6. WIND POWER

Content

6.1 The resource

Winds result from large scale movements of air masses in the atmosphere. These movements of air are created by the differential solar heating of the earth`s surface and, consequently, of the above air. Therefore, wind energy, is an indirect form of solar energy, like hydro, for example. In the equatorial regions the air is heated more strongly than at other latitudes, causing it to become lighter and less dense. This warm air rises to high altitudes and flows northward and southwards towards the poles, where the air near the surface is cooler. This movement ceases at about 30^0N and 30^0S, where the air begins to cool and sink and a return flow of this cooler air takes place in the lowest layers of the atmosphere.

The areas where the air is descending are zones of high pressure. Conversely, where air is ascending, low pressure zones are formed. This horizontal pressure gradient drives the flow of the air from high to low pressure, which determines the speed and the initial direction of wind motion. The greater the pressure gradient, the greater is the force on the air and the higher is the wind speed. Since the direction of the force is from higher lo lower pressure, the initial tendency of the wind is to flow perpendicular to the isobars (lines of equal pressure). However, as soon as wind motion is established, a deflective force is produced due to the rotation of the earth, which alters the direction of motion. This force is known as Coriolis force. It is important in many of the world’s windy areas, but plays little role near to the equator.

In addition to the main global wind systems there, a variety of local effects exists. Differential heating of the sea and land also causes changes to the general flow. The nature of the terrain, ranging from mountains and valleys to more local obstacles such as buildings and trees, also has an important effect.

The boundary layer refers to the lower region of the atmosphere where the wind speed is diminished by frictional forces with the earth’s surface. As a result, the wind speed increases with height; it is true up to the height of the boundary layer, which is approximately 1000 m, but depends on atmospheric conditions. The change of wind speed with height is known as the wind shear.

It is clear from this that the available wind resource depends on the hub height of the turbine. This has increased over recent years, reflecting the scaling-up of wind turbine technology, with the hub heights of the multi-megawatt machines now being over 100 m.

The European accessible onshore wind resource has been estimated at 4800 TWh/year taking into account typical wind turbine conversion efficiency. The offshore resource in the region can be of 3000 TWh/year although this is highly dependent on the assumed allowable distance from the shore. A recent report suggests that by 2030 the EU could generate 965 TWh from onshore and offshore wind, amounting to 22,6% of electricity requirements.

The world onshore resource is approximately 53000 TWh/year, taking into account siting constraints. To see these figures in context, note that the UK annual electricity demand is in the region of 350 TWh and the USA demand is 3500 TWh. No figure is currently available for the world offshore resource, and this itself will be highly dependent on the allowable distance from shore.

Among the renewable resources, wind power is the most developed. On very windy sites wind farms can produce energy at cost comparable to those of the most economic traditional generators. Due to advances in technology, the economies of scale, mass production and accumulated experience, over the next decade wind power is the renewable energy form likely to make the greatest contribution to electricity production. As a consequence, more work has been carried out on the integration of this resource than any of the other renewable.

6.2 The potential of the wind

An accurate estimation of the wind potential is not possible because of the large number of factors on which it depends. A starting point could be the fraction of solar energy transferred from the earth's surface to the atmosphere, some 2-3%. Because all wind turbines are seated on the earth, they can access the wind only to a limited height, ***h***, while the atmosphere height, ***H,*** is much greater. Thus the wind energy for this layer may be written

$$W_h = W_H \frac{m_h}{m_H} = W_H \frac{\rho_0 + \rho_h}{\rho_0 + \rho_H} \frac{h}{H} . \qquad (6.1)$$

If consider $\boldsymbol{h} = 200$ m, $\boldsymbol{H} = 11000$ m, $\boldsymbol{\rho}_0 = 1{,}226$ kg/m^3, $\boldsymbol{\rho}_\mathrm{h} = \boldsymbol{\rho}_0$, $\boldsymbol{\rho}_\mathrm{H} = 0{,}24\boldsymbol{\rho}_0$, the result is:

$$W_h = 0{,}0162 W_H$$

The entire sun power which reaches the Romania's territory is evaluated at $16{,}7.10^{17}$ J/year, so that

$$W_h = 0{,}02 * 16{,}7 * 10^{17} * 0{,}0162 = 5{,}42 * 10^{14}\ J / year = 150\, TWh / year$$

If the efficiency of energy conversion with wind mills could be 40%, the theoretical wind potential for Romania is of 60 TWh/year, quantity very close to the electricity annual production of the country.

Further, we must consider the wind velocities around the year and the available surfaces for wind farms. For these reasons an evaluation of the maximum production of electricity from wind becomes less accurate.

The wind parameters of importance for energy conversion are: velocity, direction and duration. The wind speed at a given location is continuously varying. There are changes in the annual mean speed from year to year, seasonal, diurnal and from second to second. All these changes, on their different time scales, can cause problems in predicting the overall energy capture from a site, and in ensuring that the variability of energy production does not adversely affect the local electricity network to which the wind turbine is to be connected. Therefore, for energy capture purposes, is necessary a continue recording of the wind speed for long periods of time, one or more years.

The wind speed changes with the height, upon a power law like

$$v_h = v_0 h^{\alpha} , \qquad (6.2)$$

where v_0 is the wind speed at the ground level (some 1,5 m), h the height and α a coefficient depending of the relief. Some α values are: 0,03 above the sea, 0,08 above plains, 0,2 for hills and up to 0,4 for mountains. This speed change is owed to the friction of the air with the accidents of the ground.

The wind direction is important only in connection with the layout of the turbines in a farm. Between turbines must be kept a large enough distance to ensure the same wind speed for each turbine.

For energy capture purpose, only wind speed more than 3 m/s may be of importance. Such condition is fulfilled by more than 50% of Romania's territory, as follows:

- 7960 hours at Sulina;
- 7200 hours over 1800 m altitude;
- 6500 hours for altitudes between 1400 and 1800 m;
- 6000 hours for Dobrogea, center of Moldova and Banat;
- 5000 hours for the North Moldova, Baragan and Crisana;
- 3000 hours for Transilvania.

