Chapter One

1.1 Wind Turbine Components

Typical wind turbines involve a set of rotor blades (usually three) rotating around a hub. The hub is connected to a gearbox and a generator, located inside the nacelle, which houses the electrical components. The basic components of a wind turbine system are shown in Figure 1.1 and outlined as follows:

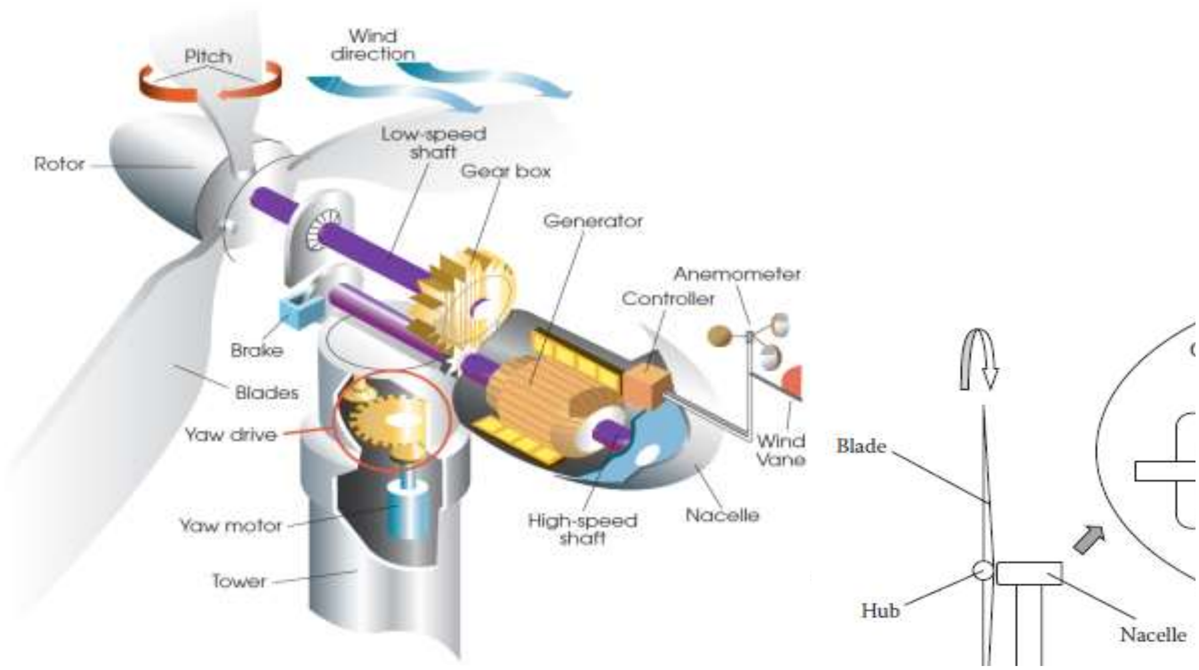
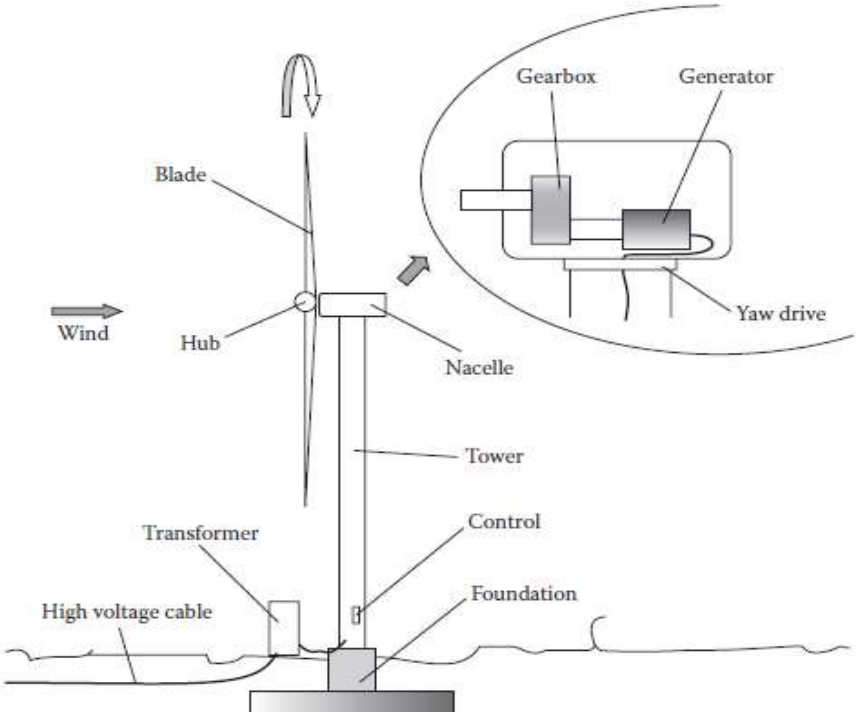


Fig 1.1 Main components of a typical modern high -power wind turbine

- Nacelle
- Rotor blades
- Hub
- Low speed shaft
- Gearbox
- High speed shaft with its mechanical brake
- Electrical generator
- Yaw mechanism
- Electronic controller
- Tower
- Anemometer



1. The nacelle:

Sits on top of the tower and contains the electrical components, the gearbox, the brake, the wind speed and director monitor, the yaw mechanism, and the generator.

