times of the order of hours or days and consists of a forecast of the load diagram at medium-long term and in the subsequent scheduling of the use of the production units.
Although wind turbines use an energy source different from that of the traditional power plants and variable, wind power plants have, however, the capability, even if limited, to take part into the primary control, through a control equal to 3-5% of the output power of the wind power plant, and into the secondary control.
In particular, when the frequency exceeds the rated value over the tolerance, the contribution to the secondary control can be obtained by shutting down some wind turbines of the wind power plant or by using the pitch angle control.
Moreover, since wind cannot be controlled, at the rated frequency, the power produced by a wind power plant can be intentionally kept under the rated power so that the wind power plant can contribute to the secondary control in case the frequency goes below the lower tolerance.
The wind source is still not programmable, but it is becoming more and more predictable, with a margin of uncertainty of almost 5% in a time period of 72 hours. This uncertainty further decreases when reducing the time interval, which is leading to an improvement of the capacity of managing the energy contribution of the wind power plants to the electric systems.

9.4 Short-term and long-term effects

The effects of the wind energy on the electric network depend on the dimensions and on the relative flexibility of the network itself, as well as on the penetration level of the wind output in the electric system.
The effects caused by the wind turbines can be divided into two categories:

- short-term effects – balance of the system in the scale of operating time (minutes or hours)
- long-term effects – supplying enough power during the load peaks.

9.4.1 Short-term effects

The variable production pattern of wind power production leads to changes in the scheduling of the other large conventional production plants and in the power flows in the transmission network.
Part of the fluctuation of the wind power, however, cannot be defined in advance or can be wrongly predicted; therefore an adequate reserve has to be provided for.
The electrical system needs power reserves both to face disturbances in the grid as well as to follow the load diagram.
Disturbance reserves are usually dimensioned according to the largest unit outage. As wind power consists of small units, there is no need to increase the amount of disturbance reserve.
Instead, the variation of wind power for the time scale of 1 hour or for a lower time affects the reserve of power used for the frequency control (load following) if the penetration level of the wind power into the electric system is such as to considerably increase the total variations of the system itself.
On average, for a 10% penetration level, the extra reserve requirement of wind power is in the order of 2-8% of the installed wind power capacity[12].
In particular, variations on wind power on the time scale of seconds and minutes (primary control of frequency) have little effect on the power reserve, since small variations in the various wind power plants placed on large areas are not correlated, and therefore they cancel out each other.
Another short-term effect of the wind power is the decrease or increase in the transmission and distribution losses, depending on where the production sites are

[10] The quantity of reserve power which must be available for primary control in a power system is usually defined by taking into account the largest generation plant which can be put out of service by a single fault.

[11] The quantity of reserve power which must be available for secondary control in a power system is usually defined by taking into account the largest generation plant which can be put out of service by a single fault and considering a possible failure in the short-term forecast of the load diagram. Therefore, in such case the power reserve corresponds to about 1.5 times the power of the largest generation plant.

[12] An increase in the power reserve obviously involves some additional costs, especially during the phase in which the most economical component of the reserve is already in use (e.g. hydro plants) and consequently it is necessary to turn to the reserves with higher operating costs (e.g. turbogas power plants).

situated in relation to the load centers.
Moreover, large amounts of intermittent wind power production can result in a lower efficiency of conventional generation caused by traditional plants operating below their optimum. As a consequence, the optimized unit commitment is complicated by the intermittent output from wind power plants.
If the intermittent wind power produced exceeds the quantity which can be handled by the network, keeping an adequate dynamic control on the electrical system, a part of the wind power shall be limited.
Substantially, this depends on the penetration level and generally when the intermittent power exceeds a 10% penetration a limitation becomes necessary.

9.4.2 Long-term effects

The intermittent nature of wind energy may influence the reliability of the electric system, which must be able to serve the loads connected to the network with low probability of failure: the required reliability of the system is usually in the order of one blackout in 10-50 years. In order to contribute to keep unchanged the reliability of the electric system, wind power should be able to replace part of the conventional production capacity, in particular during the load peaks.
Some variable sources produce power at times of peak demand.
Solar energy, for instance, follows "air-conditioning" loads; if the diurnal wind power production coincided with the load demand (e.g. wind power production increases in the morning and decreases in the evening-at night), this effect would be beneficial.
Therefore, the dispersion of wind power production on the territory and the desirable positive correlation between wind power production and power demand can determine an increase in the wind power value in the electric system.

9.5 Dynamic performance requirements of wind turbines

The expected increase in the percentage of output power from wind source in comparison with the total power injected in the electrical systems makes it necessary to define new requirements for keeping the quality of the delivered power as high as possible.
Special attention has to be paid to the dynamic behavior of wind turbines in case of network faults, in order to define the requirements which can help to guarantee operation stability and safety for the grid itself.
In fact, with the connection of wind power plants to the high and very high voltage transmission network, the disconnection of the wind turbines part of such plants for an indefinite time because of a failure on the grid, could cause a critical situation which might jeopardize the system stability, causing cascading interruptions.

Table 9.2

Short-term effects	Long-term effects
Voltage management through active power Time scale: up to several minutes	Reliability of the electric system Time scale: one year or more
Primary and secondary control of frequency through active power Time scale: several minutes to an hour	
Production efficiency of conventional thermal or hydro power plants Time scale: 1 to 24h	
Transmission and distribution efficiency Time scale: 1 to 24h	
Excess of produced energy put into the network Time scale: hours	

To face such problem, nowadays wind power plants are required to withstand any possible disturb on the distribution network, thus guaranteeing operation and service continuity of the system.

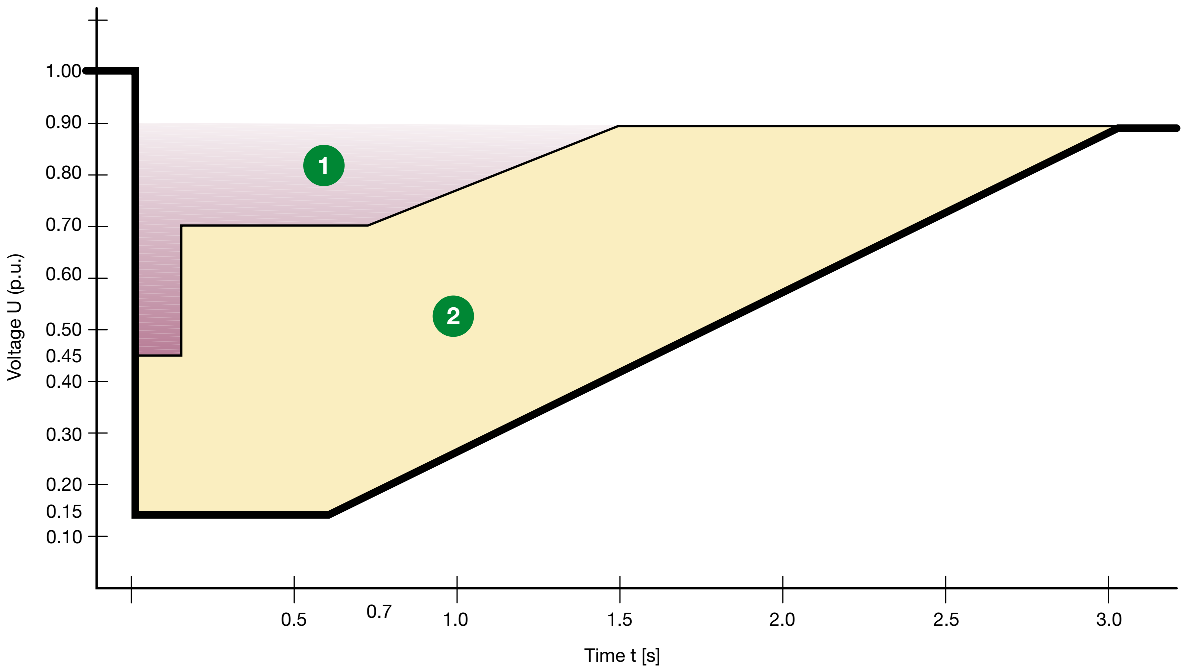
Therefore, considering the increasing integration of the wind energy into the European interconnected transmission system, wind turbines must meet the following requirements:

- in the event of three-phase short-circuits close to wind power generation plants, as a rule there shall be neither instability of the wind turbines nor disconnection from the grid for voltage-time values exceeding the bold line shown in Figure 9.7 (AWEA):
  - in particular, in zone 1, active power generation capacity must be recovered after the identification of the fault and increased at a gradient of 20% of the rated power per second
  - in zone 2 instead, a short disconnection of the turbines from the grid is allowed; however, a quick resynchronization shall follow after the fault clearing and the return to the pre-fault standard generation conditions, so that the outage lasts for maximum 10s. Therefore, the wind turbines must return to supplying active power within 2s after the fault is cleared at a gradient of 10% of rated active power per second
- in the event of short-circuits far from wind power plants, the wind generation units must not disconnect from the electrical system due to a fault which is eliminated by the network protections in 5s
- wind turbines must support the voltage in case of three-phase short circuits in the network.

  The passage from standard operation to "support of the network voltage" occurs in the event of a voltage drop higher than 10% and within 20ms from the fault identification; this passage is realized with the inflow of current of reactive type with a value equal to 2% of the rated current for each per cent of voltage drop. After 3s, return to normal operating condition is allowed.

To satisfy such requirements the new frequency converters are based on Low Voltage Ride Through (LVRT), or Fault Ride Through (FRT) technology, which enables the uninterrupted operation of the wind units even in the presence of network disturbances and supports it with the injection of reactive power.

Figure 9.7



10 ABB offer for wind power applications

ABB offers the following solutions to be used in the several parts which constitute a wind turbine. As for the technical characteristics of the different products reference is to be made to the relevant catalogues.

10.1 Electrical drivetrain – Fixed speed – Power circuit

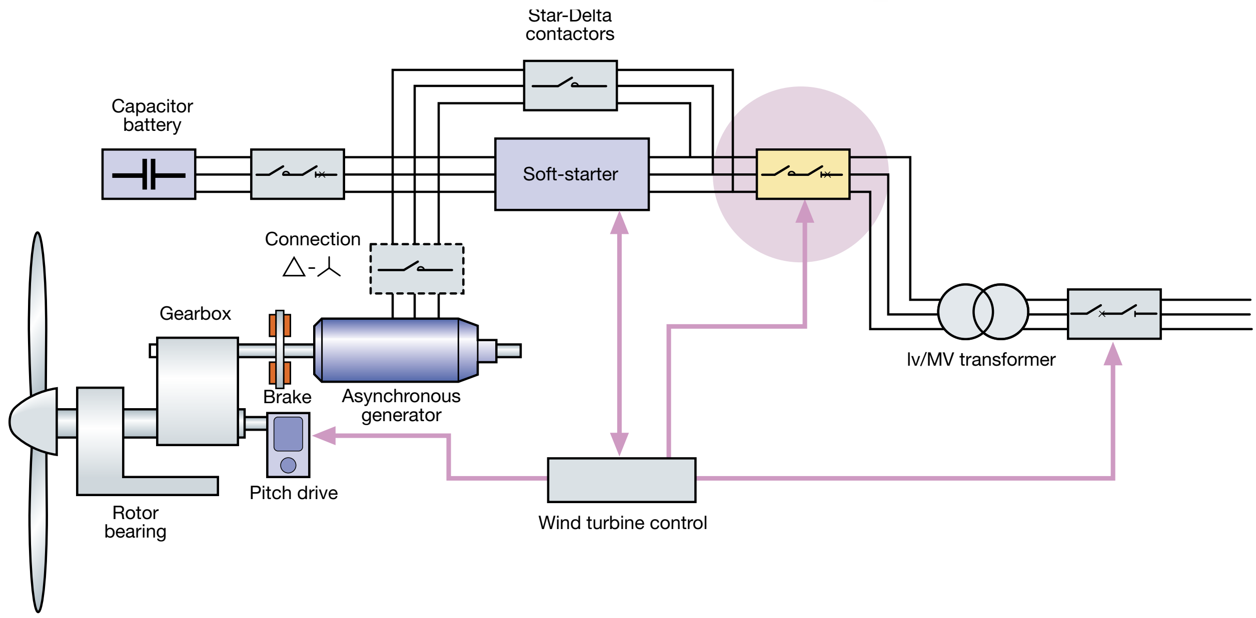
10.1.1 Circuit-breakers

Circuit-breakers are used for the protection of the supply circuit of the induction generator stator coordinated with contactors for switching operations.

In particular, for the protection against the overcurrents of the electrical devices, such as generators, cables and transformers, it is possible to use the air circuit-breakers of Emax series and molded-case circuit-breakers of Tmax T series and the new SACE Tmax XT.
Molded-case and air switch-disconnectors can be used to isolate the generator during maintenance.
Special versions are being developed for operating temperature from -40°C to +70°C.
These circuit-breakers are available in compliance with the Standards IEC, UL and CCC and in the following sizes:

- rated current up to 6300A
- rated voltage up to 690V
- breaking capacity up to 100kA

For limited-power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.



10.1.2 Contactors

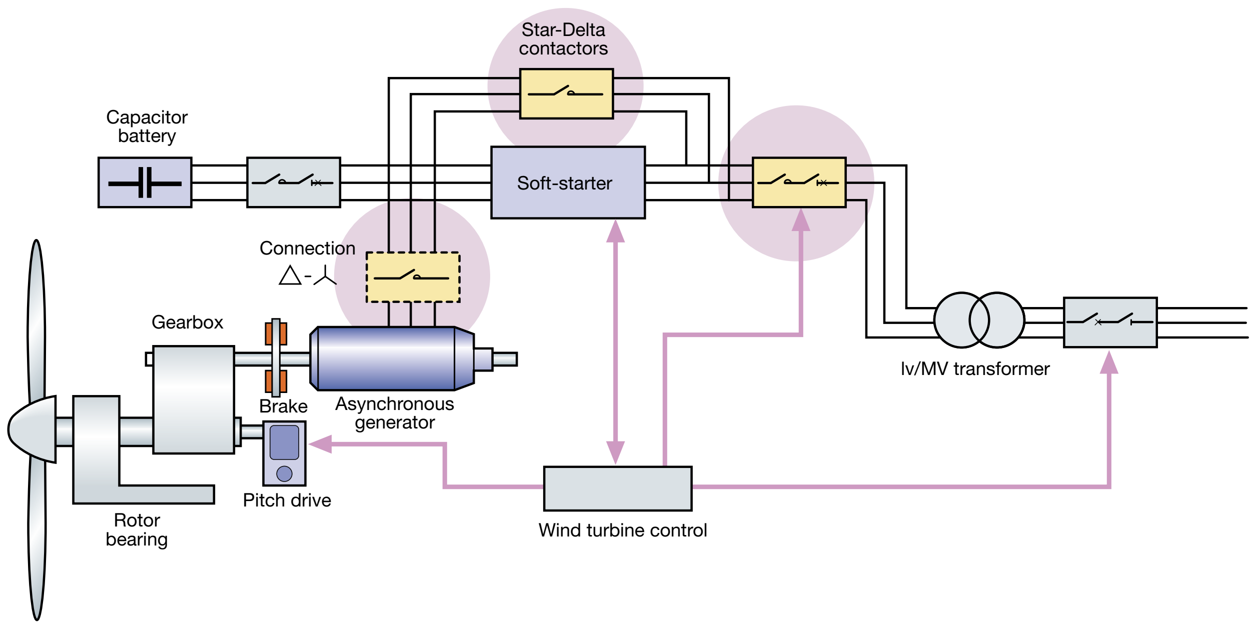
For the switching operations it is possible to use AF contactors coordinated with the circuit-breakers for circuit protections.
These contactors can be used also in the supply circuit in the presence of Softstarters or with star-delta connection to reduce the inrush current.