Fig. 1 presents the distribution of the annual durations of wind with average speed on the Romanian's territory, according to the meteorological recordings.

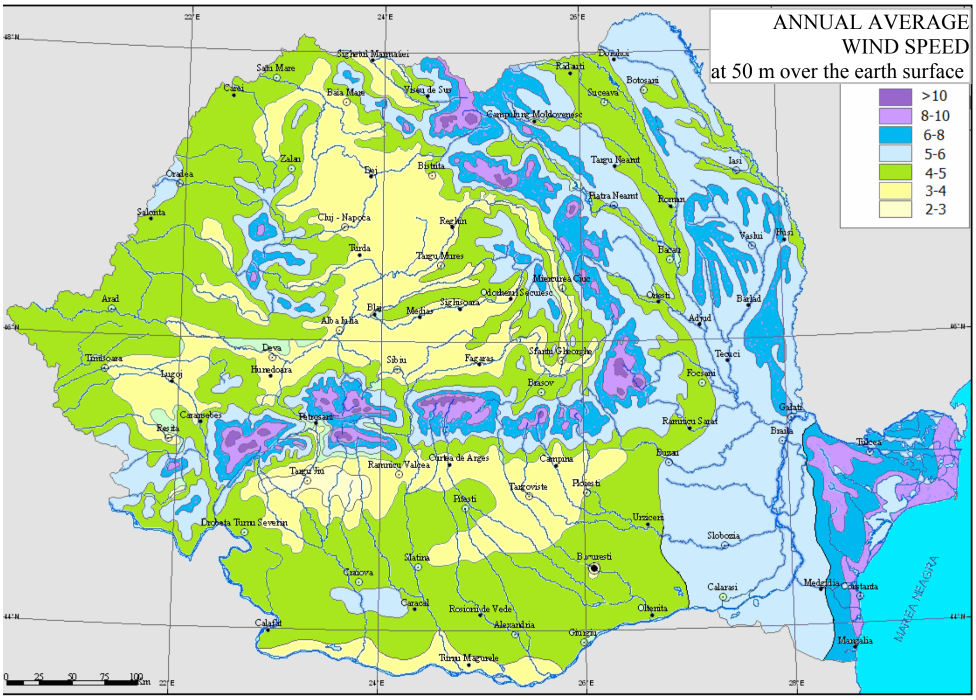

Fig. 1 – Wind speed over the Romania territory

6.3 The wind power

An air mass which flows with the speed v has a kinetic energy

$$W = \frac{1}{2} m v^2 , \tag{6.3}$$

where m is the mass of the air which pass through the surface S during the time interval t.

$$m = \rho S v t = q t . \tag{6.4}$$

$q = \rho S v$ represents the air mass flow rate through the area swept by the turbine.

The wind power obtains by dividing the energy with the time interval t:

$$P_w = \frac{1}{2}\rho S v^3 . \tag{6.5}$$

Dividing by S, and considering ρ = 1,226 kg/m^3, P_1 represents the specific wind power

$$P_1 = 0{,}613\left(\frac{v}{10}\right)^3 .$$

For example: if v = 10 m/s, $\boldsymbol{P}_1$ = 613 W/m^2; if v = 20 m/s, $\boldsymbol{P}_1$ = 4,9 kW/m^2, that is 8 times greater.

6.4 The wind turbine limit of power

None of the known wind mills can convert entirely the power of the wind which pass through it's surface. There is a limit of power, which can be determined, in a simpler way, by considering only the change of wind speed when pass through the turbine. Another theoretical assumption is the air is not compressible.

Consider an air stream passing through the swept area of the turbine (fig.2). Before the rotor, the wind speed is $\boldsymbol{v}_1$, behind the rotor, $\boldsymbol{v}_2$ and right in middle of the rotor, is $\boldsymbol{v}$. The power developed by the turbine is the difference between the upstream and downstream power of the wind:

$$P_1 = \frac{1}{2} q v_1^2 \qquad\qquad P_2 = \frac{1}{2} q v_2^2 \tag{6.6}$$

The air mass flow rate

$$q = \rho S v \tag{6.7}$$

being constant, the equation of the power developed by the turbine becomes

$$P = \frac{1}{2}\rho S v\left(v_1^2 - v_2^2\right). \tag{6.8}$$

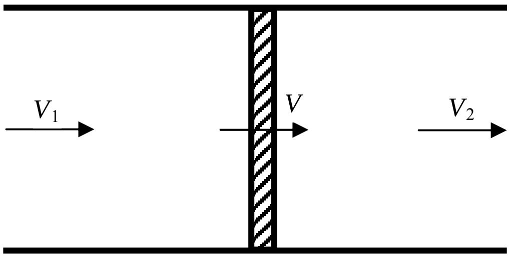

Fig. 2 The wind turbine with horizontal shaft

To determine the unknown speed v is necessary to find another equation for the power developed by the turbine. Considering the wind speed as constant, the power may be written as the product of the impulse change of the air mass and the wind speed in the rotor:

$$P = v\frac{\Delta p}{\Delta t} . \tag{6.9}$$

Because

$$\frac{\Delta p}{\Delta t} = \frac{\Delta(mv)}{\Delta t} = \frac{m\Delta v}{\Delta t} = q(v_1 - v_2) = \rho S v(v_1 - v_2),$$

the new equation of the turbine power becomes

$$P = \rho S v^2 (v_1 - v_2). \tag{6.10}$$

Both equation define the same power, and by making equal one to another, results

$$v = \frac{1}{2}\left(v_1 + v_2\right), \tag{6.11}$$

which means the wind speed changes linearly.