2. Rotor blades:

The diameter of the blades is a crucial element in the turbine power; typically, the longer they are, the greater the output. However, their design and the materials incorporated by them are also key elements. Blades are often made of fiberglass reinforced with polyester or wood epoxy. Vacuum resin infusion is a new material connected to a technology presented by manufacturers like Suzlon. Typically, blades rotate at 10–30 revolutions per minute, either at a constant speed (the more traditional solution) or at a variable speed.

Rotor is the most important and prominent part of a wind turbine. The rotor receives the kinetic energy from the wind stream and transforms it into mechanical shaft power. Components of a wind turbine rotor are blades, hub, shaft, bearings and other internals.

3. Gearboxes and direct drives:

Most wind turbines use gearboxes, whose function is to increase the rotational speed required by generators. Some new technologies are exploring direct drives generators to dispense with the expensive gears. Gears connect the low-speed shaft to the high-speed shaft and increase the rotational speeds from about 10 to 30 rotations per minute (rpm) to about 1000–1800 rpm, which is required by most generators to produce electricity. The recent design uses "direct-drive" generators that operate at lower rotational speeds and do not need gearboxes. Gearbox is an important component in the power trains of a wind turbine. Speed of a typical wind turbine rotor may be 30 to 50 r/min whereas; the optimum speeds of generator may be around 1000 to1500 r/min. Hence, gear trains are to be introduced in the transmission line to manipulate the speed according to the requirement of the generator. An ideal gear system should be designed to work smoothly and quietly even under adverse climatic and loading conditions-throughout the life span of the turbine. Due to special constraints in the nacelle, the size is also a critical factor.

Figure 1.a Three-stage wind turbine gearbox for medium speed drive train

4. Brake:

A disk used to stop the rotor blades in emergencies and to ensure the safety of the turbine in case of very high damaging winds or other exceptional situations.

Braking action may be required for several reasons. There are several types of braking a turbine rotor: aerodynamic brakes, electro brakes and mechanical brakes. In case of aerodynamic braking, the blade is turned in such a direction that the lift effect which causes rotation, does not appear. In case of electro-magnetic braking, energy produced by the generator of a wind turbine is dumped into a resistor bank, thereby converting it into heat. Another type of braking is conventional mechanical braking for which disc brakes are provided in the nacelle. A mechanical drum brake or disk brake is also used to hold the turbine at rest for maintenance. Such brakes are also applied after blade furling and electro braking have reduced the turbine speed, as the mechanical brakes would wear quickly if used to stop the turbine from full speed. In large wind turbines, normally there is a combination of at least two brakes, most turbines use aerodynamic brakes together with mechanical braking or even also with an electro braking system.

5. Controller:

A set of electrical components that controls the starting, the stopping, and the turbine rotor blade speed. Typically, in the constant wind speed model the controller starts up the turbine at wind speeds around 8 to 16 miles per hour (mph) (3.58 to 7.15 m/s) and stops the machine at around 55miles per hour (24.6 m/s) (to avoid the damage caused by turbulent high winds).

6. Generator:

The generator converts the mechanical energy of the rotating shaft into electrical energy. Generator is one of the most important components of a wind energy conversion system. In contrast with the generators used in other conventional energy options, generator of a wind turbine has to work under fluctuating power levels, in tune with the variations in wind velocity. Different types of generators are being used with wind machines. Small wind turbines are equipped with DC generators of a few Watts to kilo Watts in capacity. Bigger systems use single or three phase AC generators. As large-scale wind generation plants are generally integrated with the grid, three phase AC generators are the right option for turbines installed at such plants. These generators can either be **induction generators** or **synchronous generators.**

7. The yaw mechanism of wind power generators:

In more typical wind turbines, the yaw mechanism is connected to sensors (e.g., anemometers) that monitor wind direction, turning the tower head and lining up the blades with the wind. The turbines must face upwind for power production. The yaw drive is used to keep the rotor facing into the wind as the wind direction changes. Downwind turbines don't require a yaw drive, since the wind blows the rotor downwind.

8. Tower:

Supports the nacelle and rotor. The electricity produced by the generator comes down cables inside the tower and passes through a transformer into the electricity network.

9. Hub

The hub of the rotor is attached to the low speed shaft of a wind turbine.

10. Anemometer

It measures the wind speed and transmits wind speed data to the controller.

10. Base or Foundation:

Large turbines are built on a concrete base foundation. When a wind turbine ceases production, it is a simple task to dig these out or cover them, leaving little trace behind.

11. Low Speed Shaft

The low speed shaft of a wind turbine connects the rotor hub to the gearbox. The rotor rotates at about 10–30 rotation per minute (rpm) in a 1000kWe wind turbine. The shaft contains pipes for the hydraulics system to enable the aerodynamic brakes to operate.

12. High Speed Shaft with its Mechanical Brake

This drives the generator and employs a disc brake, which can be applied mechanically, electrically, or hydraulically to stop the rotor in emergencies.

14. Wind Vane

It measures wind direction and directs the yaw drive to appropriate orientation so that the turbine is properly aligned with respect to the wind direction.