The wide available product range (from AF9 to AF2050) allows switching of load currents up to 2050A in AC-1.
In particular, the contactors AF1250 and AF2050 have been designed to be used in applications as wind power systems. They stand out for:

- compactness: AF1250 is the most compact 1260A (AC-1) contactor on the market, with the same overall dimensions of AF580 and AF750 contactors; AF2050 has the same overall dimensions as AF1650 but with higher current (AC-1 rating)
- electronically controlled coil and wide voltage range
- wide range of accessories: all the accessories can be used for AF580, AF750, AF1350 and AF1650 contactors.

If LVRT (Low Voltage Ride Through) without UPS as back-up function is required, a special version of contactors shall be used: AF...T.

AF1350T – AF2050T contactors offer "T-function" (time delay) built-in together with the electronically controlled coil.

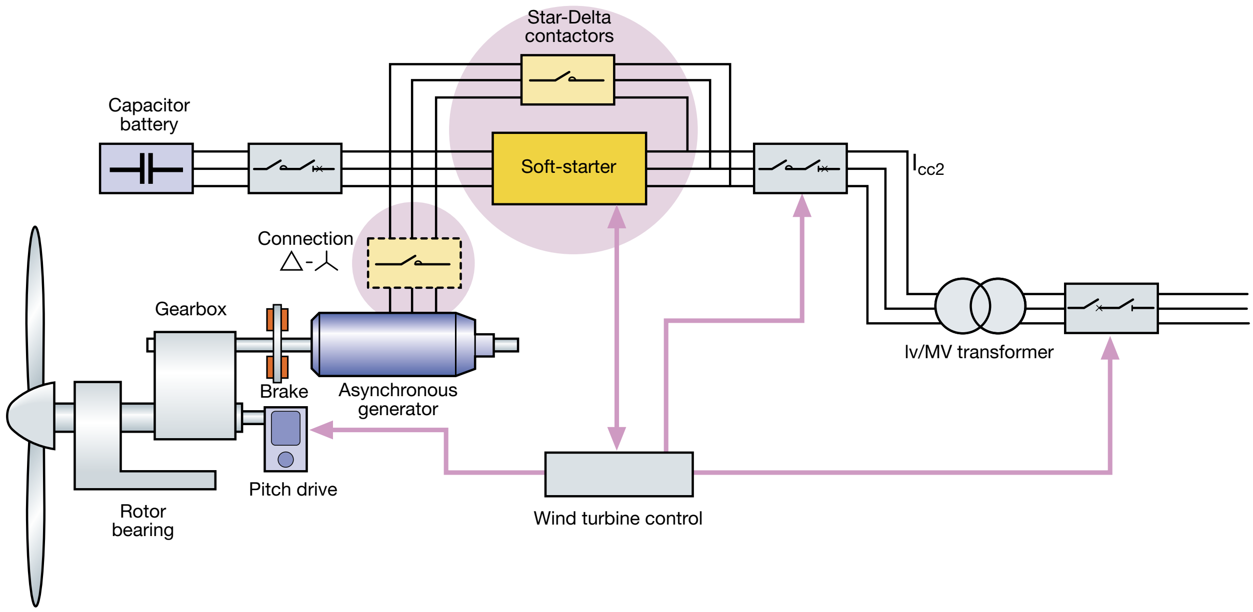


10.1.3 Solutions for inrush current reduction

The connection of asynchronous generators to the grid causes inrush current peaks which must be reduced to acceptable values.

To this purpose two different solutions can be adopted:

- softstarter - depending on the wind turbine rating, different softstarter ranges are possible:
- PSS – current ratings 18A-300A (availability of the main functions only)
- PST(B) – current ratings 30A-1050A (advanced functions)
- star-delta connection, by using contactors in the same way as for asynchronous motor starting in industrial applications.

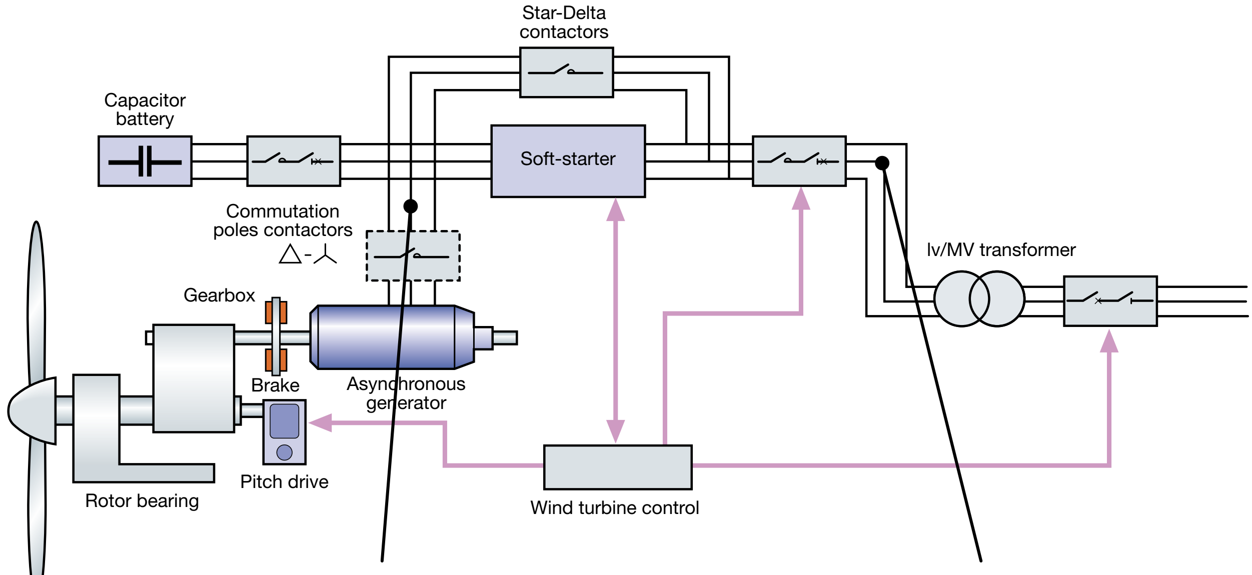


10.1.4 Surge protective devices (SPDs)

Type 1 surge protective devices can be installed near the main circuit-breaker for the protection against direct strike lightning and Type 2 near the generator as an additional protection of it against indirect strike lightning.

- Type 1 **OVR T1 25 440-50 (x3)**
  - I_{imp} = 25kA/phase (10/350)
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2kV
  - I_{fi} = 50kA

- Type 2 **OVR T2 3L 40 440/690 P TS**
  - I_{max} = 40kA/phase (8/20)
  - I_{imp} ≥ 1.5kA/phase (10/350) in compliance with Std. IEC 61400-24
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2.9 kV

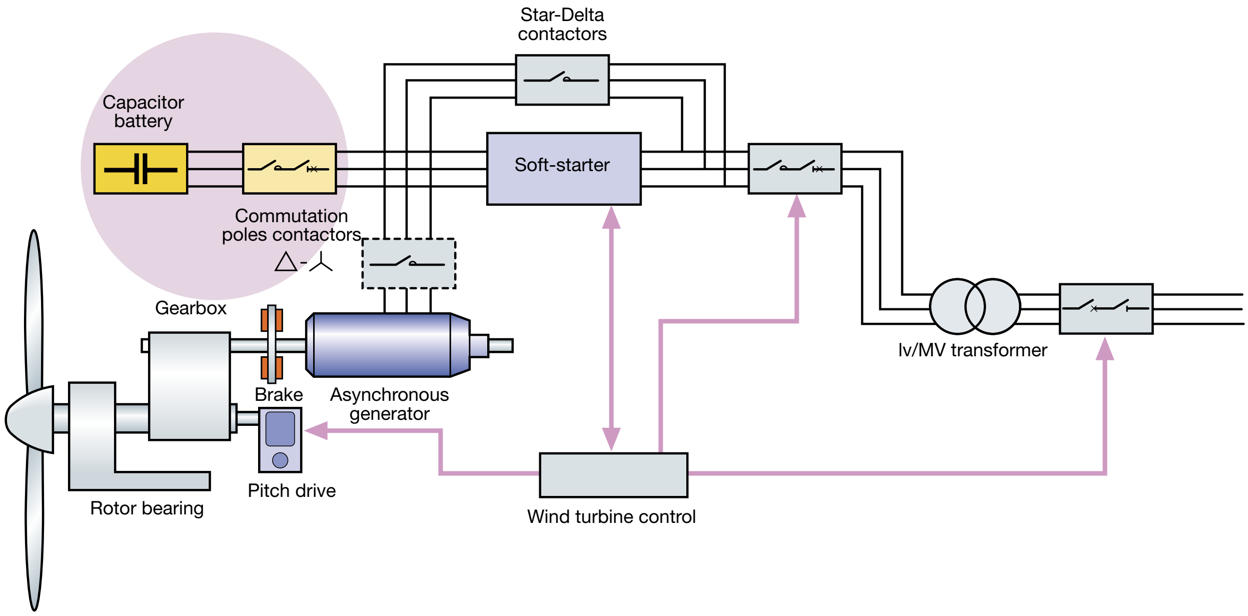


Type 2

Type 1

10.1.5 Switching and protection of capacitors

As for the choice of capacitor banks, of switching contactors and of protective circuit-breakers reference is to be made to the information of the Technical Application Paper QT8 – *Power factor correction and harmonic filtering in electrical plants.*



10.2 Electrical drivetrain – Fixed speed – Main auxiliary circuit

10.2.1 Circuit-breakers

Circuit-breakers are used for the protection of the main auxiliary circuit against overloads. In particular, molded-case circuit-breakers of series Tmax T or of the new series SACE Tmax XT can be used.
Special versions are being developed for operating temperatures from -40°C to +70°.

These circuit-breakers are available in compliance with Standards IEC, UL and CCC and in the following sizes:

- rated current up to 320A
- rated voltage up to 690V
- breaking capacity up to 100kA.

For limited power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.

10.3 Electrical Drive Train – Doubly-fed – Power circuit

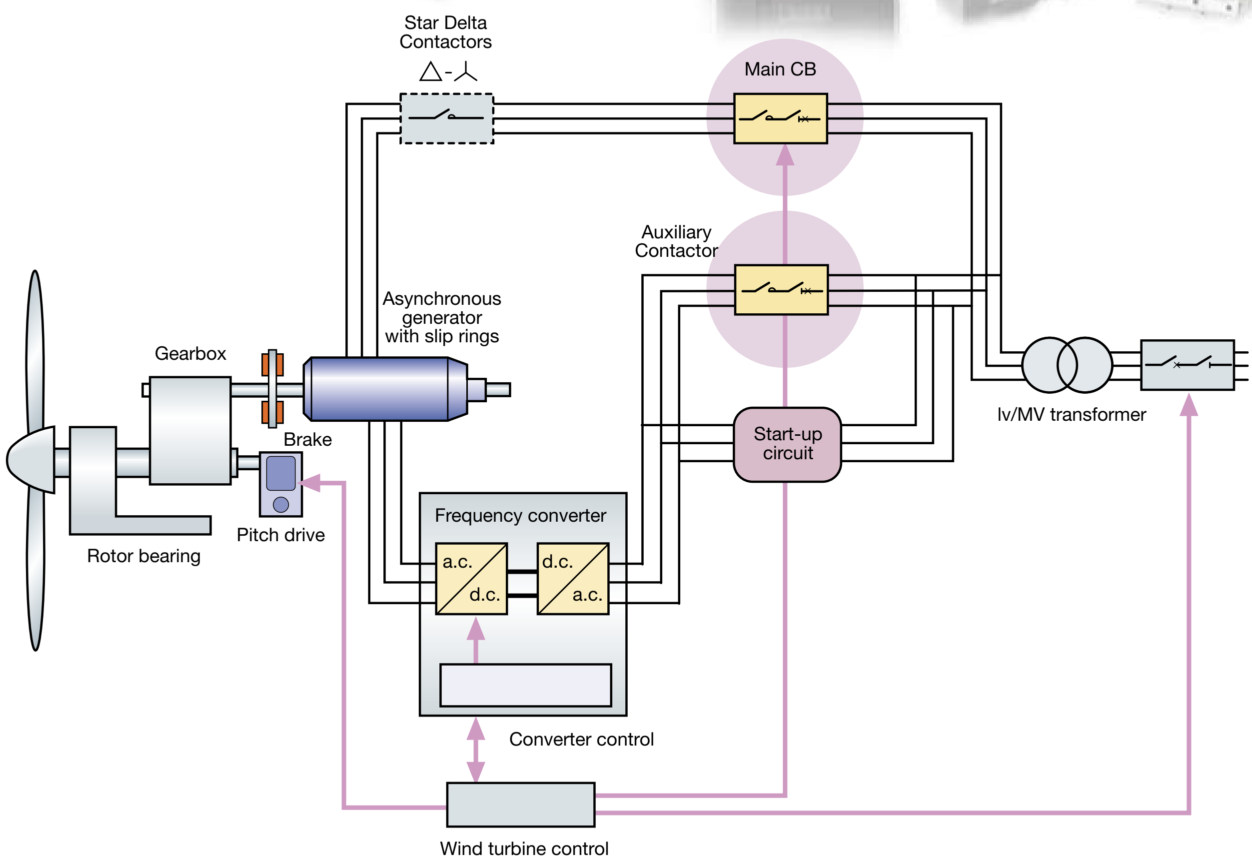
10.3.1 Circuit-breakers

Circuit-breakers are used to protect the supply circuits of the stator and the rotor of the slip-ring induction generator.
The circuit-breakers are coordinated with the contactors for switching operations.
In particular, for the protection against the overcurrents of the electrical devices such as generators, cables and transformer it is possible to use air circuit-breakers of the Emax series and molded-case circuit-breakers of the Tmax T series and the new SACE Tmax XT.

Molded-case and air switch-disconnectors can be used to disconnect the generator in case of maintenance.
Special versions are being developed for operating temperatures from -40°C to +70°.
The circuit-breakers typically used comply with Standards IEC, UL and CCC and are available in the following ratings:

- rated current up to 6300A
- rated voltage up to 1150V
- breaking capacity up to 100kA

For limited power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.

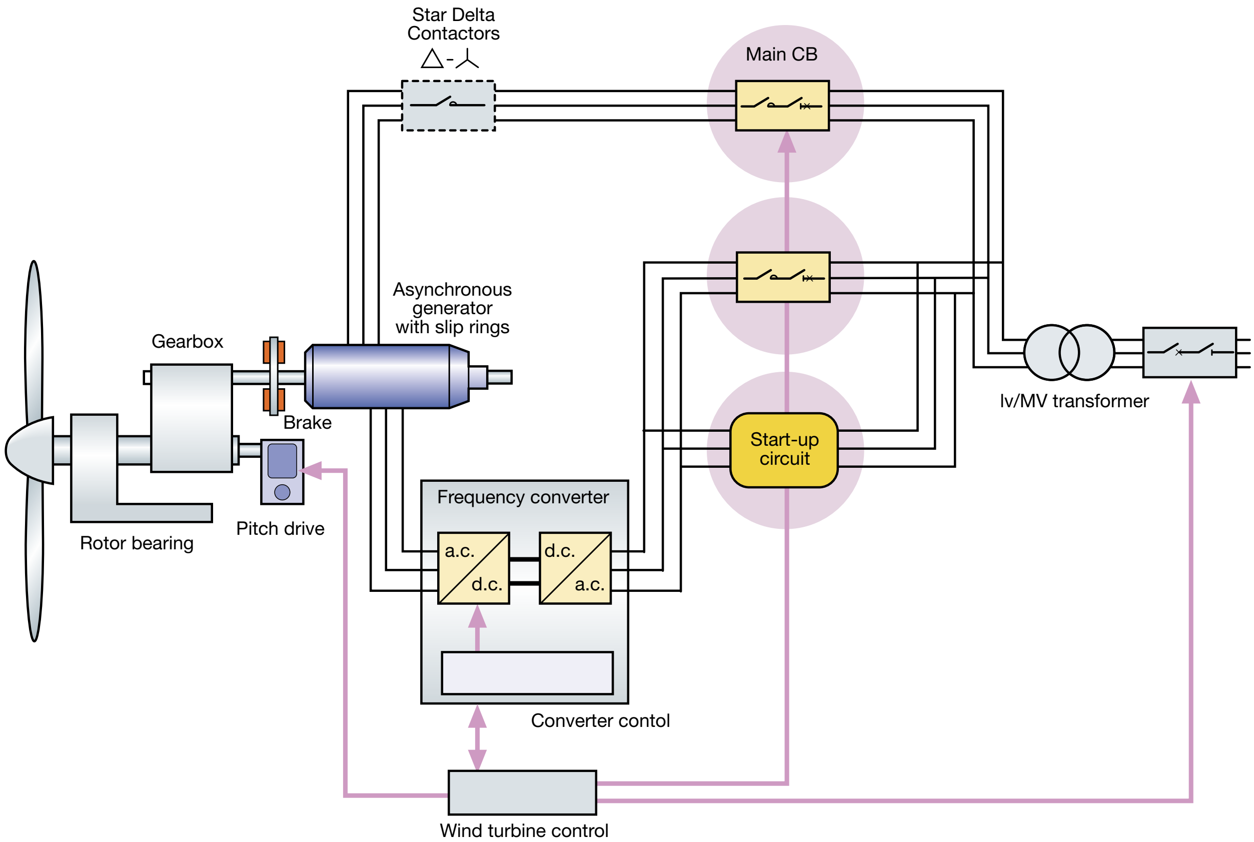


10.3.2 Contactors

For switching operations it is possible to use AF contactors coordinated with the circuit-breakers for circuit protection. These contactors can be used also in the supply circuit in the presence of Softstarters or in star-delta connection to reduce the inrush current.