By introducing this wind speed in the first equation of the rotor power results

$$P = \frac{1}{4}\rho S\left(v_1 + v_2\right)\left(v_1^2 - v_2^2\right) = \frac{1}{2}\rho S v_1^3 \frac{1}{2}\left(1 + \frac{v_2}{v_1}\right)\left(1 - \frac{v_2^2}{v_1^2}\right).$$

If we note

$$x = \frac{v_2}{v_1},$$

the previous equation for power becomes

$$P = \frac{1}{2}P_v\left(1 + x\right)\left(1 - x^2\right). \tag{6.12}$$

Obviously, the power ***P*** depends on the value of the ratio ***x***. The value of this ratio for what the power ***P*** becomes the highest one is the solution of equation

$$\frac{dP}{dx} = 0.$$

There are two solutions

$$x_1 = -1;\ x_2 = \frac{1}{3}. \tag{6.13}$$

For x_1 = -1, the power ***P*** is null. For x_2 = 1/3, the power is

$$P = \frac{16}{27}P_w = 0{,}592 P_w. \tag{6.14}$$

Thus, the highest power which a wind turbine can develop is smaller than 60% of the wind power over the rotor area. This figure is known as the **limit of Betz**, the scientist which first demonstrated it. None of the developed wind turbines can reach this limit despite the simplifying hypothesis of the calculus.

6.5 Operating parameters of the wind turbines

The *mechanical power* at the wind turbine shaft is

$$P_m = c_p P_w. \tag{6.15}$$

P_w represents the power of the wind stream and c_p is the power coefficient. This coefficient depends on the rotor design as well as on its rotation speed through the ratio λ

$$\lambda = \frac{u}{v}, \tag{6.16}$$

named rapidity. ***u*** represents the linear speed at the blade end, while ***v*** is the wind speed. The function $c_p(\lambda)$ is non/linear, having a maximum, like fig.3 presents.

The *rated power* of a wind turbine is equal to the rated power of the attached electric generator. The rated power of the generator is a constant while the wind power grows very fast with the wind speed.

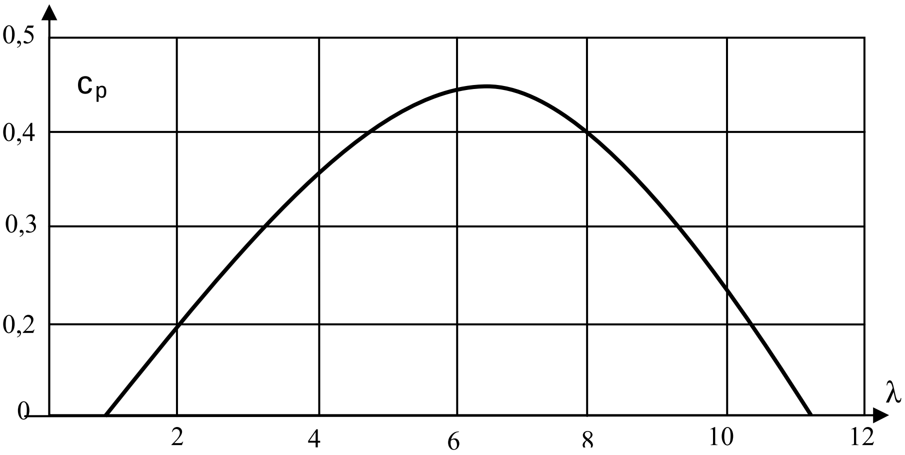

Fig. 3 Power coefficient of a wind turbine

As consequence, the delivered electric power of a wind turbine depends on the wind speed as the fig.4 shows. At $\boldsymbol{v}_{\min}$ the active couple overcomes the friction couple of the moving pieces and the rotor starts to rotate, if the electric generator is not connected to the grid. At $\boldsymbol{v}_{\mathrm{n}}$ the delivered power equals the rated power. For wind speed greater than $\boldsymbol{v}_{\mathrm{n}}$, the delivered power may be kept constant by the action of the control system. Some methods for power control are: moving the rotor blades round the axe, limiting the area exposed to the wind, mechanical or electric brake system. These systems can control the delivered power until the wind speed reaches $\boldsymbol{v}_{\max}$. Beyond this wind speed the operation of the turbine must be stopped.

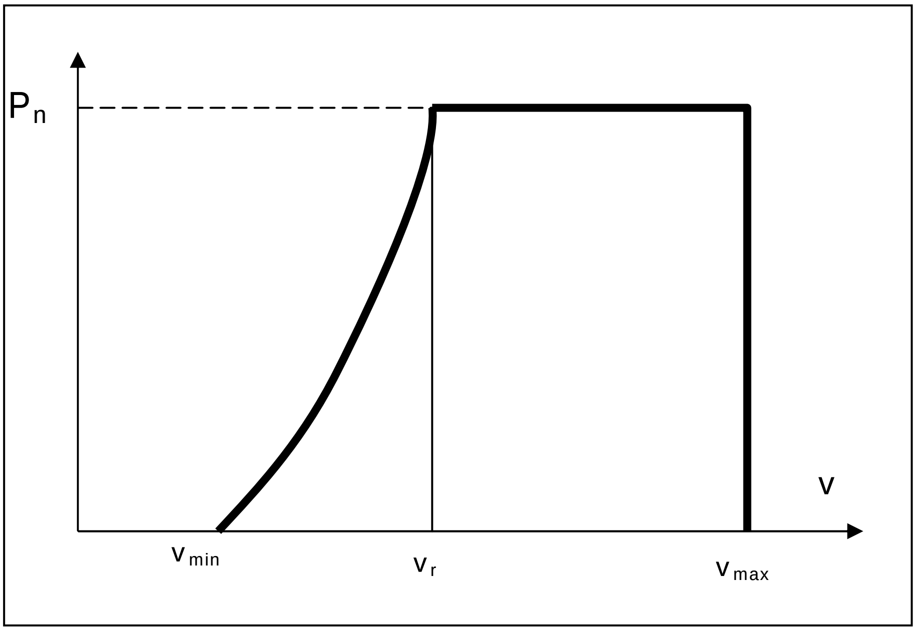

Fig. 4 – Power of the wind turbine depending on the wind speed

The rated power divided by the swept area of the rotor represents the *specific rated power*. This parameter is useful to compare wind turbines of different size.