1.2 The Wind Wake and Park Effect

Since a wind turbine generates electricity from the energy in the wind, the wind leaving the turbine must have a lower energy content than the wind arriving in front of the turbine. There will be a wake effect behind the turbine, i.e., a long trail of wind which is quite turbulent and slowed down, as compared to the wind arriving in front of the turbine. The expression wake is obviously derived from the wake behind a ship. Wind turbines in parks are usually spaced at least three rotor diameters from one another in order to avoid too much turbulence around the turbines downstream. As a result of the wake effect, each wind turbine will slow down the wind behind it as it pulls energy out of the wind and converts it to electricity.

Ideally, therefore turbines should be spaced as far apart as possible in the prevailing wind direction. On the other hand, land use and the cost of connecting wind turbines to the electrical grid would force to space them closer together. As a guideline for wind park design turbines in wind parks are usually spaced somewhere between 5 and 9 rotor diameters apart in the prevailing wind direction, and between 3 and 5 diameters apart in the direction perpendicular to the prevailing winds.

In Fig. 1.2, three rows of five turbines each are placed in a fairly typical pattern. The turbines (the dots) are placed **7 diameters** apart in the prevailing wind direction, and **4 diameters** apart in the direction perpendicular to the prevailing winds.

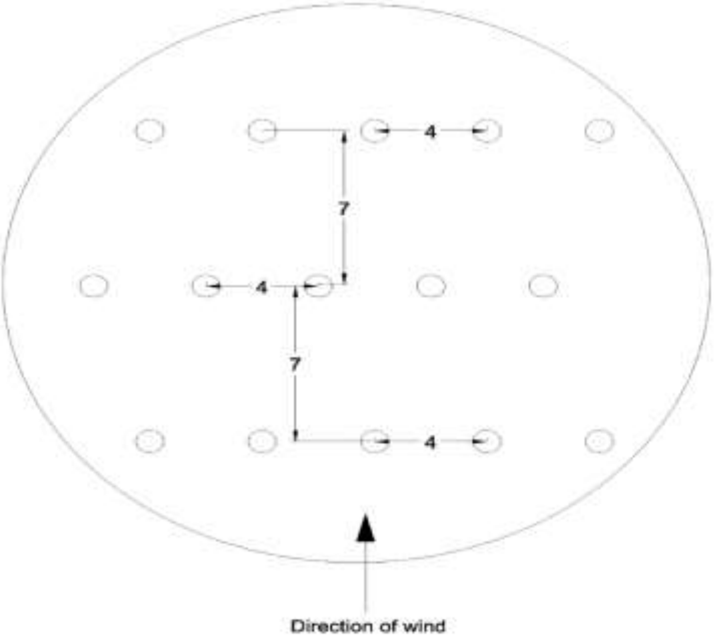


Fig. 1.2 Spacing between turbines in a wind park in terms of rotor diameters (E.g., 4 means four times the rotor diameter)

1.3 Physics of Wind Energy

The basic principles of physics on which any wind turbine works are explained in this chapter. These concepts will be helpful in understanding the science and technology behind the operation and control of wind turbines in order to harvest maximum energy from the wind.

1.3.1 Energy Content in Wind

A wind turbine obtains its power input by converting the force of the wind into torque (turning force) acting on the rotor blades. The amount of energy which the wind transfers to the rotor depends on the density of the air, the rotor area, and the wind speed.

(a) Density of Air

The kinetic energy of a moving body is proportional to its mass (or weight). The kinetic energy in the wind thus depends on the density of the air, i.e., its mass per unit of volume. In other words, the ‘‘heavier’’ the air, the more energy is received by the turbine.

At normal atmospheric pressure and at 15°C, the density of air is 1.225 kg/m^3, which increases to 1.293 kg/m^3 at 0°C and decreases to 1.164 kg/m^3 at 30°C. In addition to its dependence upon temperature, the density decreases slightly with increasing humidity. At high altitudes (in mountains), the air pressure is lower, and the air is less dense. It will be shown later in this chapter that energy proportionally changes with a variation in density of air.

(b) Rotor Area

When a farmer tells how much land he is farming, he will usually state an area in terms of square meters or hectares or acres. With a wind turbine it is much the same story, though wind farming is done in a vertical area instead of a horizontal one. The area of the disc covered by the rotor, (and wind speeds, of course), determines how much energy can be harvested in a year. A typical 1000 kW wind turbine has a rotor diameter of 54 m, i.e., a rotor area of some 2300 m^2. The rotor area determines how much energy a wind turbine is able to harvest from the wind. Figure 1.3 gives an idea of the normal rotor sizes of wind turbines: If the rotor diameter is doubled, one gets an area which is four times larger (two squared). This means that four times as much power output from the rotor will also be obtained. Rotor diameters may vary somewhat from the figures given below, because many manufacturers optimize their machines to local wind conditions: A larger generator, of course, requires more power (i.e., strong winds) to turn at all. So if one installs a wind turbine in a low wind area, annual output will actually be maximized by using a fairly small generator for a given rotor size (or a larger rotor size for a given generator).

The reason why more output is available from a relatively smaller generator in a low wind area is that the turbine will be running more hours during the year.