The wide product range (from AF9 to AF2050) allows switching of load currents up to 2050A in AC-1.
In particular, the contactors AF1250 and AF2050 have been designed to be used in applications as wind power systems.

They stand out for:
- compactness: AF1250 is the most compact 1260A (AC-1) contactor on the market, with the same overall dimensions of AF580 and AF750 contactors; AF2050 has the same dimensions as AF1650 but with higher current (AC-1 rating)
- electronically controlled coil and wide voltage range
- wide range of accessories: all accessories can be used for AF580, AF750, AF1350 and AF1650 contactors.



If LVRT (Low Voltage Ride Through) without UPS as back-up function is required, a special version of contactors shall be used: AF...T.
AF1350T – AF2050T contactors offer “T-function” (time delay) built-in together with the electronically controlled coil.

The contactor, positioned on the stator circuit, is intended for the switching operations of higher power and consequently has larger size. Since starting up is carried out through the rotor circuit, the star-delta connection of the stator is unusual.

The contactor, positioned on the rotor circuit, is of smaller size since the power to operate is lower.
It can be installed both on the generator side as well as on the converter line side and since the control range of the converter is limited, both the installation configurations can be treated as applications at constant frequency.

Finally, the contactor positioned on the start-up circuit, for the starting up of the converter and the capacitor switching is of small size.

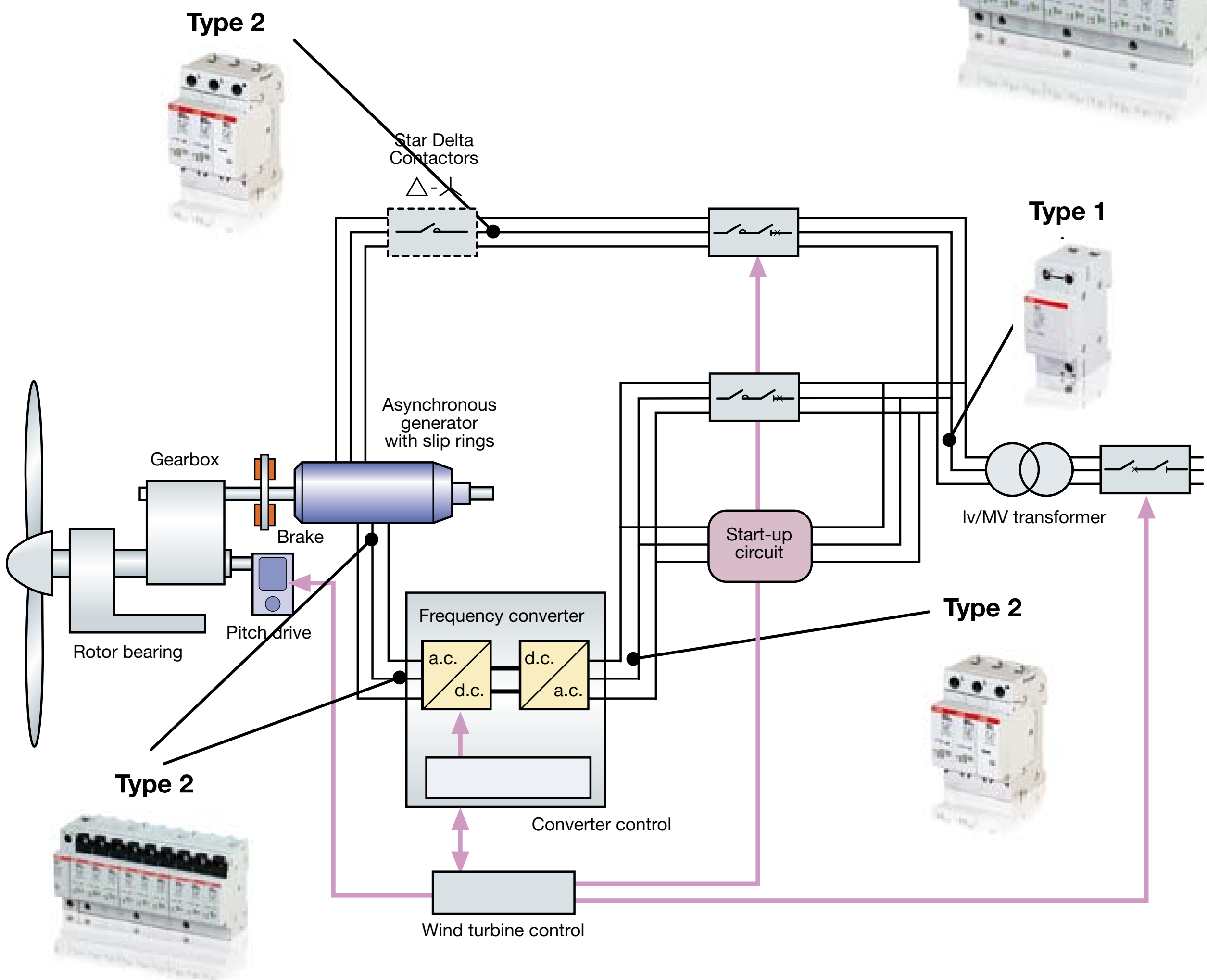
10.3.3 Surge protective devices (SPDs)

Type 1 surge protective devices can be installed near the main circuit-breaker for the protection against direct strike lightning and Type 2 near the generator as an additional protection of it against indirect strike lightning. Moreover, Type 2 surge protective devices suitable for transient overvoltages superimposed to the control voltage are installed on the generator side of the rotor converter and close to the rotor itself.

- Type 1 **OVR T1 25 440-50 (x3)**
  - I_{imp} = 25kA/phase (10/350)
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2kV
  - I_{fi} = 50kA

- Type 2 **OVR T2 3L 40 440/690 P TS**
  - I_{max} = 40kA/phase (8/20)
  - I_{imp} ≥ 1.5kA/phase (10/350) in compliance with IEC 61400-24
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2.9 kV

- Tipo 2 **OVR WT 3L 40 690 P TS**
  - I_n ≥ 20kA/phase (8/20)
  - I_{max} ≥ 40kA/phase (8/20)
  - I_{imp} ≥ 2kA/phase (10/350) in compliance with IEC 61400-24
  - U_n = 400/690V (L-PE/L-L)
  - U_{rp} ≥ 3000/3400V (L-PE/L-L)



10.4 Electrical Drive Train – Doubly-fed – Main auxiliary circuit

10.4.1 Circuit-breakers

Circuit-breakers are used to protect the main auxiliary circuit agaist overcurrents. In particular, molded-case circuit-breakers of the series Tmax T or of the new series SACE Tmax XT can be used.
Special versions are being developed for operating temperatures from -40°C to +70°.

These circuit-breakers are available in compliance with Standards IEC, UL and CCC and in the following ratings:

- rated current up to 630A
- rated voltage up to 690V
- breaking capacity up to 100kA

For limited power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.

10.5 Electrical Drive Train – Doubly-fed – Asynchronous generators

ABB doubly-fed asynchronous generators enable continuous production of reactive power and have high efficiency which results into the maximization of the kilowatt hour production.
The particular rotor design uses special carbon fiber winding-end support rings which can withstand sudden, uncontrolled overspeeds.
The increased rotor insulation allows a wide range of converters to be used.
These doubly-fed generators guarantee high power-quality thanks to the minimization of total harmonic distorsion (THD), above all by reducing the 5th and 7th order harmonic.
Main characteristics of ABB doubly-fed generators:

- rated power up to 5MW
- rated voltage from 690 up to 12000V
- rotor insulation voltage 2.5kV
- power factor: 0.9 (inductive) – 1 - 0.9 (capacitive)
- speed range from 700 to 2000 rpm
- maximum overspeed up to 3000 rpm
- air or water cooling

10.6 Electrical Drive Train – Doubly-fed – Converters

ABB converters for doubly-fed concepts synchronize the generator to the grid. Monitoring (40000 times/s) and direct control of the rotor torque guarantee speed and torque values suitable for generator running.
Liquid-cooled models are in a completely enclosed cabinets for increased protection against severe environmental conditions, such as dust, salt and high humidity.
Main characteristics of ABB doubly-fed converters:

- rated power from 0.85 to 3.8MW
- direct torque control (DTC)
- active and reactive power control
- IGBT power modules with integrated capacitors and control electronics
- low total harmonic distorsion (THD)
- air or water cooling
- liquid-cooled models are provided with a completely enclosed cabinet.

10.7 Electrical Drive Train – Full converter – Power circuit

10.7.1 Circuit-breakers

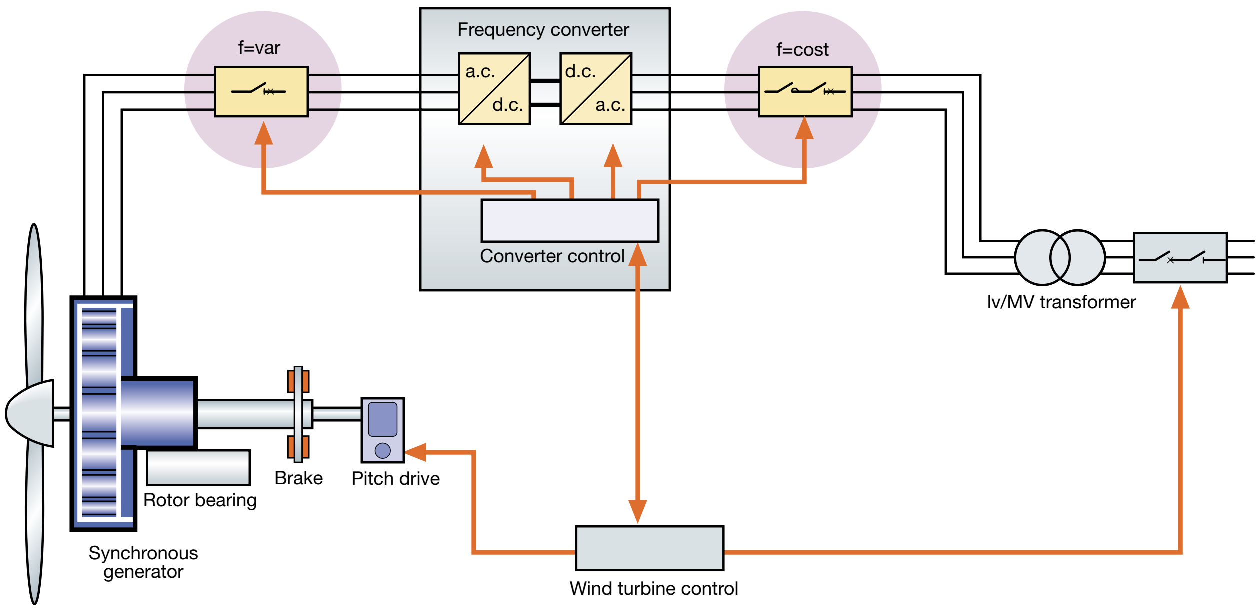
Circuit-breakers are used to protect the circuit on the grid side of the converter.

For the section between generator and converter, where electrical values at variable frequency are present, the new circuit-breakers of the series SACE Tmax VF and SACE Emax VF have been designed.
They represent the ideal solution thanks to:

- new trip units and current sensors optimized to ensure high accuracy and precision of the protection functions also with variable frequencies;
- arcing chambre and main contacts designed to guarantee high breaking capacities in the whole frequency range;
- use of high-performing materials allowing operation up to 1000V.

Main characteristics:

- rated uninterrupted current from 800A to 5000A
- rated service voltage: 1000V for Tmax VF and 1000V for Emax VF
- operating frequency from 1 to 200Hz; 4 types of protective trip units are available (two for Tmax and two for Emax circuit-breakers) according to the rated current and to the frequency range:
  - thermal magnetic trip units for low frequency (1..60Hz) up to 800A
  - PR222/VF for high frequency (20..200Hz) up to 800A
  - PR122/VF for low frequency (1..60Hz) up to 2500A
  - PR111/VF for high frequency (20..200Hz) up to 5000A
- high breaking capacity in every frequency range
- operating temperature from -25°C to +70°C; for installations under extremely critical environmental conditions the special version SACE LTT (Low Voltage Temperature) can operate from -40°C to +70°C thanks to a new generation of lubricants and to electronic and mechanical components intended for functioning at very low temperatures.



In the section between converter and grid it is possible to use air circuit-breakers of the Emax series and molded-case circuit-breakers of theTmax T series and the new SACE Tmax XT for the protection against the overcurrents of the electrical devices such as generators, cables and transformer.
Molded-case and air switch-disconnectors can be used to disconnect the generator in case of maintenance.
Special versions are being developed for operating temperature from -40°C to +70°C.

The circuit-breakers are available in compliance with the Standards IEC, UL and CCC and in the following size:

- rated current up to 6300A
- rated voltage up to 1150V
- breaking capacity up to 100kA @ 690V

For limited power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.