6.6 Layout of wind turbines

The main requirement for selecting location of wind turbines is to offer a good wind potential, proved by long time records. However, from economic reasons, among such possible locations, unused lands or areas with small density of inhabitants must be preferred first. The wind farms have some environment effects, especially when there are many turbines. Such effects are noise, landscape distortion, birds moving off and others.

Until now, were installed wind turbines with rated power from some kW to 3 MW. Future designs aim to push this limit to 10 or 20 MW, but this limit is hard to reach. Thus, to obtain capacities of some hundred of megawatt, to replace an existing power plant, tens or hundreds turbines must be installed in one or more wind farms.

For a better utilization of the land, the turbines in a wind farm must be layout as dense as possible. Between the turbines must be kept a distance large enough to avoid the mutual influence because of the turbulences arisen behind the turbines.

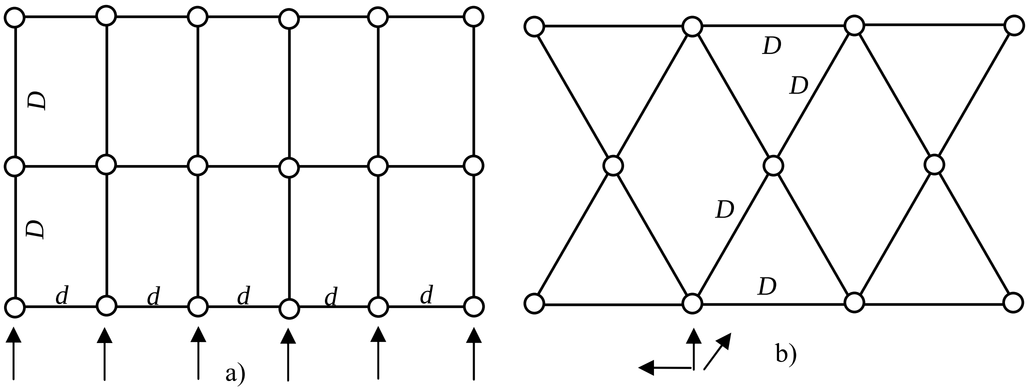

Fig. 5 Arrangements of wind mills in farm

All the turbines in a wind farm can operate in the same conditions if the wind speed restores from a turbine to the next in the wind direction. The relative positions of the turbines depend on the predominant wind direction. If, during the year, the wind has a steady direction, the turbines may be placed in the nodes of a rectangular net, like in fig. 5 a). In areas with changing wind direction, the best position of the turbines is in the corners of an equilateral triangle (fig.5 b). For both cases, the smallest distance between two turbines, along the wind direction is ***D***. This distance must be ***k*** times greater than the turbine diameter *d*, where *k* varies from 6 for a small diameter to 12 for the greatest diameter.

Another problem regarding the turbine layout is the influence of obstacles like ground accidents, trees, buildings etc. which can disturb the vertical wind speed distribution (fig.6). To avoid these influences, a distance of 20***h*** must be kept between the turbine and an obstacle having the height ***h***. At the same time, the turbine axis position must be higher than 3***h***.

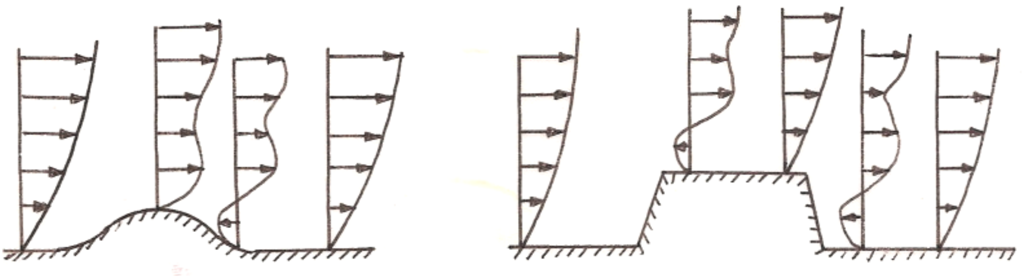

Fig.6. Wind speed disturbance behind obstacles

6.7 Classification of wind turbines

Owing to the great number of existing wind converters, a classification upon some general criteria may be of interest.

a) According to the *cinematic criterion,* two classes can be distinguished:
   - dynamic converters, which realize a motion under the wind action;

- static converters, which convert the wind power motionless.

The most of wind converters, at least the types of practical interest, are dynamic. The static converters are applications of some phenomena in gases, without any practical importance because of its very low efficiency. Such phenomena are:

- changing the air speed and pressure owing to the change of a nozzle section
- electric current induction when an ionized gas flows through parallel electrodes;
- gas heating because of friction between layers with different speed as a turbulence induces.

b) By the turbine *axis position* (relating to the wind direction) criterion, there are:

- *horizontal* (or *parallel*) axis, if the wind direction and the axis are parallel, and
- *vertical* axis (or *perpendicular*) if the two direction are perpendicular.

c) According to the *incidence angle criterion*, two classes may be of importance:

- rotor with *constant* angle of incidence
- rotor with *variable* angle of incidence.

The incidence angle is defined as the angle between the wind speed and the perpendicular on the blade surface at the defined point. Because the blade surface is curved, this angle changes from a point to another.

If the angle on incidence at every point of the blade surface is constant during a complete rotation of the turbine, the developed couple by the rotor is constant too. In such a situation, the amplitude of the blade vibration is small, and the contribution of the turbine blades to the wind power conversion is the highest possible. This behavior is characteristic for the turbine with horizontal axis.