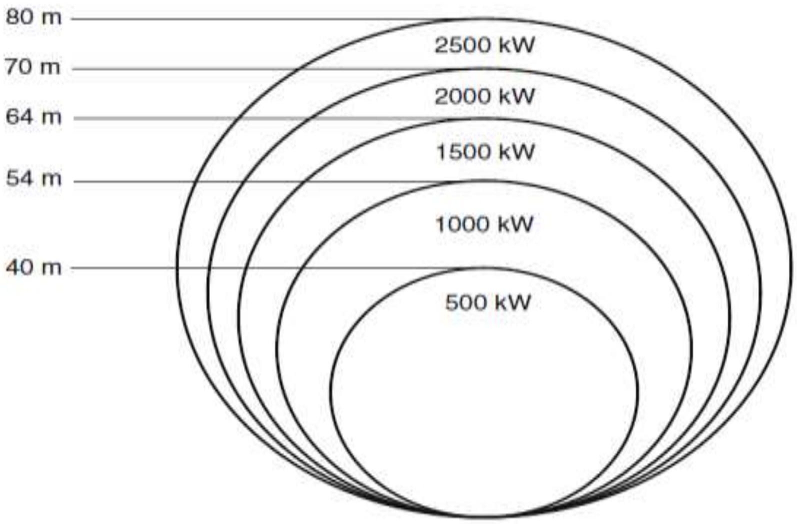


Fig. 1.3a: Power output increases with the rotor diameter and the swept rotor area

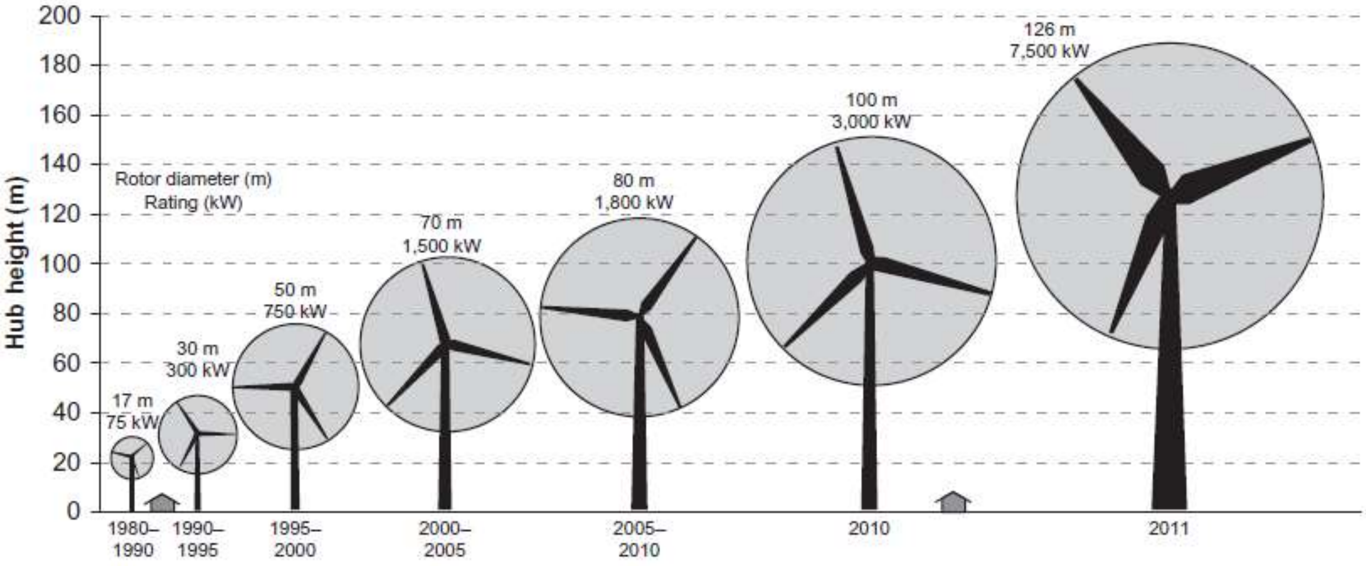


Figure 1.3b: The evolution of wind turbine rotor diameter and hub height.

(c) Wind Velocity

The power output of a wind turbine varies with wind speed and every wind turbine has a characteristic power performance curve. With such a curve it is possible to predict the energy production of a wind turbine without considering the technical details of its various components. The power curve gives the electrical power output as a function of the hub height wind speed.

Figure 1.4 presents an example of a power curve for a hypothetical wind turbine. The performance of a given wind turbine generator can be related to three key points on the velocity scale:

1. **Cut-in speed:** the minimum wind speed at which the machine will deliver useful power.
2. **Rated wind speed:** the wind speed at which the rated power (generally the maximum power output of the electrical generator) is reached.
3. **Cut-out speed:** the maximum wind speed at which the turbine is allowed to deliver power (usually limited by engineering design and safety constraints).

Power curves for existing machines can normally be obtained from the manufacturer. The curves are derived from field tests, using standardized testing methods.

A wind turbine has to operate over a huge range of wind power levels. For example, it may be designed to cut- in and start generating when the wind speed reaches 4 m/s, and cut-out to prevent damage at 24 m/s. This 6:1 range of wind speeds corresponds to a 216:1 range of intercepted power that the turbine must convert efficiently into electricity.