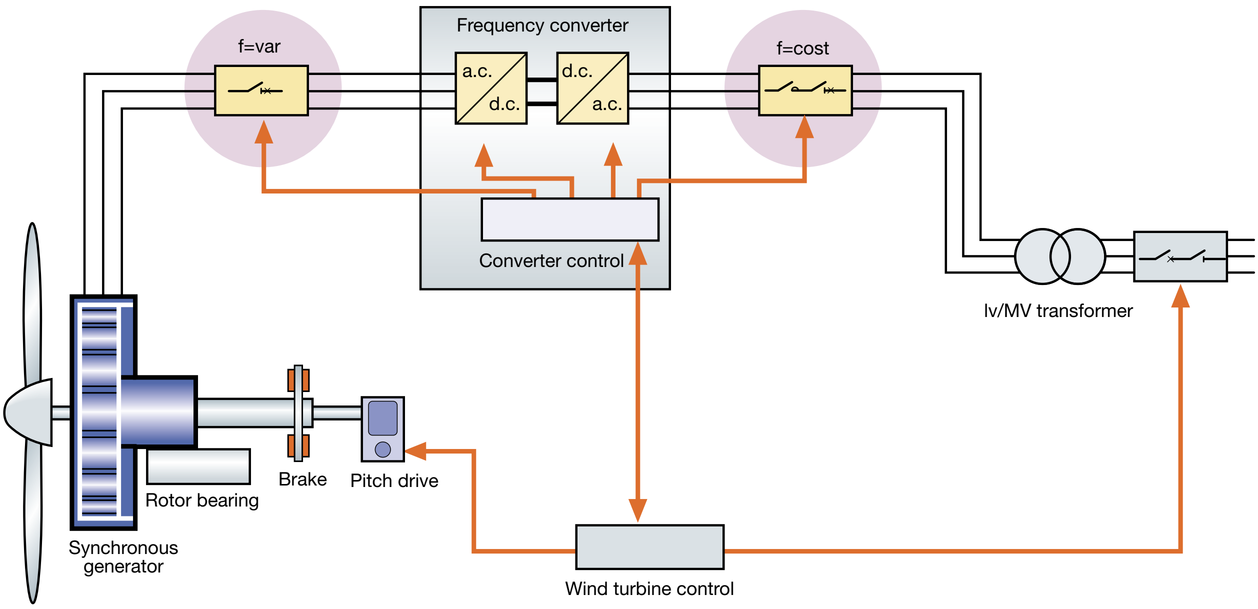
10.7.2 Contactors

For switching operations it is possible to use AF contactors coordinated with the circuit-breakers for the protection of circuits.
In addition to the circuit-breaker which guarantees disconnection and protection, these contactors can be installed on both sides of the converter and therefore they operate at low frequency on the grid side (50/60 Hz) and at variable frequency on the generator side.
In particular, for high frequency operations, the contactors are subject to derating with a derating factor of 0.8 at 400 Hz (factor equal to 1 at 150 Hz). At low frequencies there is no derating.
Switching high currents at low frequency theoretically implies reduced life for the main contacts, but usually this does not need to be considered in this case.

The wide product range (from AF9 to AF2050) allows switching of load currents up to 2050A in AC-1.
In particular, the contactors AF1250 and AF2050 have been designed to be used in applications as wind power systems. They stand out for:

- compactness: AF1250 is the most compact 1260A (AC-1) contactor on the market, with the same overall dimensions of AF580 and AF750 contactors; AF2050 has the same dimensions as AF1650 but with higher current (AC-1 rating)
- electronically controlled coil and wide voltage range
- wide range of accessories: all accessories can be used for AF580, AF750, AF1350 and AF1650 contactors

If LVRT (Low Voltage Ride Through) without UPS as back-up function is required, a special version of contactors shall be used: AF...T.
AF1350T – AF2050T contactors offer “T-function” (time delay) built-in together with the electronically controlled coil.



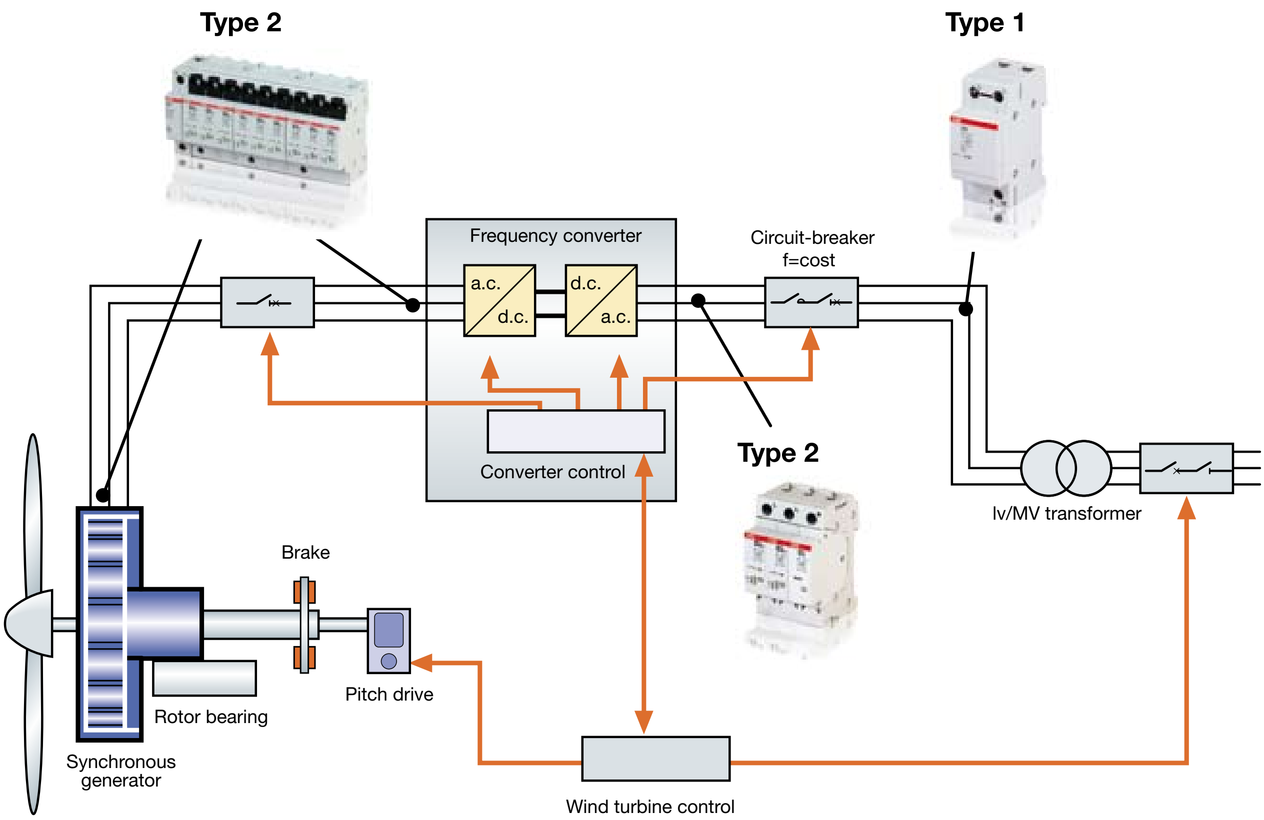
10.7.3 Surge protective devices

Type 1 surge protective devices are installed near the main circuit-breaker for the protection against direct strike lightning and Type 2 on the grid side of the converter as an additional protection against indirect strike lightning.
Moreover, Type 2 surge protective devices suitable for transient overvoltages superimposed to the control voltage are installed on the generator side of the converter and close to the generator itself.

- Type 1 **OVR T1 25 440-50 (x3)**
  - I_{imp} = 25kA/phase (10/350)
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2kV
  - I_{fi} = 50kA

- Type 2 **OVR T2 3L 40 440/690 P TS**
  - I_{max} = 40kA/phase (8/20)
  - I_{imp} ≥ 1.5kA/fase (10/350) in compliance with IEC 61400-24
  - U_n = 400/690V (L-PEN/L-L)
  - U_c = 440/750V (L-PEN/L-L)
  - U_t = 690V (L-PEN)
  - U_p = 2.9 kV

- Type 2 **OVR WT 3L 40 690 P TS**
  - I_n ≥ 20kA/phase (8/20)
  - I_{max} ≥ 40kA/fase (8/20)
  - I_{imp} ≥ 2kA/fase (10/350) in compliance with IEC 61400-24
  - U_n = 400/690V (L-PE/L-L)
  - U_{rp} ≥ 3000/3400V (L-PE/L-L)



10.8 Electrical Drive Train – Full converter – Main auxiliary circuit

10.8.1 Circuit-breakers

Circuit-breakers are used for the protection of the main auxiliary circuit against overcurrents.
In particular, it is possible to use molded-case circuit-breakers of the Tmax T series and the new series SACE Tmax XT.
Special versions are being developed for operating temperature from -40°C to +70°C.

These circuit-breakers are available in compliance with the Standards IEC, UL and CCC and in the following sizes:

- rated current up to 250A
- rated voltage up to 690V
- breaking capacity up to 100kA

For limited power wind installations it is possible to use the miniature circuit-breakers of System Pro *M* Compact series.

10.9 Electrical drivetrain – Full converter – Generators

For full-converter concept high-, medium- or low-speed permanent magnet generators suitable for onshore as well as offshore turbines are available.
For high-speed concept ABB offer includes also asynchronous generators.

10.9.1 Permanent magnet generators

The proven high voltage insulation technology and vacuum pressure impregnation system (VPI) allows maximization of the operational life of generators and enable high momentary overload capacity.
All ABB generators offer maximum efficiency at every speed and especially at low speeds thanks to robust design and reduced maintenance.
ABB know-how and design experience in the realization of permanent magnet generators ensure:

- design of the magnetic circuit suitable for all the three low, medium and high-speed concepts
- proper selection of the neodymium magnet available on the market with the suitable characteristics for each individual case
- correct dimensioning and functioning at low temperatures, which prevent demagnetization even during faults
- reliable fastening of the magnets, optimized for all the different rated speeds, and for all demanding applications causing mechanical stresses.

10.9.1.1 High speed generators

These types of ABB permanent magnet generators provide high power from the smallest frame size, with the highest efficiency over the whole speed range.
Main characteristics:

- rated power from 1 to 6MW
- rated voltage from 690V to 3300V
- rated speed from 1000 to 2000 rpm
- fatigue-resistant magnet fastening

10.9.1.2 Medium speed generators

These generators are integrated with the gearbox to provide a very compact design with the highest efficiency over the whole speed range.
A separate modular design is also available.
Main characteristics:

- rated power from 1 to 6MW
- rated voltage from 690V to 3300V
- rated speed from 120 to 450 rpm

10.9.1.3 Low speed generators

These generators form a structurally integrated unit with the wind turbine. Inner and outer rotor designs are available with the highest efficiency over the whole speed range.
Main characteristics:

- rated power from 1.5 to 3MW
- rated voltage from 690V to 3300V
- rated speed from 14 to 30 rpm

10.10 Electrical drivetrain – Full converter – Converters

Full power converters isolate the generator from the grid and provide low-voltage ride through (LVRT) supporting the grid through active and reactive power control.
They set and monitor the generator torque and speed and protect against sudden variations of the grid parameters which otherwise would cause additional mechanical stresses on the drivetrain.
These converters are suitable for both onshore as well as offshore installations.

10.10.1 Low voltage converters

Direct torque control (DTC) monitors the generator torque 40000 times/s thus guaranteeing an efficient control of the generator speed and torque to offer high power quality.
Liquid-cooling transfers the heat from the converter to outside the turbine thus making the cabinet be completely enclosed and without openings which could let humidity, salt and dust in.
Converters over 2 MW offer a design option to use parallel connected sub-converters for increased efficiency and optimized turbine installation.
Main characteristics:

- rated power from 0.8 to 6 MW
- liquid cooling
- contactor or circuit-breaker on grid side for connection/disconnection
- IGBT power modules with integrated DC capacitors and control electronics
- reduction in torsional oscillations
- low total harmonic distortion (THD)
- possibility of tower base installation

10.10.2 Medium voltage converters

Designed for large turbines and for tower base installation, ABB medium voltage converters use IGCT semiconductor technology which enables quick and homogenous switching with reduced conduction losses.
Main characteristics:

- rated power from 2.5 to 10MW
- rated voltage 3.3kV
- liquid cooling
- IGCT technology
- harmonic elimination control algorithm
- high efficiency
- integrated cooling unit
- integrated generator breaker
- lighter cables with smaller cross-sectional area
- possibility of tower base installation

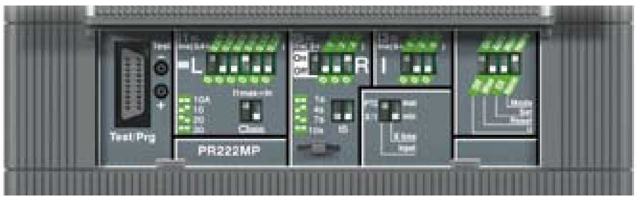
10.11 Blade pitch control system

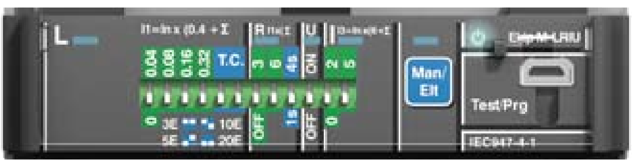
ABB offers several devices for the switching and protection of the actuators which adjust the Pitch angle of the blades.

10.11.1 Molded-case circuit-breakers

Tmax T and SACE Tmax XT circuit-breakers for motor protection with integrated electronic trip units suitably designed for this application - PR222MP and Ekip M respectively – which include protections against:

- overload (L) with fixed trip time depending on the trip class defined by the Std. IEC 60947-4-1
- rotor block (R) with adjustable threshold and trip time
- instantaneous short-circuit (I) with adjustable threshold and instantaneous trip time
- phase unbalanced (U) with adjustable threshold in ON or OFF.





10.11.2 Short-circuit current limiters

Short-circuit current limiters are used for coordinated protection in motor applications up to 690V, enabling selectivity and minimizing the installation space when used as back-up for different motor starters. They limit the short-circuit current until the downstream protective devices trip.
Two models are available:

- S800SCL-SR – technical characteristics:
  - rated current: 32, 63, 100A
  - rated voltage: 400, 690V
  - breaking capacity:
    up to 100kA @ 440V
    up to 65kA @ 600V
    up to 50kA (65kA) @ 690V
  - accessories: Smissline adaptor

Number of downstream motor starters: up to 12..15 motors for each S800SCL-SR

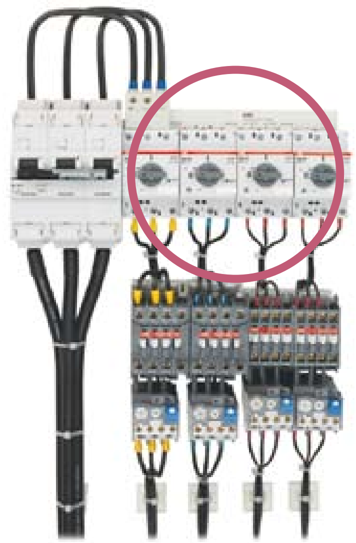
- WT63, based on S700 technology, increases the short-circuit level of MMS up to 35kA @ 690V and ensures Type 2 coordination (normal start-up).

Main technical characteristics:

- maximum motor size: 37kW @ 690V
- maximum total current (AC-3): 50A/pole
- maximum total in rush current: 450A/pole
- maximum ambient temperature: 55°C

10.11.3 Manual motor starters

MS325, MO325 of the former generation still available.



MS116, MS132 of the new generation with:
- high short-circuit ratings
- 690V insulation voltage
- disconnection function
- environment operating temperature from -25° to +60°C (55°C for MS116)
- trip class 10
- phase loss sensitivity

In particular, MS116 has 12 setting ranges from 0.1 to 16A:
- 0.1/10A @ 400V with Ics=50kA
- 16A @ 400V with Ics=16kA

while MS132 has 15 setting ranges from 0.1 to 32 A:
- 0.1/10A @ 400V with Ics=100kA
- 10/25A @ 400V with Ics=50kA
- 32A @ 400V with Ics=25kA

10.11.4 Contactors

ABB offers a complete range of contactors:
- A- range, which is modern but which has been on the market for several years (Types A, AE, AL ….)
- AF type, which are available since some years, but which have been recently implemented for motor starting up to 18.5kW. They offer the following advantages:
  - AF technology – less sensitive to control voltage variations (AC or DC)
  - reduced number of versions resulting in improved logistics and stock-keeping
  - reduced overall dimensions
  - AF..Z version for PLC-control thanks to reduced coil consumption.

Sizes: AF09 (4kW), AF12 (5.5kW), AF16 (7.5kW), AF26 (11kW), AF30 (15kW), AF38 (18.5 kW).

10.11.5 Overload relays for motor protection

New generation (TF/EF) for motors of power up to 18.5kW, offering the following advantages:
- perfect match to the contactor
- phase loss sensitivity
- automatic/manual reset/sealable
- stop and test function

In particular for TF42 relays:
- trip class 10
- operating temperature from -25° to +60°C

whereas for EF19 and EF45 electronic relays:
- trip class 10E, 20E, 30E
- EF19 from 0.1 to 18.9A
- EF45 from 9 to 45A
- operating temperature from -25° to +70°C

10.11.6 Smissline system

Motor starter combined in a single pre-wired unit mounted on the plug-in smissline module for the smissline busbar system. The main components of this combined system are:

- motor starter MO325
- contactor
- electronic thermal relay
- smissline unit

Main advantages:

- reduction in installation space and wiring time
- signaling integrated into the system via bus (LA, LB)
- one order code only.