Alternatively, if the angle of incidence changes during the turbine rotation, the force developed by the blade is variable too. Besides the increased mechanical strength on the blades, if the incidence angle becomes negative, the blades put up resistance to the motion.

d) The *active force criterion*

The wind action against the turbine blades develops an active force having two main components: the *resistance force* and the *lifting force*. The resistance force is created by the transmission of the impulse from the mass of air striking the blades. The lifting force appears owing to different curvature on the two surfaces of the blades, having as consequence different air pressures which determine a force perpendicular on the wind speed direction. The size of these components differs depending on the rotor design. There are:

- turbine with aerodynamic resistance
- turbine with both resistance and lifting forces
- turbine with lifting force.

The turbines with aerodynamic resistance have vertical axis, and the blades move in the direction of the wind. The parameter λ have values under 1. The turbines with lifting force have, generally, axis parallel with the wind direction, and the parameter λ may be much greater than 1.

e) The *trajectory criterion*

If the mobile part of the converter executes a rotation, it is called *wind turbine*. Other converter, called *wind engine*, executes a translation or oscillation under the influence of the wind.

6.8 Wind turbines types

Vertical axis turbines

Some types of wind turbines work owing to the aerodynamic resistance force. The rotors in fig. 7 are called “with simple resistance” because only the blades moving in the wind direction develop active forces. The rotation is possible only if a half of the rotor is screened by the shell (a) or if the blades are so assembled to receive the wind if they move in the direction of the wind (b). Fig.7 c) shows a more complex design, where the blades are mounted on joints thus, during the active motion, they lean upon rods on the inner wheel nave.

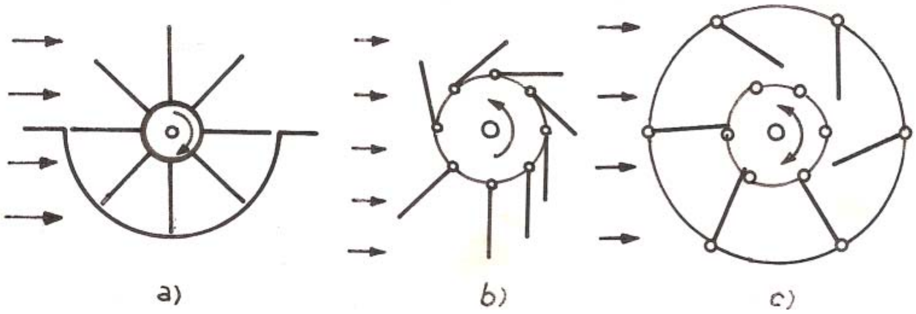

Fig.7 Wind turbines with “simple” resistance

Such complicated solutions are avoided by the rotor with difference of resistance, fig. 8 a).

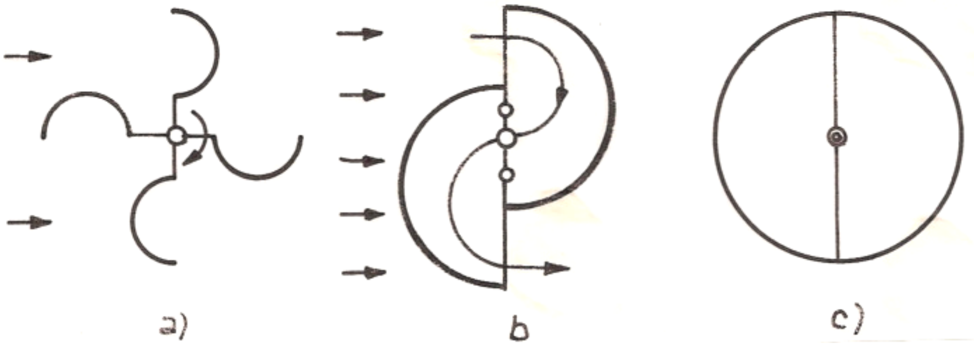

Fig.8 Wind turbines with difference of resistance

Because the blades which move in the direction of the wind are concave while the blades moving against the wind are convex, the active force will be the difference between the forces developed by the wind on both types of blade.

An interesting solution is the Savonius rotor (fig.8,b), which consists of two half-cylinder having parallel axes. Between the two axes a variable gap can be set, so that the area offered to the wind is variable too. The active force is owed both to the different resistant forces and the impulse created through the change of the air direction inside the rotor. As consequence, this rotor starts at the lowest wind speed, i.e. 3-5 m/s.

The power control is made by changing the opening size according to the wind speed. Beyond the highest allowable wind speed, the distance between the two axes diminishes to zero. Thus the extracted power from the wind becomes null (fig.8 c).

The wind turbines with vertical axe, intended for high power (Darrieus) are presented in fig. 9. The rotor blades are flexible, so during the rotation it arrange like a chain, what diminish the bending effort. The stretch effort is much better beard than the bending one. Darrieus turbine were built up to 200 m high.

Such turbine rotates owing to the lifting force, so it need higher wind speed to start, than Savonius, for example. Sometimes the rotor starts with the assistance of the electric generator utilized as motor. Another possibility is to add a Savonius rotor on the same axe.

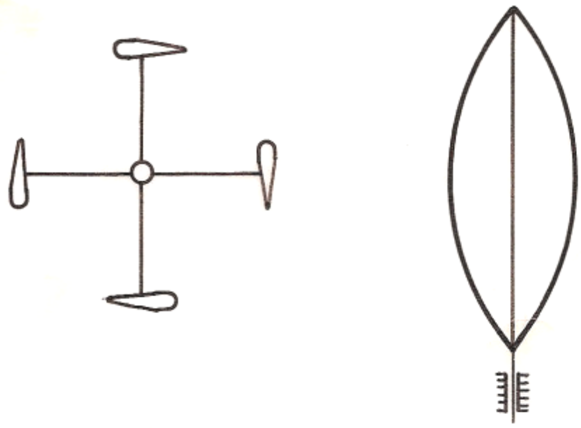

Fig.9 Wind turbines with vertical axe

Horizontal axe turbines

Although there are few types of turbine with axe parallel with the wind speed, those performances are the best concerning the rated power, the power coefficient size and the control of the delivered power. These performances are due to the constant angle of the incidence which minimizes the air turbulence beyond the rotor. Such turbines represent a development of the aircraft propeller (fig.10), having 3, 2 or only one blade with aerodynamic profile. If the rotor have (fig.10 c), only a blade, a counter-weight is compulsory in order to be equilibrated. Fig.11, d presents a solution to double the rotational speed of the shaft.