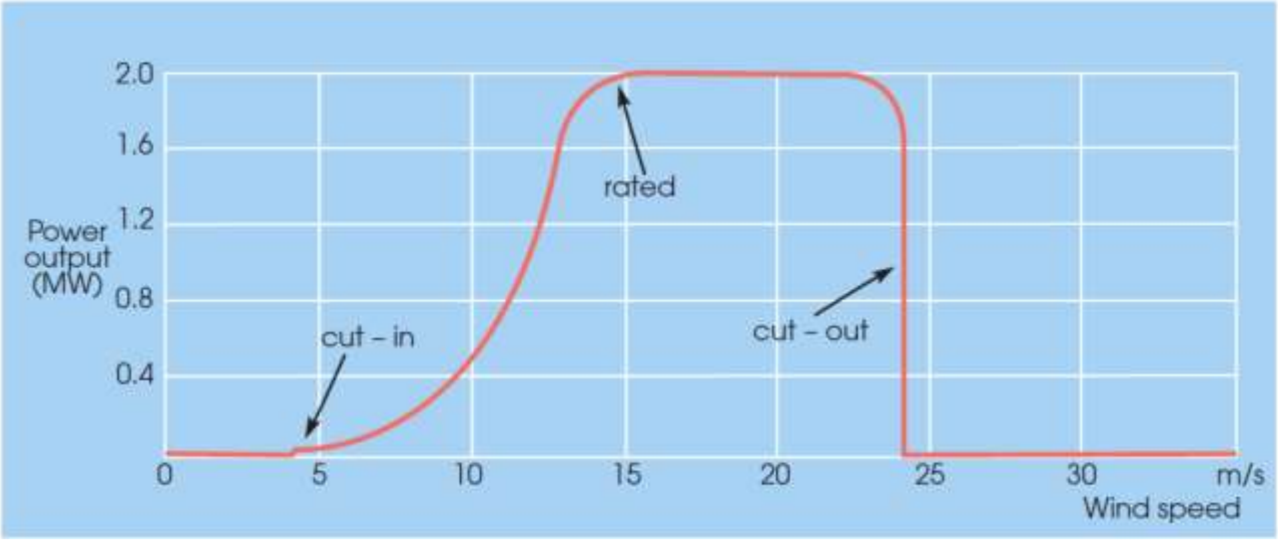


Figure 1.4 : Typical power curve for a 2MW wind turbine

Wind turbines need reliable safety systems to prevent damage in extreme winds. If a machine that is designed to cut out at 24 m/s fails to do so and a 35 m/s storm develops, the intercepted power increases threefold and may threaten disaster.

The above points are illustrated and amplified by Figure 1.5 showing the all important cubic relationship between wind power and speed. Power is given in kilowatts per square metre of intercepted area (kW/m^2). Speed is indicated in metres per second (m/s), and also in knots (nautical miles per hour), which are often used to measure wind strengths at sea.

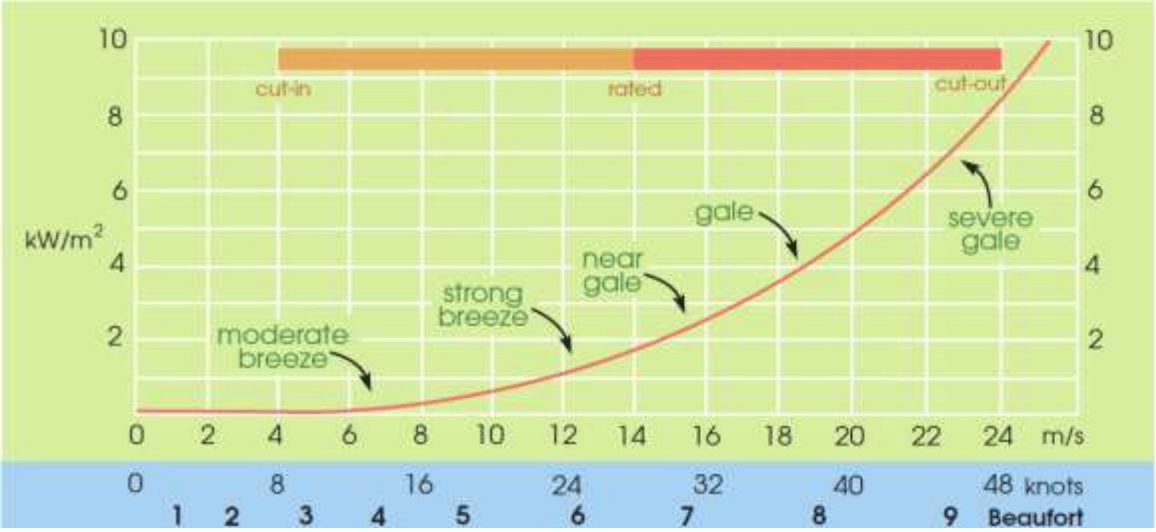


Figure 1.5: Power in the wind.

The horizontal bar at the top of the figure indicates typical cut- in and cut- out speeds of a large wind turbine, together with the speed at which it reaches its rated (peak) output power. Between cut- in and rated speeds we expect the power generated to follow an approximately cubic curve; between rated speed and cut- out it stays close to the rated value. Turbine manufacturers provide tables, or graphs, showing the electrical power produced by their machines at different wind speeds. A typical power curve for a 2 M W turbine is shown in Figure 1 .4.