10.11.7 Miniature circuit-breakers

S200 and S800 miniature circuit-breakers include D and K characteristics suitable for motor protection applications.

Main characteristics:

- compact solution
- rated current from 0.5 to 125A
- breaking capacity from 6 to 50kA (according to voltage).

For DC circuits, S280UC series is available with the following main characteristics:

- rated voltage: 220Vdc (1pole), 440Vdc (2,3,4 poles)
- rated current from 0.5 to 63A
- B, K, Z characteristics.

10.11.8 Surge Protective Devices (SPDs)

For the protection against indirect strike lightning Type 2 SPD for three-phase circuits are available:

- OVR T2 3L 40 440 P TS for applications at 400V
- OVR T2 3L 440/690 P TS for applications at 690V
- OVR T2 3N 40 275 P TS (3P+N) for applications at 230/400V with I_{max}=40kA and U_p=1.4kV

For the protection of direct current circuits at 24/48Vdc the following Type 2 SPD can be used:

- OVR 2 15 75 s P TS with I_{max}=15kA and U_p=0.3/0.6kV

For the protections of the given circuits the following devices can be used:

- OVR TC xx V P with Imax=10kA, Uc=6/12/24/48/200V and possibility of connection with RJ11 and RJ45

10.11.9 Electronic products and relays

Power supplies
- CP-E 24/20, CP-S 24/20, CP-C 24/20
- CP-E 24/10, CP-S 24/10, CP-C 24/10

Analogue converters
- CC-U RTD R (-40°C)

Safety relays
- C6700, C6701, C6702

Timers
- CT-MFE

Interface relays
- CR-M, CR-P, R600 (2 c/o), R600 (1 c/o)

Three-phase monitoring relays
- CM-MPS

Single-phase monitoring relays
- CM-EPS.2 (dc), CM-ESS.M

Panel heaters

Controllers
- Logic relay: CL-Range or AC 500 (eCo)

10.11.10 Fuses and fuse holders

Main characteristics:
- AC-22B in compliance with Std. IEC 60947-3
- rated current: 20A and 32A
- rated voltage: 400V and 690V
- fuses type aM/gG

10.11.11 Modular sockets

Main characteristics:
- 16mm^2 terminals
- safety shutters

- Pozidriv® screws
- Options:
  - embedded fuse
  - coloured versions
  - embedded indicator light

10.11.12 Motors

As mechanical actuators for the blade pitch control system, ABB suggests solutions with:
- 6 pole motors
- power from 1.1 to 4kW, but higher powers are also available

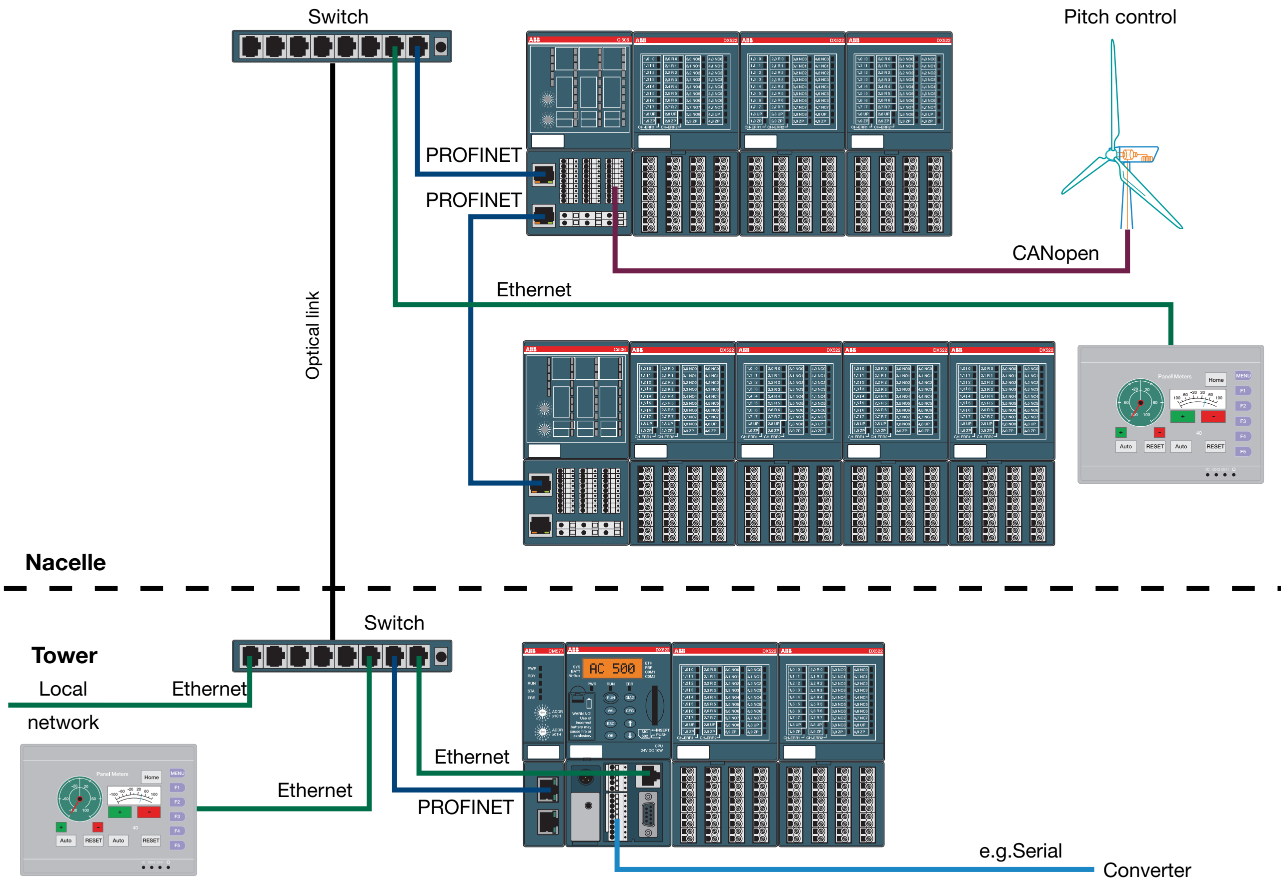
10.12 10.12 Yaw control system

The yaw control system consists of several motor starters, generally 3 to 10 in number.
ABB offer is similar to that for the blade pitch control system.

10.13 Turbine main controller

10.13.1 Controller

Control and protection systems guarantee that the turbine operates in a defined range of physical quantities. PLC AC500 solution is used for wind turbine control, typically to set the reference speeds, for turbine orientation to the wind and for turbine startup and shutdown operations.



10.13.2 Auxiliary equipment

ABB offers also a complete range of products which can be used with the main controller:

- power supplies: 2 x CP-C 24/10 or 24/20, CP-A RU, CP-A CM, CP-C MM + CP-B buffer module C 24/10; if the circuit-breaker is required to trip, use CP-C/S type
- interface and monitoring relays: CR-P, CR-M, R600, R600 opto
- analogue converters (CC-E I/I)
- serial data converters (ILPH)
- timers (CT-MFE)

10.13.3 Protections against overcurrents

For the protection of the controller against overcurrents miniature circuit-breakers of series S200 and S280UC can be used:

- S200 for AC voltage of the main circuit 230/400Vac
  - rated current from 0.5 to 63A
  - trip characteristics B, C, D, K, Z
- S280UC for DC voltage: 220Vdc (1 pole) and 440Vdc (2,3 and 4 poles)
  - rated current from 0.5 to 63A
  - trip characteristics B, K, Z

10.13.4 Surge Protective Devices (SPDs)

For the protection against indirect strike lightning Type 2 SPDs for three-phase circuits are available:

- OVR T2 3N 40 275 P TS (3P+N) for applications at 230/400V wit I_{max}=40kA and U_p=1.4kV

For the protection of direct current circuits at 24/48Vdc the following Type 2 SPDs can be used:

- OVR 2 15 75 s P TS with I_{max}=15kA and U_p=0.3/0.6kV

For the protections of the given circuits the following devices can be used:

- OVR TC xx V P with Imax=10kA, Uc=6/12/24/48/200V and possibility of connection with RJ11 and RJ45

10.13.5 Fuses and fuse holders

Main characteristics:

- AC-22B in compliance with Std. IEC 60947-3
- rated current: 20A and 32A
- rated voltage: 400V and 690V
- fuses type aM/gG

10.13.6 Modular sockets

Main characteristics:

- 16mm² terminals
- safety shutters
- Pozidriv® screws
- Options:
  - embedded fuse
  - coloured versions
  - embedded indicator light

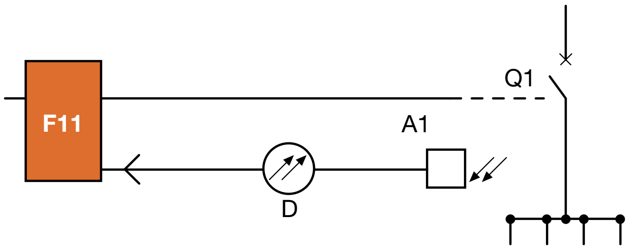
10.14 Hydraulic and cooling systems

Turbine systems are supported by hydraulic pumping and cooling systems that are used to transfer heat losses from internal equipment (such as generators, gearboxes, converters…) outside of the turbine.
Furthermore, hydraulic systems can be used in the safety circuits such as the braking systems.
ABB offer is similar to that for the blade pitch control system.

As actuators for pumping, motors from 2 to 8 poles, powers from 0.06 to 55kW are available for all the common voltages, whereas for the cooling systems 2,4 and 6 pole motors with powers from 0.75 to 7.5kW and two speed 2/4, 4/8 and 4/6 pole motors are available.

10.15 Arc Guard system

This system consists of an optical sensor inside the switchgear able to detect the light radiation caused by the electric arc; this sensor is connected to the TVOC-2 arc monitor, which in its turn is connected to the circuit-breaker.
Main advantages:
- increased protection degree in comparison with the protection systems based on overcurrents only
- increased safety for the personnel and improved productivity
- prevention from explosions due to short-circuit and circuit disconnection in a few milliseconds.



10.16 Insulation monitoring relays

The unearthed main circuit may be monitored to signal any possible insulation fault by using ABB monitoring relays.
They can be used to measure directly the insulation resistance in unearthed AC or DC systems with voltage levels up to 690Vac and 1000Vdc.

10.17 Connection to the grid

Large-sized turbines of MW order are usually connected to MV grids, whereas small-medium size turbines are generally connected to low voltage grids.
For medium voltage connection, ABB offer includes LV/MV transformers and switchboards equipped with MV circuit-breakers.

10.17.1 LV/MV transformers

ABB transformers have a compact design that allows the transformer to be installed through the tower door, without disassembly. They are designed to reduce losses and operate under severe environmental conditions characterized by high vibrations, salt, dust and also 100% of relative humidity.
Main characteristics:

- dry-type transformers up to 40 MVA and 72.5 kV
- liquid-filled transformers up to 40 MVA and 72.5 kV
- classes E2, C2, F1
- multiple forced cooling system solutions
- insulation temperature up to 180°C for dry-type transformers
- organic liquid cooling options
- suitable for onshore and offshore turbines.

10.17.2 Switchgear

ABB SafeWind is a compact switchgear solution suitable for all voltage levels. It provides protection and switching of wind power plants also in harsh operating environments.
It has both IEC as well as Chinese GB approvals and it is the only product approved by GB for 40.5kV. The slim design width (420mm) suitable for a 36kV circuit-breaker allows it to be installed through the tower opening.
Main characteristics:

- solutions available for 12kV, 24kV, 36kV and 40.5kV
- combination of standardized modules to ensure application flexibility
- circuit-breaker and switch-fuse protection
- advanced solutions available for electric arc protection
- suitable for onshore and offshore turbines.

For low voltage connection of small-medium sized turbines ABB offer includes:

- interface relays
- circuit-breakers
- switch-disconnectors
- contactors
- energy meters

10.17.3 CM-UFS interface relays

CM-UFS interface relays, which comply with both the ENEL Directive for the connection to the electrical distribution network as well as with Std. DIN V VDE V 0126-1-1, fully satisfy the safety requirements for installations and personnel in case of faults and malfunctioning of the public grid occurring during parallel connection.
Main characteristics:

- protection against minimum voltage
- protection against maximum voltage
- protection against minimum frequency
- protection against maximum frequency
- DIN-rail mounted, 22 mm overall dimensions
- adjustable connection of the neutral conductor
- 3 LEDs for the indication of the operating status
- power supply from the controller circuit
- measure of the r.m.s. value
- usable also for the control of single-phase plants
- 2 switchover contacts (SPDT)
- installation: DIN rail EN 60715 (35 mm) through SNAP DIN-rail adapters

CM-UFS.1 interface relay
For the markets where VDE German Standards are acknowledged:

- maximum voltage [Vn] > 115%
- minimum voltage [Vn] < 80%
- maximum frequency [Hz] > 50.2
- minimum frequency [Hz] < 47.5
- average value [Vn] 10 minutes 110÷115% adjustable

CM-UFS.2 interface relay
Specific for the Italian market, in compliance with the most recent ENEL Distribution specifications (edition 1st December 2008):

- maximum voltage [Vn] > 120%
- minimum voltage [Vn] < 80%
- maximum frequency [Hz] > 50.3 or 51 upon request of ENEL's personnel
- minimum frequency [Hz] < 49.7 or 49 upon request of ENEL's personnel.

10.17.4 Miniature circuit-breakers

These circuit-breakers with breaking capacity up to 50kA allow a reduction in the overall dimensions and weight of the switchgear where they are installed.
They find applications in a wide range of temperature and altitude.
A wide range of rated currents (from 10 to 125A) and several trip curves (characteristics B, C, D, K, Z) are available.

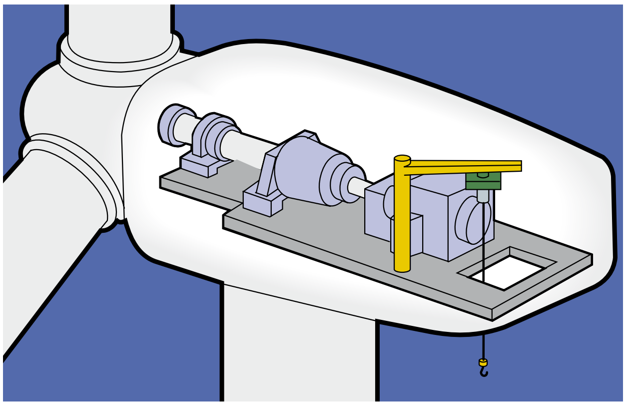
10.17.5 Delta Max energy meters

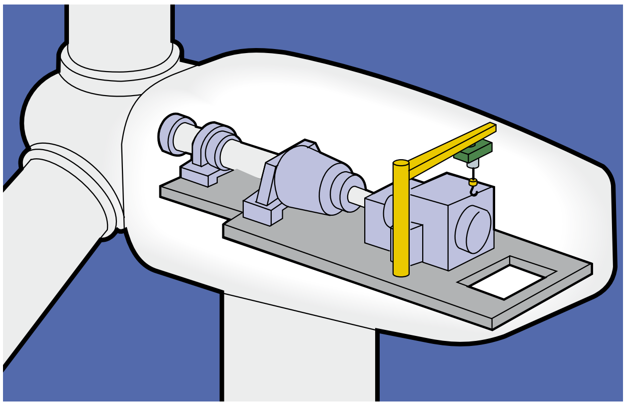
These energy meters allow:

- full control over energy generation and consumption
- possibility of long distance communication
- applications up to 500Vac

10.18 Auxiliary circuits

There are many small supporting systems in a turbine, from lift systems (lifts, hoists…. used for the ascent/descent of personnel or equipment to and from the nacelle) to fans and internal lightning systems.
ABB products are used also in such systems.