The size of the turbines with horizontal axe is pushed up to 5 MW so far, and 10-20 MW are already in design. Such turbines must to be installed on tower of 80-100 m and more, and the blade length has 50-90 m. Higher the turbine size is, lower is the rotational speed of the rotor. Because the speed of the electrical generator is much greater, a gear box is inserted between the turbine and the generator.

Wind engines

Some types of wind converter can perform another type of motion than a rotation. Fig.11,a presents a vertical aerodynamic blade which oscillates due to the lifting force. A mechanism converts the oscillating motion into a rotating one. The design in fig.11, b represents a number of sails or rigid panel which shifts linearly under the wind pressure. The two drums transform the movement of translation into a rotational one.

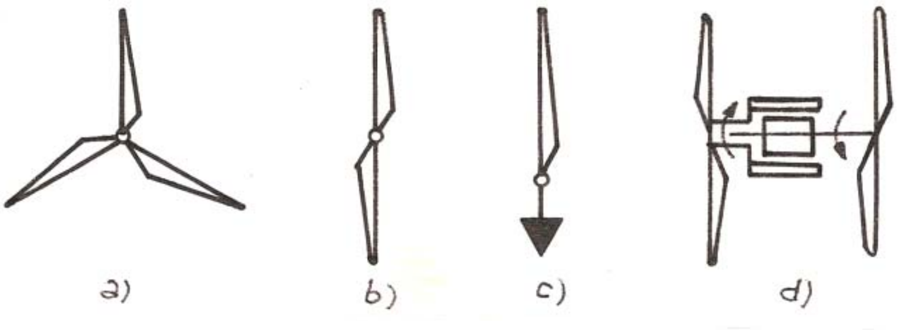

Fig.10 Horizontal axe turbines

6.9 Condensing the wind power

While the sun rays can be easily concentrated with mirrors or lens, is more difficult to condense the wind. Convergent, divergent or mixed nozzles allow reducing the air section, adequately increasing the speed (fig.12). As consequence, the size of the turbine rotor diminishes but the rotation speed (r.p.m) increases.

Condensing the wind power has little extent because the size and weight of nozzles are too high, and consequently expensive. Also, the power consumed to align the nozzle with the wind reduces the conversion efficiency.

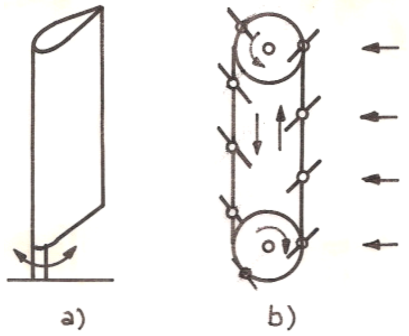

Fig.11 Wind engines

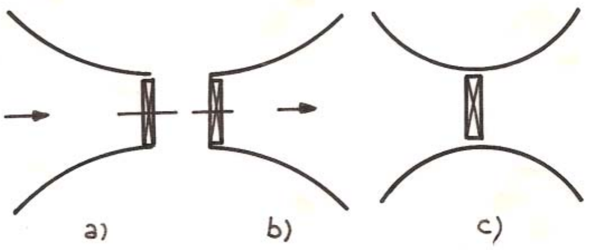

Fig.12 Wind concentration

6.10 Combined wind converters

TORNADO converter (fig.13,a) utilizes, simultaneously, horizontal and vertical air streams. A huge vertical cylinder has, at the lower end, a convergent nozzle where is located the rotor. More tight slits are cut up in the cylinder and can be closed with shutters. During the operation, the shutters on a quarter of the surface are open. Thus, the air streams, entering the cylinder, rotate and ascend under the difference of atmospheric pressure between the lower and the top ends of the cylinder.

The Thermal tower (fig.13, b) utilizes the air heating by the sun to magnify the ascendant air speed due to the pressure difference between the ground and the tower top. At the tower bottom, is a large thermal collector; the air heated reduces its density so that it runs upright into the tower with increased speed. Such a installation is adequate for windy and sunny desert areas.

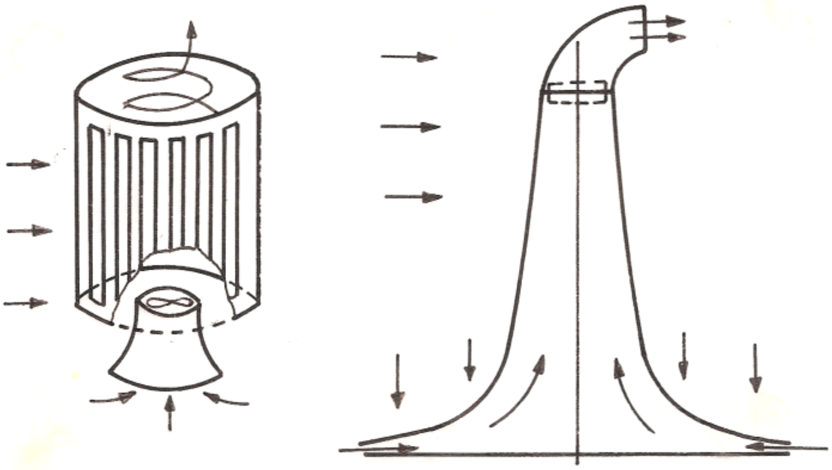

Fig.13 Combined wind converters

6.11 Wind energy conversion into electricity

A wind turbine, itself, changes the linear wind speed into a rotational movement and the rotor axe transmit the kinetic energy of the wind to equipment which utilizes directly the mechanical energy or convert it into another energy form.