1.4: Wind Characteristics:

Wind is an indirect solar energy source. Its characteristics can be summarized as follows:

- ✓ It is environmentally clean source of energy.
- ✓ It is a dilute source of energy.
- ✓ It is perennially available.
- ✓ Its availability is unpredictable.
- ✓ Data are available about its availability pattern around the day for different months of the year.

1.5: Classification of Wind Turbines:

Although there are several ways to categorize wind turbines, they are broadly classified into horizontal axis machines and vertical axis machines, based on their axis of rotation.

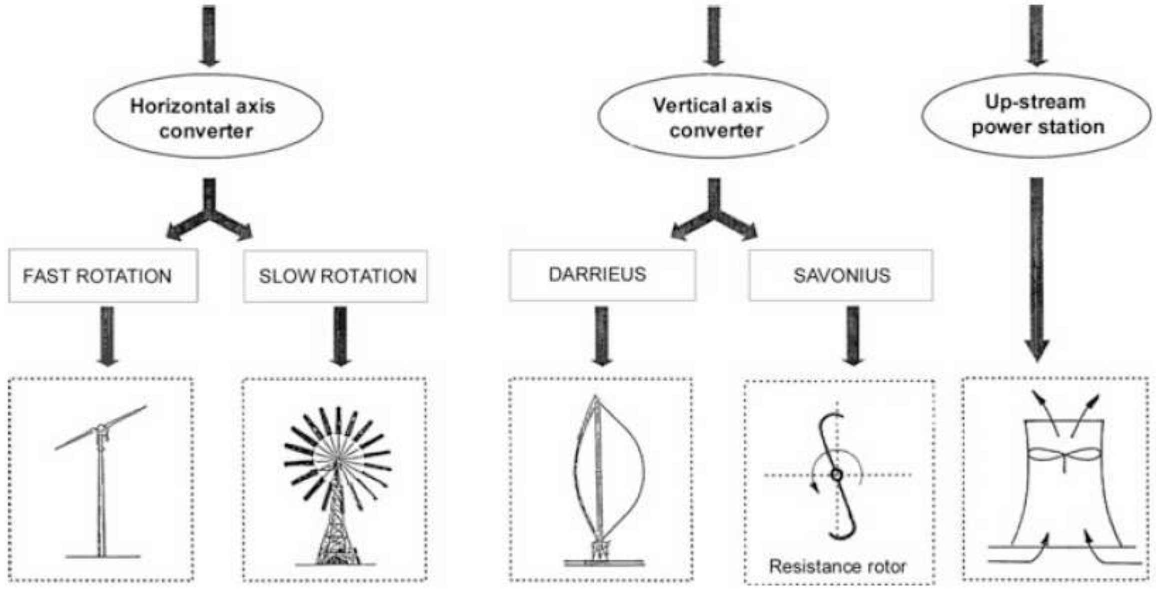


Fig.(1.6) Classification of wind turbines

1.5.1: Horizontal axis wind turbines:

Wind energy converters which have their axis of rotation in a horizontal position are realized almost exclusively on the basis of "propeller-like" concepts. This design, which includes European windmills as much as the American wind turbine or modern wind turbines, is the dominant design principle in wind energy technology today.

Horizontal axis wind turbines (HAWT) have their axis of rotation horizontal to the ground and almost parallel to the wind stream (Fig. 1.7).

Most of the commercial wind turbines fall under this category. Horizontal axis machines have some distinct advantages such as low cut-in wind speed and easy furling. In general, they show relatively high power coefficient. However, the generator and gearbox of these turbines are to be placed over the tower which makes its design more complex and expensive. Another disadvantage is the need for the tail or yaw drive to orient the turbine towards wind.

Depending on the number of blades, horizontal axis wind turbines are further classified as single bladed, two bladed, three bladed and multi bladed.