10.18.1 Miniature circuit-breakers type S500HV

Suitable for the protection of control circuits: computers and bus systems. They are high-performance three-phase circuit-breakers having the following main characteristics:

- breaking capacity 1.5kA
- trip characteristics K, 0.21A 1000Vac

10.18.2 Residual current circuit-breakers (RCCBs)

F500 residual current circuit-breakers are the only ones suitable to be used at 690Vac and have a built-in circuit-breaker for overcurrent protection, with trip characteristic C, rated current 10A and rated residual current 30 mA.

Also thermal magnetic residual current circuit-breakers series DS200 are available with the following main characteristics:

- rated current: from 6 to 32A
- breaking capacity: 4.5-6-10kA
- trip characteristics: B, C, K
- residual current sensitivity: from 10 to 300mA

ABB offers also residual current circuit-breakers of series F200 with the following main characteristics:

- rated current: from 16 to 125A
- type: AC, A, B
- residual current sensitivity: from 10 to 500mA

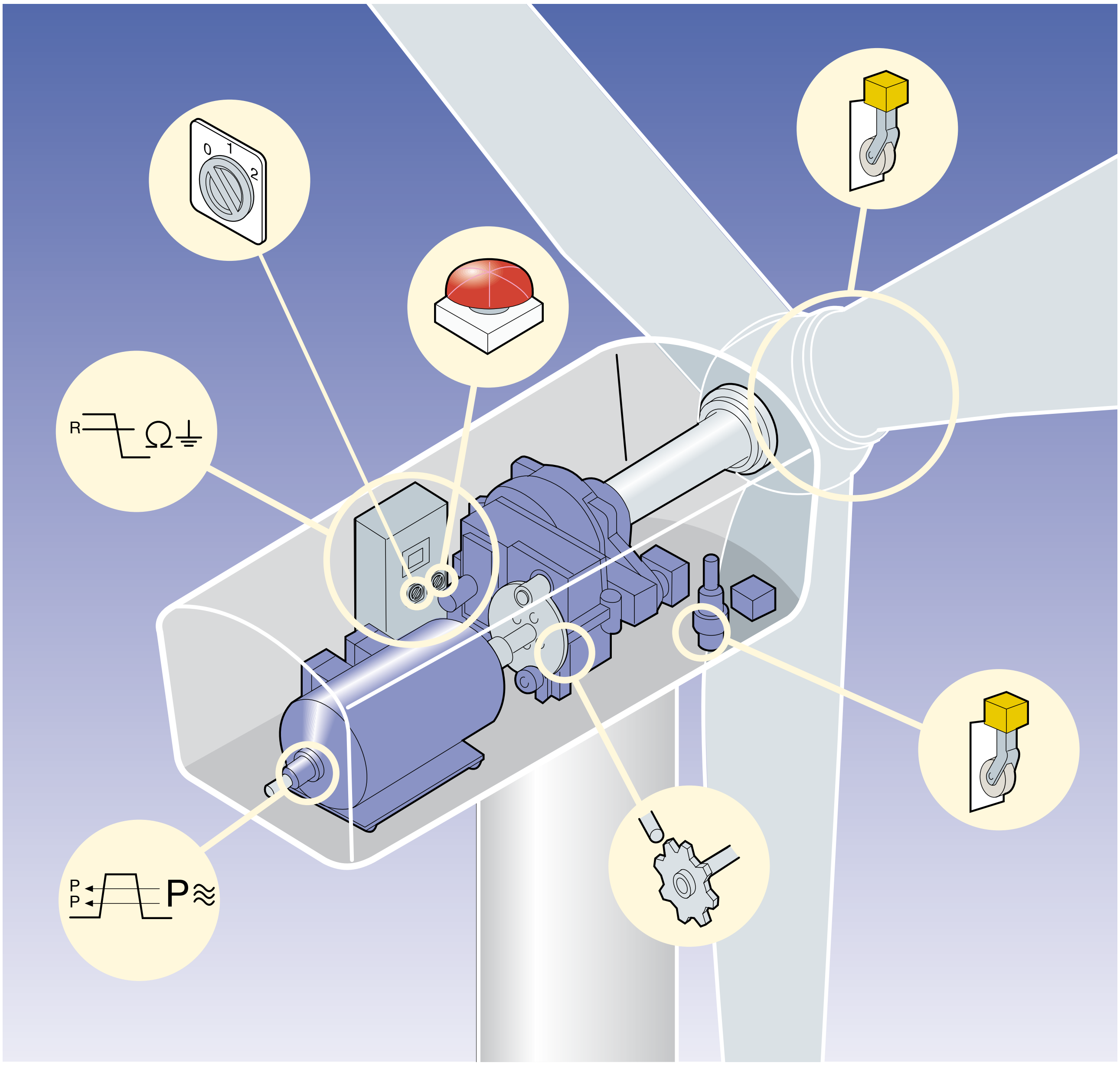
10.18.3 Temperature control

The temperature control system allows the inside temperature to be kept within limits suitable to guarantee the proper operation of the other devices, even when the turbines are exposed to harsh environmental conditions:

- temperature monitoring relay type CC-U/RTDR
- anti-condensation panel heater 300W/230V

10.18.4 Safety systems

ABB is developing a complete range of safety systems for the personnel and for the realiability of the wind turbine, in particular for machine safety (Jokab).



Annex A: Economic incentives and energy valorization

A.1 Obliged quotas and incentive mechanisms

The Law Decree 79/1999 has introduced the obligation, for the producers and importers of electrical energy derived from non-renewable sources, to inject into the national grid, as from 2002, a minimum amount of electrical energy produced from renewable sources through power plants put in service after 1/4/1999.
The amount (in percentage) is determined based on the energy produced and imported from non-renewable sources in the previous year, reduced by the electrical energy produced in co-generation, by the self-consumptions of the power plant and by exports, with 100 GWh exemption for operator. Initially, this amount had been fixed at 2%, but then the Law Decree 387/2003 has established an annual progressive increase of 0.35% in the three-year period 2004-2006. Moreover, the Financial Act 2008 has introduced a further 0.75% increase per year for the period 2007-2012. Subsequent Ministerial Decrees shall define the rises for the years after 2012 (Table A.1).

The subjects who have to fulfill the obligation can also do it by purchasing from other producers some certificates, called Green Certificates (CVs), attesting the production of the equivalent quota from renewable sources. Thus a market is created in which the demand is given by the subjects who have to fulfill the obligation and the offer is constituted by the producers of energy from renewable sources and being entitled to CVs.
As a matter of fact, to promote electrical energy production through renewable sources, the Law Decree 79/1999 has introduced the system of the Green Certificates. However, before the Financial Act dated 2008, such incentives were certificates granted in proportion to the energy produced for a period of 12 years and without distinction for the different renewable sources.
Revenues derived from the sale of CVs in a market where there is a certain obliged demand determine the incentive to the production of energy from renewable sources. In addition to the sale of the CVs, a further source of revenue derives from the valorization of the energy injected into the grid and becomes the only source at the end of the incentive period (Table A.2).

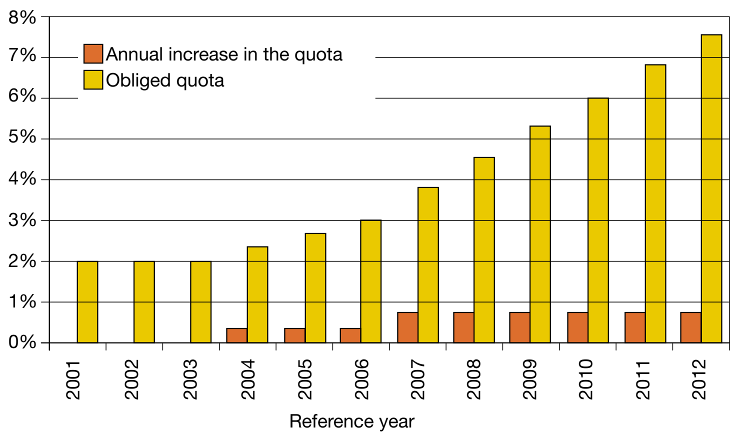
Table A.2 – Revenues for renewable source plants entered service by 31/12/2007

Energy valorization	Incentive	Energy valorization
First 12 years	Sale of the CVs assigned according to the energy produced (without distinction for the different sources)	Self-consumption and Market prices or Dedicated withdrawal[1] or Net metering[2]
Afterwards	–	

[1] With power not higher than 10 MVA or with any power in case of renewable sources non-programmable
[2] With power not higher than 20 kW

Table A.1 – Annual increase in the "Obliged quota", introduced by the Law Decree 79/1999

Reference year	Obliged quota	Fulfilment year
2001	2%	2002
2002	2%	2003
2003	2%	2004
2004	2.35%	2005
2005	2.70%	2006
2006	3.05%	2007
2007	3.80%	2008
2008	4.55%	2009
2009	5.30%	2010
2010	6.05%	2011
2011	6.80%	2012
2012	7.55%	2013



[1] *The importers of electrical energy can ask for exemption from the obligation for the amount of energy produced from renewable sources and certified accordingly.*

[2] *Initially CVs were granted for a period of 8 years. Afterwards the Law Decree 152/2006 extended the period to 12 years.*

The Financial Act dated 2008 has introduced some modifications to the above described mechanism for the plants which entered service after 31/12/2007. The main amendments regarding incentives through CVs are two:

- the incentive period has been extended for 15 years
- the number of CVs granted has been differentiated according to the renewable source.

Besides, for smaller plants a new incentive system has been introduced as an alternative to the system of the CVs. In fact, in case of small plants, the right is given to opt for tariffs of withdrawal for the energy injected into the grid, paid out for a period of 15 years and differentiated according to the renewable sources.

Such tariffs are called all-inclusive, since they include both the incentive component for the energy produced, as well as the sale component for the energy injected into the grid (Table A.3).

Besides, according to the Financial Act dated 2008, as further modified by the Law Decree 99/2009, the generation of electrical energy from wind power plants entered service after 30/06/2009 is entitled to the CVs or to the all-inclusive tariffs provided that such plants do not benefit from other public national, regional, local or Community incentives as Feed-In Tariff granted after 31/12/2007.

A.2 Green Certificates

They are certificates which prove the production of energy from renewable sources. Initially their size was fixed in 100MWh, but it has progressively been reduced to 1MWh with the Financial Act of 2008. Green certificates are released according to the net energy generated by the plant (E_a)[3], which however is not always the reference term for the definition of the number of CVs, since there are different types of intervention on plants (new construction, development, total or partial restructuration…[4]) which entitle to incentives of all or of part of the net generated energy.

As regards the plants put in service before 31/12/2007, the energy corresponding to the number of recognized CVs (E_{cv}) coincides with the energy recognized as incentivable (E_i) for the whole incentive period (12 years), that is:

$E_{cv}=E_i$ with E_i as function of the intervention class and of E_a

The Financial Act dated 2008 has introduced a difference in the incentive entity for the plants put in service from 01/01/2008, based not only on the type of intervention carried out and on the produced net energy, but also on the type of renewable source.

[3] It is the energy measured at the output of the generation set, decreased by the energy absorbed by the auxiliary services, by the transformer losses and by the line losses up to the point of parallel with the grid.

[4] For a detailed description of the different intervention classes to which a different formula corresponds, which links the energy recognized as incentivable (E) to the net produced energy (E_a), reference shall be made to the Guide to the incentives for the production of electrical energy from renewable sources published by GSE.

Table A.3 – Revenues for renewable source plants entered service after 31/12/2007

	A) Any size of power		**B) For smaller plants only (as an alternative to scheme A)**	
Operation period	**Incentive**	**Energy valorization**	**Incentive**	**Energy valorization**
First 15 years	Sale of the CVs assigned according to the energy produced (distinctly for the different sources)	Self-consumption and Free market or Dedicated withdrawal[2] or Net metering[3]	All-inclusive tariffs for the withdrawal of the energy injected into the grid (separate according to the different sources)	
Afterwards	–		–	Self-consumption and Free market or Dedicated withdrawal or Net metering[3]

[1] With power not higher than 1MW (200 kW for onshore wind power plants)
[2] With power not higher than 10 MVA or with any power in case of renewable sources non-programmable.
[3] With power not higher than 200 kW.

Therefore the CVs are assigned by multiplying the incentivable energy (E_i) by a coefficient K depending on the renewable source used:

$$E_{cv}=K \cdot E_i$$

The coefficient K is 1 for onshore wind power plants and 1.5 for offshore wind power plants.

The Green Certificates have a validity of three years, that is the certificates issued in a given year can be used to fulfill the obligation set by the Law Decree 79/1999 relevant to the two following years.

The economic valorization of the CVs constitutes the incentive for the generation of electric power from renewable energy sources, except for photovoltaics, for which incentive is given by Feed-In-Tariffs. Defining P_{cv} the price [€/MWh] of the CVs sold, the value of the incentive I_{cv} [€] is expressed by:

$$I_{cv} = P_{cv} \cdot E_{cv}$$

The price of the CVs is defined according to the supply and demand law. Transactions of the CVs can be carried out on the market organized by GME (Gestore dei Mercati Energetici - Power Exchange Market Administrator) or under bilateral contracts. The Financial Act 2008 has introduced a new modality for the calculation of the offer price of the CVs of GSE: as from 2008 they are placed on the market at a price equal to the difference between 180 €/MWh and the annual average value of the transfer price of electrical energy registered in the previous year[5].
The application of this new calculation modality has resulted in offer prices for the CVs of GSE equal to 112.88 €/MWh for the year 2008, 88.66 €/MWh for the year 2009 and 112.82 €/MWh for the year 2010.
The price of the CVs of GSE represents the maximum price for the whole market. While up to 2005, due to the poor offer, the certificates were exchanged at a price near to that of GSE, starting from 2006 the CVs' offer of qualified producers has exceeded the corresponding demand necessary to cover the obligation; such situation has caused a reduction in the sale prices of the CVs. To avoid the excessive loss of value of the CVs under conditions of excess supply, two standard provisions were introduced.
The first one, which is a part of the Financial Act 2008, provides that, upon request of the producers, GSE withdraws the CVs expiring in the year at a price equal to the average price registered in the previous year, relevant to the transactions of all the CVs, independently of the year to which they refer, carried out both in GME's regulated market as well as under bilateral contracts.
The second provision, introduced by the Ministerial Decree 18/12/2008, provides that, in the three-year period 2009-2011, upon request of the holders, GSE withdraws the CVs issued for the production relevant to the years up to 2010. The withdrawal price of the above mentioned certificates is equal to the average market price in the three-year period before the year when the withdrawal request is put forward. In 2010 the withdrawal price of the CVs from GSE, in compliance with such provision, is equal to 88.91 €/MWh (VAT excluded), corresponding to the average weighed price of the transactions of all the certificates registered by GME in the three-year period 2007-2009.
The CVs can be required:

- effective, according to the net energy really generated by the plant in the year before the year of issue
- planned, according to the expected net production capacity of the plant.