The main domains to utilize directly the mechanical energy are:

- water pumping for irrigation or water supplying for houses and cattle;
- water pumping for storage in reservoirs in order to generate electricity for counterbalancing the temporary lack of wind;
- air compressing for different utilizations, including gas turbines;

Another possibility is to convert the mechanical energy into heat either through rubbing or electrical induction.

All these utilizations, together, are of little weight comparatively with generation of electricity. The wind turbines are designed, mainly, to generate electricity. The bloc diagram of such a conversion chain is represented in fig.14

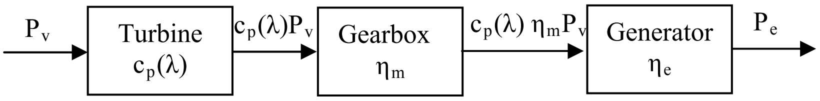

Fig. 14 Conversion of wind energy into electricity

Between the rotor and the electric generator a gearbox in inserted in order to obtain the right rotational speed for the generator. Also, a brake may be added in order to stop the turbine operation when the wind speed is too high.

The electrical power may be written

$$P_e = c_p(\lambda)\eta_m\eta_e P_w , \tag{6.17}$$

Where $c_p(\lambda)$ is the power coefficient of the rotor, η_m is the mechanical efficiency, η_e is the electrical efficiency and P_w is the wind power related to the swept area of the rotor. Because the wind power and the power coefficient are variable, the energy delivered in the time gap t determines by integration:

$$P_e = \frac{1}{2}\rho S\eta_m\eta_e \int_0^t c_p(\lambda)v^3(t)dt . \tag{6.18}$$

There are some possibilities to generate electricity from the wind power. Although is possible to use electricity as direct current or alternating current, the second current shape is mostly preferred everywhere. Alternating current can be generated either with a synchronous or asynchronous generator.

Synchronous generator

Because, in the electric grid, the current has constant frequency, the synchronous generator speed must be constant too. Despite the control systems of the turbine speed and the presence of the gearbox, is very difficult to maintain constant the speed of the generator while the wind speed is very inconstant. To uncouple the generator speed from the current frequency, the generated current with variable frequency may be rectified and than inverted before to be injected in the public grid (fig.15,D).

Asynchronous generator

This type of generator, known as *induction generator* is an asynchronous machine which becomes a generator if its rotational speed is higher than the synchronism one. It has as main advantage, the frequency of the generated current is imposed by the public grid to that is connected. The rotor of an induction generator may be of squirrel cage type (SCIG) or wounded (WRIG). Depending of that design has the machine, different schema are utilized to connect the generator to the grid (fig.15 A,B,C).

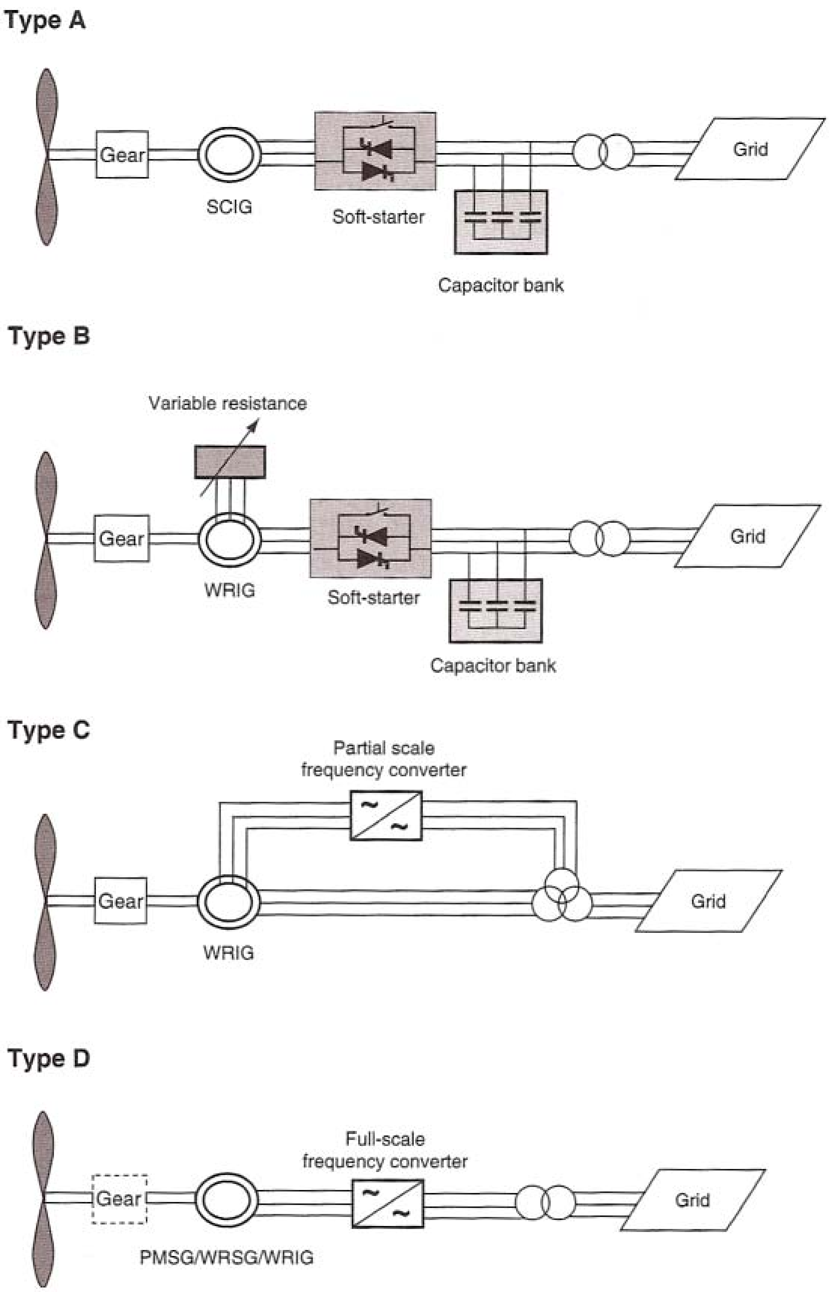

Fig.15 Typical wind turbine configurations.
SCIG=squirrel cage induction generator; WRIG=wound rotor induction generator; PMSG= permanent magnet synchronous generator; WRSG=wound rotor synchronous generator.