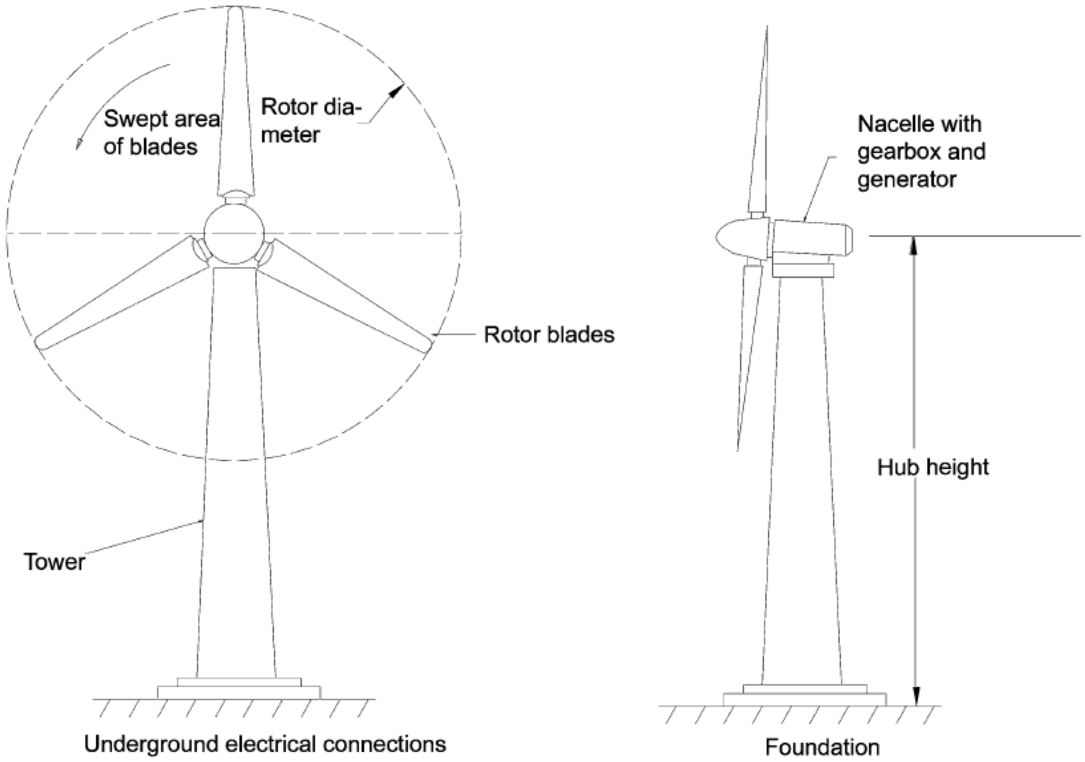


Fig.(1.7): Horizontal axis three blade wind energy converter

1.5.2: Advantages and disadvantages of Horizontal axis wind turbines:

Advantages:

- variable pitch.
- tall tower - higher wind speeds.
- high efficiency.
- steady angle of attack.

Disadvantages:

- tall tower/large blades - difficult to transport, challenging to install
- main components installed at top of tower.
- high visibility.
- yaw control is necessary.

1.6: Vertical axis wind turbines:

The axis of rotation of vertical axis wind turbine (VAWT) is vertical to the ground and almost perpendicular to the wind direction as seen from Fig. 1.8. The VAWT can receive wind from any direction. Hence complicated yaw devices can be eliminated. The generator and the gearbox of such systems can be housed at the ground level, which makes the tower design simple and more economical. Moreover the maintenance of these turbines can be done at the ground level. For these systems, pitch control is not required when used for synchronous applications.

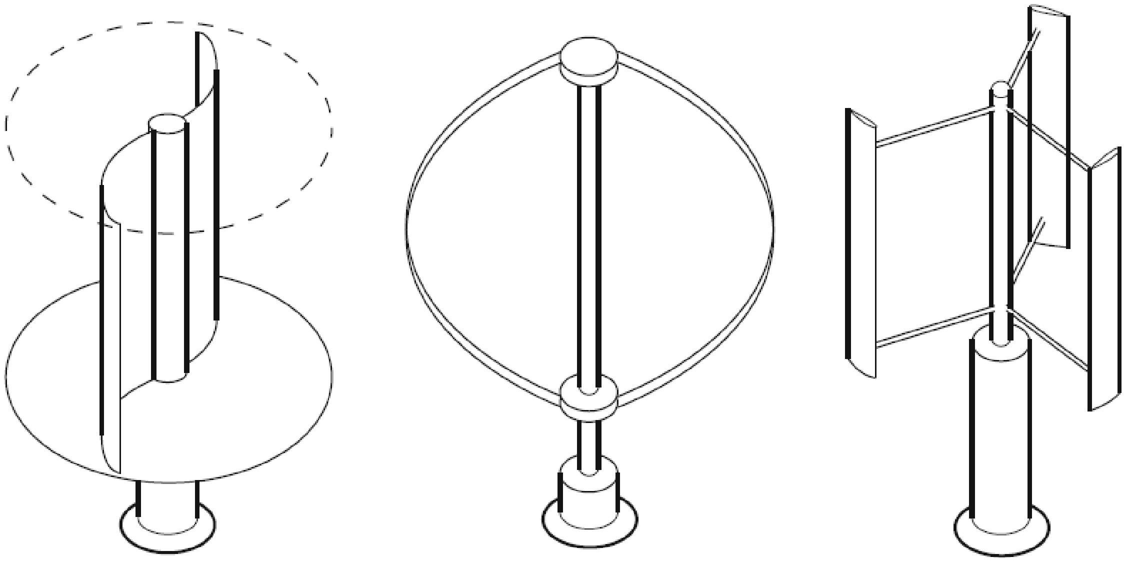


Fig.(1.8): vertical axis wind turbine

1.6.1: Advantages and disadvantages of Vertical axis wind turbines:

Advantages:

- smaller support structure compared with HAWTs.
- yaw control not needed.
- generator components typically located on the ground.
- typically, less noise compared to HAWTs.
- can take advantage of higher wind speeds produced by local structures and geography.

Disadvantages:

- cyclic loading makes fatigue failure more likely.
- lower wind speeds due to shorter structure.

1.7 Upwind or Downwind Turbine

Depending on the orientation and direction of flow, the HAWT can be classified to upwind and downwind as shown in figure(1-9). Upwind machines are those machines that have the rotor facing the wind. In these machines the wind meets the rotor first and then leaves from the direction in which the nacelle is located. Downwind machines have the rotor placed on the leeward side of the tower; this means the nacelle comes first in the path of the wind and then the blades, as shown in Fig. 1.9.