GSE, after a verification of the reliability of the data given by the producers, issues effective the due green certificates within 30 days from the receipt of the request, rounding off the net energy production (MWh) using a commercial criterion.
If a plant, for which planned green certificates have been issued, cannot really produce energy in an amount equal to or higher than the corresponding value of the CVs obtained and the producer is not in a position to return the exceeding ones, GSE compensates this difference by withholding the green certificates relevant to the energy produced for the same year by other plants owned by the same producer. If in the reference year there is not a sufficient number of certificates, GSE can compensate also with the production of the year following that in which the debt has formed. If also this further possibility of compensation is missing, GSE encashes the bank guarantee in its favor.
In the opposite case instead, in which the effective production of the plant exceeds the expected production capacity, at the act of compensation, GSE issues in the producer's favor, the remaining owing certificates.
Starting from 2008, by the month of June each year, upon request of the producer, GSE withdraws the CVs expiring in that year exceeding those necessary to fulfill the obligation. To this purpose, the annual average price is that relevant to the transactions of all the CVs, independently of the reference year, exchanged in the previous year in GME's regulated market or under bilateral contracts.
Moreover, to guarantee a gradual transition from the old incentive mechanisms to the new ones and in order not to penalize the investments already started, in the three-year period 2009-2011, by June, GSE shall withdraw, upon holders' request, the green certificates issued for the production relevant to the years 2006-2010. The withdrawal price is equal to the average market price of the previous three-year period.
Legislative Decree of 3rd March 2011 No. 28 provides that GSE withdraws yearly the CVs issued for the energy production relevant to the years from 2011 to 2015, if any exceeding those necessary to comply with the obligation quota. The withdrawal price is equal to 78% of the price defined in Financial Act 2008.

[5] *Such price is defined by AEEG, every year by 31st January.*

A.3 All-inclusive tariffs

The Financial Act of 2008 has introduced a new incentive system (afterwards regulated by Ministerial Decree 18-12-2008 and by Resolution AEEG ARG/elt 1/09), which is available as an alternative to the Green Certificates, for renewable source plants (with the exception of photovoltaic technique) entered service after 31-12-2007 and with rated power not exceeding 200kW for wind power plants.
To such plants all-inclusive tariffs are granted for a 15-year period. Up to the end of the incentive period, all-inclusive tariffs represent the only remuneration source; at the end of such period, however, a possibility of valorization of the generated energy persists (sale of the energy injected into the grid or net metering).
Moreover, while CVs are recognized based on the net energy produced E_a and therefore they reward also self-consumed energy, all-inclusive tariffs are paid out only on the basis of the amount of energy fed into the grid E_r[6]. Also for all-inclusive tariffs, on the basis of the type of intervention carried out on the plant, the size of the incentive changes. In particular, the net energy injected into the grid (E_r) changes, which can receive incentives based on the type of intervention: it is according to the amount of energy E_i that tariffs are paid out. For wind power plants with size smaller than 200kW, from the Table enclosed to Financial Act 2008, as amended by Law 99 dated 23/07/2009, it results an incentive all-inclusive tariff of 300 €/kWh.
Legislative Decree of 3rd March 2011 No. 28 provides that the all-inclusive tariffs remain constant for the whole validity period and keep to the above mentioned value for all the plants entering service within 31st December 2012.
The right of option between green certificates and all-inclusive tariffs is exercised through a qualification request for the plant[7] addressed to GSE. Prior to the end of the incentive period, only one shift is allowed from an incentive system to the other one; in case of shifting, the period of duration granted for the new incentive system is reduced by the time period already enjoyed with the previous system.

[6] *If a wind power plant draws from the grid the electric power necessary for the supply of auxiliary services, the energy subject to all-inclusive tariff incentive is not the total amount of energy actually fed into the grid, but this value deducted the above mentioned withdrawals.*

[7] *The qualification of renewable source plants (IAFR) attests the possession of the requisites foreseen by the rules and entitling to incentives.*

A.4 Valorization of the energy fed into the grid

A.4.1 Dedicated withdrawal

The dedicated withdrawal from GSE represents a simplified mode at producers' disposal to sell on the market the energy fed into the grid, as an alternative to bilateral contracts or to sale on stock. Dedicated withdrawal is available to wind power plants of any rated power. To access the system, the producer recognizes to GSE a money consideration to make for the administrative costs equal to 0.5% of the equivalent value of the pay for the withdrawn energy, up to the maximum amount of €3500 per year per plant.
For a plant with rated active power higher than 50kW the producer grants to GSE a further compensation for the metering accounting service currently equal to 3.72 Euro/month for plant.
For the power generation plants connected in low or medium voltage, GSE grants to the producer a compensation for electrical energy transmission and distribution services, which is currently equal to 0.00388 €/kWh.
For the electrical energy fed into the grid, GSE recognizes to the producer, for each hour, the market price referred to the zone where the plant is positioned.
For the plants with rated active power up to 1 MW, minimum guaranteed prices have been defined (Resolution AEEG 280/2007) and they are periodically updated by AEEG. The minimum guaranteed prices are recognized by GSE for the first 2 million kWh of electrical energy injected into the grid on annual basis. In the case in which, at the end of every solar year, valorization at the minimum guaranteed prices should result lower than that achievable at market prices, GSE shall recognize to the producer the relevant adjustment.
The values of the minimum guaranteed prices updated for 2010 are the following:

- up to 500.000 kWh per year, 101.8 €/MWh
- over 500.000 kWh up to 1,000,000 kWh per year, 85.8 €/MWh
- over 1,000.000 kWh up to 2,000,000 kWh per year, 75.0 €/MWh.

Dedicated withdrawal is an "indirect" sale of energy, advisable for the plants feeding-in a quantity of power exceeding their own requirements.

Moreover it can be noticed the general higher return of the minimum guaranteed prices in comparison with the market prices.
In short, dedicated withdrawal is more easily managed than the sale of energy on stock market.

A.4.2 Net Metering

Net Metering is regulated on a financial basis by GSE (Gestore Servizi Energetici - Electrical Utilities Administrator) as a form of contribution linked to the valorization at market price of the energy exchanged with the grid. Net Metering is available to wind power plants up to 20 kW if entered service before 31/12/2007 and up to 200 kW if entered service after that date.
In this case GSE recognizes a contribution to the user; this contribution is a sort of refund for the fees paid for the withdrawal of electrical energy from the grid. To calculate this contribution, determined on solar annual basis, the following items are taken into consideration:
- the amount of electrical energy exchanged with the grid (the minimum amount between the energy fed into and withdrawn from the grid in the reference period)
- the equivalent value in Euros of the electrical energy injected into the grid
- the value in Euros of the withdrawal fee for the supply of the energy from the grid, divided into energy fee and services fee (transport and dispatching of the electrical energy).

In particular, the Net Metering contribution paid by GSE to the user consists of:
- an energy quota, that is the recognition of the minimum value between the energy fee and the equivalent value in Euros of the electrical energy injected into the grid
- a services quota, that is the refund of the services fee only for the energy exchanged with the grid.

If the equivalent value of the energy fed into the grid is higher than the energy fee, the settlement is “banked” as a credit for the user, who can either use it as a compensation for the energy fee in the subsequent years or ask for the payment.
Net metering contribution is calculated by GSE planned on a three-month basis and it is paid out when its amount exceeds the minimum threshold of 100 Euros. On a year basis, the balance for the contribution accrued in the year is calculated and paid, without applying any minimum threshold for the payment.
Besides, GSE grants a contribution equal to 50 Euros for every kW of power of the plant within the 30 days following the end of the three-month period of the drawing up of the Net Metering agreement. The above mentioned contribution is gradually reabsorbed with the subsequent down payments and adjustments.
Generally speaking, Net Metering is favorable when, yearly, the valorization of the electrical energy injected into the grid is totally compensated with the energy fee; besides, for the totality of the energy exchanged with the grid, the charges for the use of the grid are reimbursed by GSE to the user of Net Metering and exclusively to the users who are also owners of plants supplied by renewable sources also the general system fees are reimbursed.

Annex B: Connection to the grid and measure of the energy

As regards medium-large sized wind power plants connected to medium voltage or high voltage grids, here below are some information and indications about connection criteria. In particular, for the connection to the medium voltage distribution networks of the turbines the indications in Chapter 4 of the Technical Application Paper No.10 "*Photovoltaic plants*" are valid, together with some additional suggestions given here.

B.1 Connection to the MV grid

The total generation power which can be connected to the MV grid referred to each Primary Substation (HV/MV) without modifying it is limited by the likelihood that reversals of the power flow with respect to the normal passage from high to medium voltage occur. If this passage results to be reversed for a time exceeding by 5% the total annual operating time, it is necessary to equip the Primary Substation and its relevant HV lines with protection and control devices suitable to the bidirectional power flow.
As regards MV/lv transformation, three-phase transformers with delta connection on the primary winding must be used or, for particular requirements, with different connections subject to agreement of the Distributor.

B.1.1 Limits for the transformer size

The Distributor communicates the maximum power limit of the single transformer and/or of more transformers in parallel on the same lv busbar installable by the Consumer to avoid tripping of the protective devices on the MV line supplying the plant in case of short-circuit on the lv busbars. Such limit shall not be generally lower than 2000kVA (20kV grids) and 1600kVA (15kV grids). Lower limits can be defined by the Distributor in case of particular structure of the existing MV grid. The Consumer can install larger size transformers provided that, owing to the impedances positioned between the delivery point and the lv side of the transformers, the fault current at the secondary winding of the transformer is limited to a value equivalent to that obtained by considering only the limitation due to the sizes prescribed for the above mentioned transformers. In the case where the Consumer has a plant not compatible with the limitations above, the connection through MV single feeders can be taken into consideration, by setting the protections ad hoc.

B.1.2 Limits on the contemporary connection of transformers

To limit the inrush current, the Consumer cannot install transformers for a total power exceeding three times the above mentioned limit values for each voltage level, even with separated lv busbars. In the contrary case, the plant must be equipped with suitable devices to prevent the contemporary energization of the transformers which cause overcoming the given limitations. Such devices shall intervene in case of lack of voltage for more than 5s and shall provide for the reconnection of the transformers according to total powers not exceeding the given limits, with reconnection times at intervals of at least 1s.

B.1.3 General Device (DG)

Generally speaking, to command opening of the General Device (DG) through the General Protection (PG) an undervoltage release shall be used or, as an alternative, a shunt opening release, provided that the PG is equipped with a suitable control and recording system to allow any possible verification (data logger). Table B.1 shows the minimum settings for the different protection functions of the PG for Consumers with powers not exceeding 3MVA. For higher powers, the Consumer can agree with the Distributor upon different settings, as a function of the service requirements and of the characteristics of the distribution grid.

B.1.4 Interface protection device (PDI)

In addition to the protections listed and described in the Technical Application Paper QT10 "Photovoltaic Plants", for the plants able to support the grid voltage (synchronous generators, self-excited asynchronous generators, inverters operating as voltage generators) with total power ≥400kVA, upon Distributor's request, the maximum homopolar voltage V_0 protection is provided on the MV side with 15% value and with 25s intentional delay (CEI 0-16 Interpretation Sheets) and it is necessary to provide for a support in case of failure of opening of the interface device.
This support function consists in transmitting the trip command from the interface release to another tripping device; this protection function is formed by a circuit, depending on the closed position of the DDI and acts on the general device or on a generator device, with a maximum delay of 1s. The timer is activated by the trip circuit of the PDI.
A protection against the network loss is being studied, to be agreed upon between the Distributor and the Consumer as a function of the characteristics of the grid to which the generation plant is connected.
If required by the grid conditions (e.g. for output powers exceeding 1MVA), the Distributor can require the installation of a remote trip system to guarantee the opening of the Interface Device in case of tripping failure of the protections.

For generation powers approximately higher than 3MVA, the Consumer is connected to a MV antenna line; besides, as an alternative to the remote trip, a logic can be implemented in the Primary Substation to which the MV line is connected to make the feeder circuit-breaker open in case of tripping failure of the protections of the Distributor, when the defined conditions occur (for example loss of HV grid, HV/MV transformer protection tripping).
Both the remote trip as well as the Primary Substation logic are realized and kept in service by the Distributor grid and in both cases the installation of the possible protection in the event of grid loss is not necessary.

B.2 Connection to the HV grid

The continuous growth of wind energy production is highlighting some problems regarding the infrastructure of the grid. In particular, some high voltage lines have shown a transport capability insufficient to dispatch all the energy produced (at high wind regimes) by the wind power plants currently connected to the distribution grid. This has the consequence of grid congestions which result in the intervention of the Electrical Utilities Administrator (GSE) to reduce the power injected from such plants (lack of production which can also exceed 20%). The Authority has recently provided to reform the compensation system for the potentially available but not produced energy due to the limitations, entrusting GSE with the task of defining a system for the assessment of the lack of production. However, it is necessary to boost the grid so that the situation does not get worse further to the installation of new power plants.
For the connection to the HV grid, the plants shall satisfy the following requirements.

B.2.1 Protections against external faults

The wind power plants connected to the public networks with rated voltage higher than 30kV shall be equipped with protections sensitive to the external faults; their tripping shall be coordinated with the other network protections and their settings are established by the Network Administrator (CEI 11-32 V3).
The protections against external faults command the opening of the main circuit-breaker/s and, in case of failure of opening, the generator circuit-breakers or other interposed circuit-breakers properly coordinated to guarantee selectivity shall trip as support.
The protections which operate the main circuit-breaker/s are:

- Maximum and Minimum Frequency
- Maximum and Minimum Voltage HV side
- Maximum Homopolar Voltage HV side

Instead, the protections which command the generator circuit-breakers are:

- Maximum and Minimum Frequency
- Maximum and Minimum Voltage.

Table B1

		SETTINGS		
		First threshold	Second threshold	Third threshold
PROTECTION DEVICES	Maximum phase[1] I 50 and 51	Optional activation Value and tripping time to be agreed upon with the Distributor	Value: 250A Fault extinction time: 500ms	Value: 600A Fault extinction time: 120ms
	Maximum homopolar I (neutral isolated) 51N	Only if protection 67N is not present Value: 2A[2] Fault extinction time: 170ms	Only if protection 67N is present Value: 140% I_0[3] Fault extinction time: 170ms	-
	Maximum homopolar I (neutral compensated)[4] 51N	Only if protection 67N is not present Value: 2A[2] Fault extinction time: 450ms	Always present, also with 67N Value: 140%I_0[5] Fault extinction time: 170ms	-
	Earth fault directional[1] 67N	With neutral isolated I_0: 2A U_0: 2V Tripping range (I_0 delay with respect to U_0): 60°-120° Extinction time: 170ms	With neutral compensated I_0: 2A U_0: 5V Tripping range (I_0 delay with respect to U_0): 60°-250° Extinction time: 450ms	-

[1] *Values refered to 15-20kV voltages; analogous values must be defined for other voltage values.*
[2] *Lower values are possible, however not lower than 1A, in case of grids having a particularly limited extension..*
[3] *Value of the single-phase fault current to earth given by the Distributor.*
[4] *For Consumers who do not need 67N, only the first threshold (with 2A value and 170ms fault extinction time) can be used.*
[5] *Typically 70A for grids at 20kV and 56A for grids at 15kV.*

B.2.2 Protections against internal faults

Internal faults in wind power plants, which could affect other plants connected to the grid, must be eliminated in a quick and selective way. The settings of the protections are agreed upon with the Network Administrator (CEI 11-32 V3).

As for the HV side of the MV/HV transformer, the protections which command the circuit-breaker of the relevant transformer are:

- Maximum Current
- Transformer Residual Current

On the contrary, for the MV side, the protections must be suitable both against the faults between phases as well as the faults phase-to-earth.

B.2.3 Performances required

The performances which can be required to a wind power plant according to its installation site and with the purpose of maintaining the reliability and safety of the network are:

- limitation of the generated disturbances
- gradual injection of power into the grid
- disconnection or reduction of the power injected into the grid
- immunity from voltage reductions;
- control of the active power;
- control of the reactive power.

B.2.3.1 Limitation of the generated disturbance

The Owner of the wind power plant is bound to install machines and components resulting in values of harmonic emissions and voltage dissymmetry positively considered during designing by the Administrator of the connection network.

B.2.3.2 Gradual insertion of the power to be injected into the network

The positive gradient of delivery of the instantaneous efficient power shall not exceed 20% of the efficient power per minute, or shall not exceed other gradients agreed upon with the Network Administrator; such gradient must be complied with during the start-up of the wind power plant compatibly with the wind source. The wind turbines must not be put into service if the network frequency exceeds 50.3 Hz.