Fig.16 presents a section through the nacelle of a large size wind turbine with a gearbox between the rotor and the generator. Fig.17 presents another design, whose generator work at the rotor speed without gearbox. To that end, the diameter of the generator is much larger because it needs more magnetic poles.

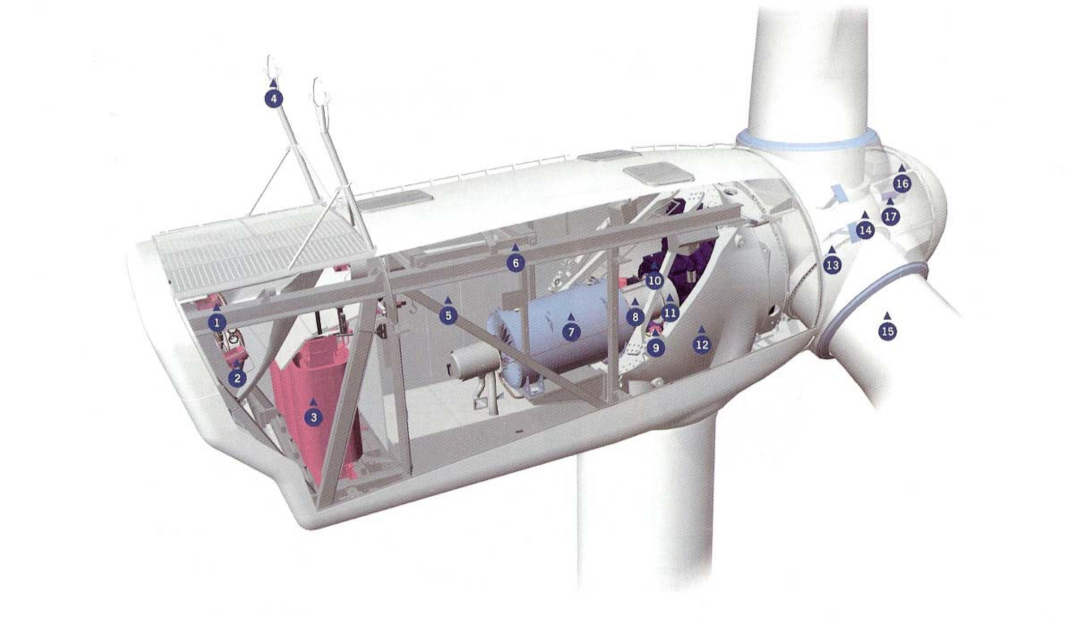

Fig.16 Nacelle Vestas V90 3 MW
1=oil cooler; 2=generator cooler; 3=transformer; 4=wind sensor; 5=top controller; 6=service crane; 7=generator; 8=coupling; 9=yaw gears; 10=gearbox; 11=brake; 12=machine foundation; 13=blade bearing; 14=blade hub; 15=blade; 16=pitch cylinder; 17=hub controller;

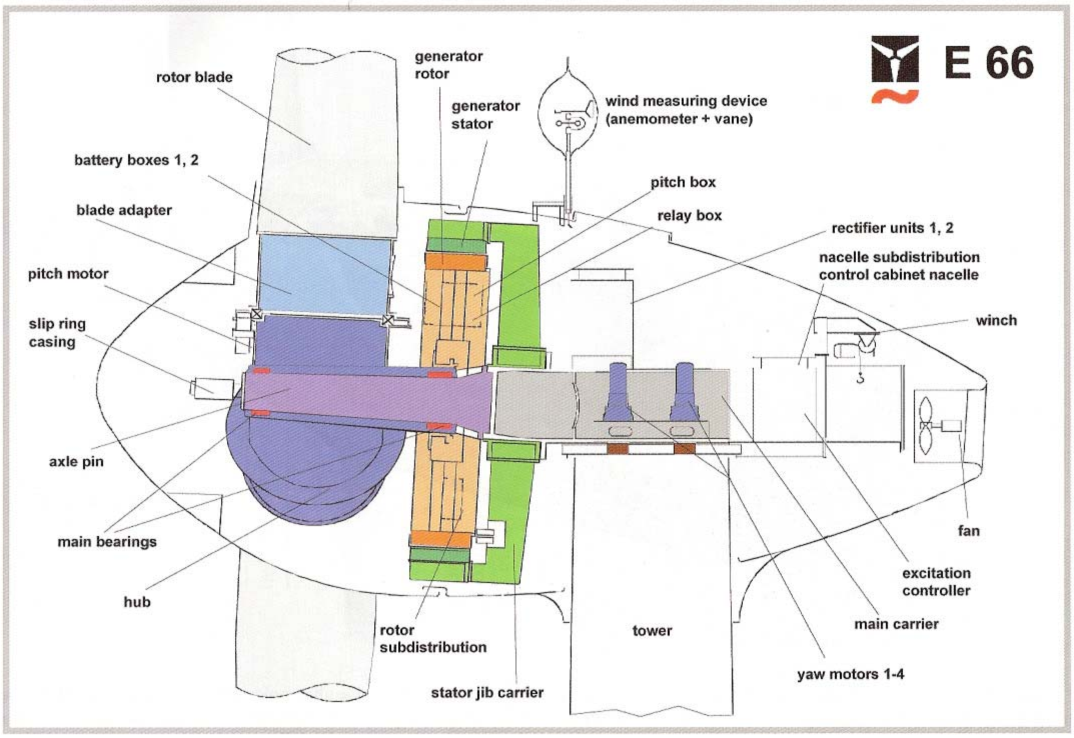

Fig.17 Nacelle Enercon E66 1,5 MW