B.2.3.3 Disconnection or reduction of the power injected into the network

The wind power plant shall be equipped with one of the following systems:

- production control system, able to modify, both automatically as well as manually, the power injected into the grid upon remote control of the remote control centers of the Owner of the plant
- automatic remote disconnection system, able to operate instantaneous disconnection – total or partial – of the wind power plant from the grid upon remote control also from a subject different from the Owner.

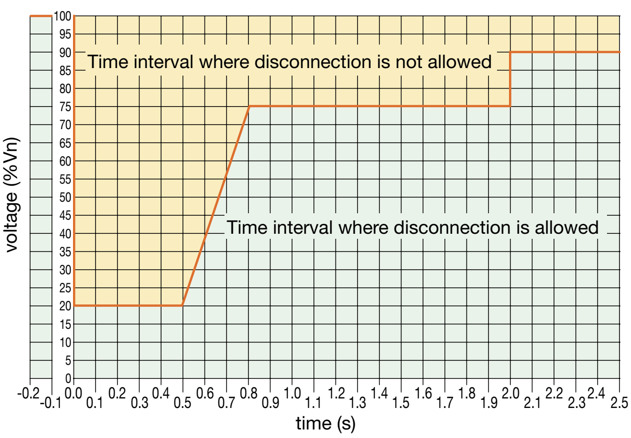
B.2.3.4 Immunity from voltage reductions

Wind power plants must be able to maintain the connection to the grid in case of faults external to the plant properly cleared by the network protections.

The values of duration and the value of voltage reduction, typical for the network faults, to be tolerated by the wind power plant at the generator terminals without disconnection are reported in Figure B.1 (CEI 11-32 V3).

A reduction of the instantaneous efficient power injected into the grid is accepted during the fault clearance time, but, when the standard operating conditions restore, the instantaneous efficient power injected into the grid must get back to a value close to that before the fault occurrence, compatibly with the present wind conditions.

Figure B1



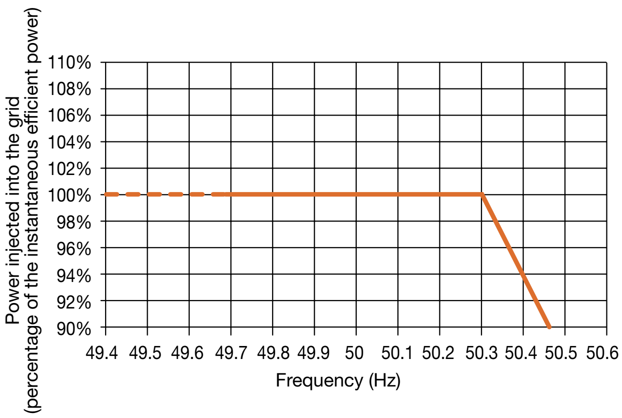
[6] *The instantaneous efficient power of a wind power plant is the sum of the instantaneous efficient powers, expressed in MW, of the single wind turbines, that is the sum of the active powers delivered by the wind turbines as a function of the "instantaneous" meteo conditions.*

B.2.3.5 Control of the active power

The wind power plant must be equipped with an automatic control system which, depending on the real capacity of the available wind, allows (Figure B.2):

- injection into the grid of the instantaneous efficient power for frequencies from 47.5 to 50.3 Hz;
- reduction of the instantaneous efficient power as a function of the positive frequency error, with a droop ranging from 2% and 5%, for frequencies higher than 50.3 Hz and up to a value of 51.5 Hz.

Figure B.2



B.2.3.6 Control of the reactive power

The control system of the single turbine regulates the reactive power at the terminals of the generator so that the power factor is adjustable from 0.95 in advance and 0.95 delayed. The power factor can be kept fixed to a value chosen and agreed upon between Network Administrator and Owner.

[7] *The automatic system can also disconnect in sequence the different generators, separately or in groups.*

B.3 Measure of energy

B.3.1 Measure of the produced energy

According to Resolution AEEG 88/2007 (in addition to Resolution AEEG 150/2008) "Disposizioni in materia di misura dell'energia elettrica prodotta da impianti di generazione" ("Provisions regarding the measure of the electrical energy produced by power generation plants") responsible for the measure of the electrical energy produced by installations with rated power not higher than 20 kW is the Network Administrator, whereas for the installations with power exceeding 20 kW responsible is the producer, who has the authority to apply to the Network Administrator, but always keeping the responsibility for such service.
Positioning of meters is agreed upon with the energy producer based on functional choices and in compliance with the following requirements for wind power plants:

- location as near as possible to the terminals of the generator and however on the load side of the auxiliary service systems;
- inside the property of the energy producer or on the boundary of such property as specified by the producer;
- guaranteeing to the Network Administrator the proper performance of his own tasks;
- being equipped with suitable antifraud devices;
- ability to detect energy production on hour basis;
- being equipped with devices for data query and acquisition via remote of measures from the Network Administrator.

B.3.2 Measure of the energy injected and drawn from the grid

The "Integrated Text of the provisions of the Authority for electrical energy and gas as regards supply of the transmission, distribution and measure of the electrical energy services – TIT" (Resolution AEEG 348/2007) defines the responsibility of the measurement service[8] as follows:

- as regards the injection points[9], responsible for the installation and maintenance of the meters is the subject Owner of the plant; as regards the withdrawal points, responsible is the Distributor
- as regards the injection points, responsible for the activities of collection, recording and validation of measures is the Network Administrator; as regards the withdrawal points, responsible is the Distributor.

[8] *The measurement service consists in the activities of installation and maintenance of the equipment and of collection, recording and validation of measurements.*
[9] *A connection point is considered an injection point when it is devoted to a production plant and the energy withdrawals from the grid are exclusively oriented to energy production; in all the other cases the connection point is considered as a withdrawal point.*

In case of power generation plants positioned at a connection point through which energy is withdrawn by users different from the auxiliary services of the power plant itself, a single bidirectional meter must be installed at this connection point by the competent Distributor.
The Distributor himself shall be responsible for the maintenance of the meter, as well as for collection, validation and recording of the measurements of the electrical energy injected and withdrawn.

The meters relevant to power generation plants connected to very high, high and medium voltage must:
- allow survey and recording, at each hour, of the withdrawn energy and of the active and reactive electric power injected and withdrawn at the injection and withdrawal points
- be equipped with an automatic system to signal any possible irregularity in the operation
- allow access to surveys and records for the Owner of the site where the meter is installed
- be prepared, upon request of the Owner of the site where the meters are installed and paid by him, for the installation of devices to monitor electric power injections and withdrawals.

In case of connection points used solely to inject electrical energy and to withdraw the electrical energy necessary to supply the auxiliary services (“pure” injection points), the energy producers are obliged to install the bidirectional meters prescribed by Resolution AEEG 292/2006. In the contrary case, this obligation falls on the Distributor.

Annex C: Earthing systems

C.1 Dimensioning

As regards the wind turbines connected to the MV grid, to the purpose of dimensioning the earthing system, the Distributor communicates to the Consumer the value of the single-phase ground fault current (I_f) and the fault clearance time.
When designing the ground electrode, it is possible to take into consideration the value of the earth current (I_e) reduced with respect to the earth fault current (I_f) due to the effect of the metal shield of the cables (CEI 11-1): as conservative hypothesis, it is possible to assume a reduction factor equal to 0.7 (CEI 0-16).
In case of networks with isolated neutral, the current I_f communicated to the Consumer must be increased by 10% by the Distributor with respect to the current value calculated or measured with a minimum of 20A rise. However, the earthing arrangement must be dimensioned to be suitable for both the following conditions (CEI 0-16):

- earth fault current and fault clearance time communicated by the Distributor
- ground fault current of 40A at 15kV (50A at 20kV) and fault clearance time exceeding 10s.

When dimensioning the earthing system according to the touch voltages[1], reference is made to the voltage limits U_{Tp} reported in Figure C.1[2] and for the relevant fault duration the settings of the protective devices must be taken into account. Such values of admissible touch voltages are considered as satisfied if the total earth voltage value, measured or calculated, does not exceed of 50% the touch voltage of Figure C.1 and the values calculated in Table C.1 (CEI 11-1).

Figure C.1

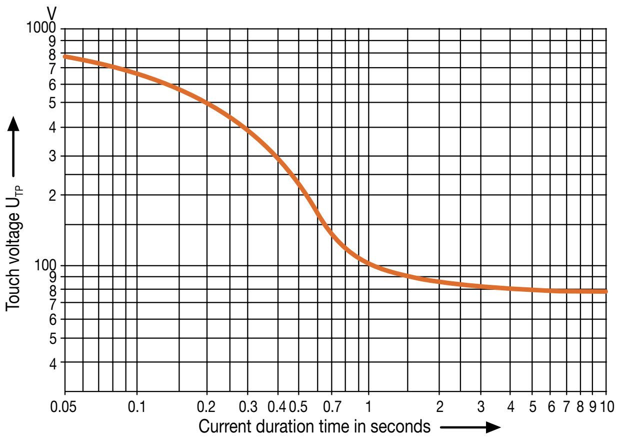


Table C.1

Fault duration t_f [s]	Acceptable touch voltage U_{Tp} [V]
10	80
1.1	100
0.72	125
0.64	150
0.49	220
0.39	300
0.29	400
0.20	500
0.14	600
0.08	700
0.04	800

The low voltage neutral conductor can be grounded on the earthing system of MV plants to constitute an earthing arrangement in common, provided that during earth faults in the LV part of a MV plant dangerous touch voltages do not occur: to this purpose it is sufficient that the total voltage U_e of the common earthing system does not exceed - in TN systems – the touch voltage limit value U_{Tp} (CEI 11-1).

C.2 Practical example

Values communicated by the Network Administrator:

- ground fault current I_f=50A;
- fault duration t_f≥10s.

From Table C.1, it results U_{Tp}=80V.
According to the prescriptions of the Standard CEI 0-16, it is possible to assume a current $I_e = 0.7 \cdot I_f = 0.7 \cdot 50 = 35A$.
Therefore the limit value of the ground resistance is equal to:

$$R_e = \frac{U_{Tp}}{I_e} = \frac{80}{35} = 2.3\Omega \qquad [C.1]$$

Supposing to have a meshed ground grid, for the calculation of the ground resistance (CEI 11-1 Annex K) the following formula can be used:

$$R_e = \frac{\rho_e}{2D} \qquad [C.2]$$

where:

- ρ_e is the ground resistivity [Ωm];
- D is the diameter of a circle with an area equal to that of the meshed ground electrode [m].

As a consequence, in the case under consideration, with a R_e=2.3Ω and assuming to have a clayey ground (ρ_e= 200 Ωm) the diameter of the meshed grid shall be:

$$D = \frac{\rho_e}{2R_e} = \frac{200}{2 \cdot 2.3} = 43.5m \qquad [C.3]$$

If the meshed grid is made using braided bare copper ground electrodes, the minimum cross-section is 25 mm² (CEI 11-1 Annex A).

[1] *Touch voltages are generally higher than step voltages and since the latter have higher acceptable values (from foot to foot), it can be supposed that no dangerous voltages usually occur.*

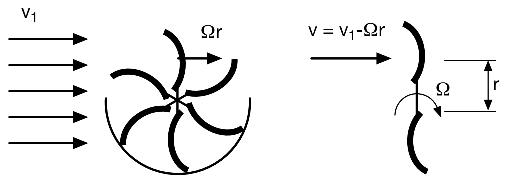
[2] *The curve represents the voltage which can be applied to the human body, from bare hand to bare feet (at 1m distance from the vertical projection of the mass) for the indicated time only. If the duration of the earth fault current exceeds what is reported on the graph, 75V can be considered as limit value of the touch voltage.*

Annex D: Drag type turbines vs lift type turbines

In the drag turbines the motive force which makes the axis of the turbine rotate is the resulting aerodynamic drag force F_r, which is a function of the resistance coefficient C_b and of the relative wind speed $v = v_1 - v_t = v_1 - \Omega \cdot r$ with respect to the rotor surface (see Figure D.1) according to the following relation [3.32]:

$$F_r = \frac{1}{2} \cdot C_b \cdot A \cdot \rho \cdot v^2 = \frac{1}{2} \cdot C_b \cdot A \cdot \rho \cdot (v_1 - \Omega \cdot r)^2 \quad \text{[D.1]}$$

Figure D.1

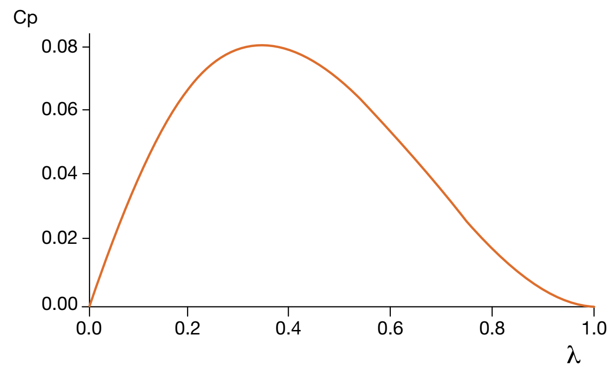


The mechanical power extracted by the wind and transmitted to the rotor is the product of the total resistance force F_r for the equivalent peripheral speed of the rotor surface v_t at the application point of the force:

$$P = F_r \cdot v_t = \frac{1}{2} \cdot C_b \cdot A \cdot \rho \cdot (v_1 - \Omega \cdot r)^2 \cdot \Omega \cdot r$$
$$= \frac{1}{2} \left[C_b \cdot \lambda \cdot (1-\lambda)^2 \right] \cdot \rho \cdot A \cdot v_1^3 \quad \text{[D.2]}$$

The power coefficient $C_p = C_b \cdot \lambda \cdot (1-\lambda)^2$ (illustrated by the graph in Figure D.2 as a function of the coefficient λ which represents the tip speed ratio TSR) is null, not only for $\lambda = 0$ (rotor still) but also for the limit value $\lambda = 1$ (rotation speed of blades, equal to the wind speed with consequent reduction to zero of the draft force).
The maximum value for the power coefficient is reached for $\lambda = 1/3$ and it is equal to 0.08.
As it can be noticed, the maximum value theoretically achievable by C_p in drag based turbines is definitely lower than that one achievable with the lift turbines subject to the Betz limit (C_{pmax}=0.59): this represents the main limit, in terms of efficiency of power extracted from the wind, of drag turbines in comparison with lift turbines.

Figure D.2



This limitation depends both on the minor value of the drag coefficient C_b compared with the lift coefficient C_a under no-stall conditions (see Figure 3.8), as well as on the manufacturing concept of drag turbines, in which the relative wind speed v with respect to the surface of the blades is always lower than the absolute wind speed v_1 (Figure D.1):

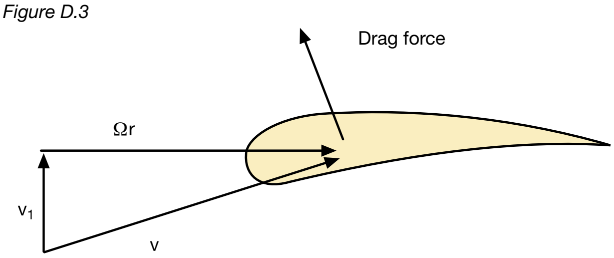
$$v = v_1 - \Omega \cdot r = v_1 \cdot (1-\lambda) \qquad \text{with } \lambda < 1 \quad \text{[D.2]}$$

In lift turbines, instead, the relative speed of the air flow lapping over the blades is always higher than the absolute wind speed (Figure D.3):

$$v = \sqrt{v_1^2 + (\Omega \cdot r)^2} = v_1 \cdot \sqrt{1+\lambda^2} \qquad \text{with } \lambda \text{ up to 10-12} \quad \text{[D.3]}$$

Since the lift motive force F_p is a function of both the coefficient C_a as well as of the relative speed v (see [3.31]), it follows that in the lift turbines the motive force developed is definitely higher than the motive force generated in the drag turbines, which results in a higher torque delivered to the rotor shaft and therefore a greater efficiency as regards the power extraction from the wind.

Figure D.3



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