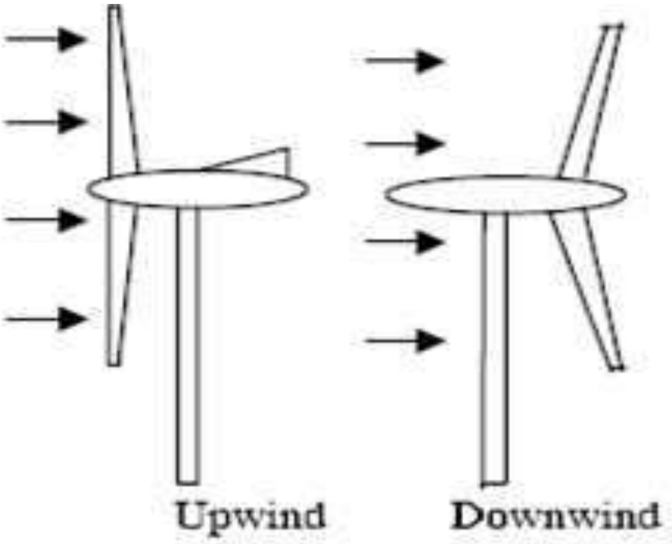


Fig.(1.9): Upwind and downwind turbines

(a) Upwind Machines

The basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design. On the other hand, there is also some wind shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The basic drawback of upwind designs is that the rotor needs to be placed at some distance from the tower. In addition, an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

(b) Downwind Machines

They have the theoretical advantage that they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design that makes the nacelle follow the wind passively. For large wind turbines this is a somewhat doubtful advantage, since for optimal energy efficiency of wind energy converters, the yaw control must be applied very accurately.

Another advantage of the downwind design is that the rotor may be made more flexible. This is an advantage both in regard to weight and the structural dynamics of the machine, i.e. the blades will bend at high wind speeds, thus taking part of the load off the tower.

The basic drawback is the fluctuation in the wind power due to the rotor passing through the wind shade of the tower. This may give more fatigue loads on the turbine than with an upwind design.

Out of these two options, upwind machines are more commonly used due to an increased energy output and hence their being more economical.

1.8 Wind Turbines: With or without Gearbox

(a) Design with Gearbox

The principle of a design of a wind turbine with gearbox, is shown in Figs. 1.10 and 1.11. The main aspect of this design is the split shaft system, where the main shaft turns slowly with the rotor blades and the torque is transmitted through a gearbox to the high-speed secondary shaft that drives the few-pole pair generator.

The transmission of torque to the generator is shut off by means of a large disk brake on the main shaft. A mechanical system controls the pitch of the blades, so pitch control can also be used to stop the operation of the converter, e.g. in stormy conditions. The pitch mechanism is driven by a hydraulic system, with oil as the popular medium. For constructions without a main brake, each blade has its pitch angle controlled by a small electric motor.

The gearbox concept was in many cases accompanied by an insufficient life time because of failure of gearboxes. After many years of operational experiences and a lot of research and development activities it got solved.

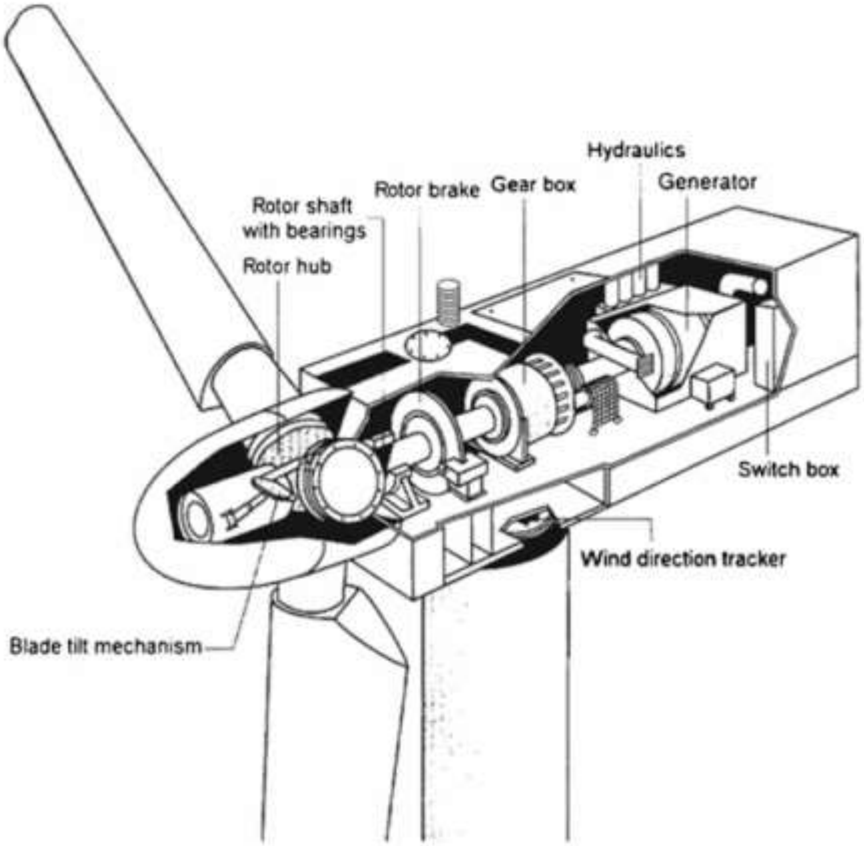


Fig.(1.10): wind turbine with gearbox

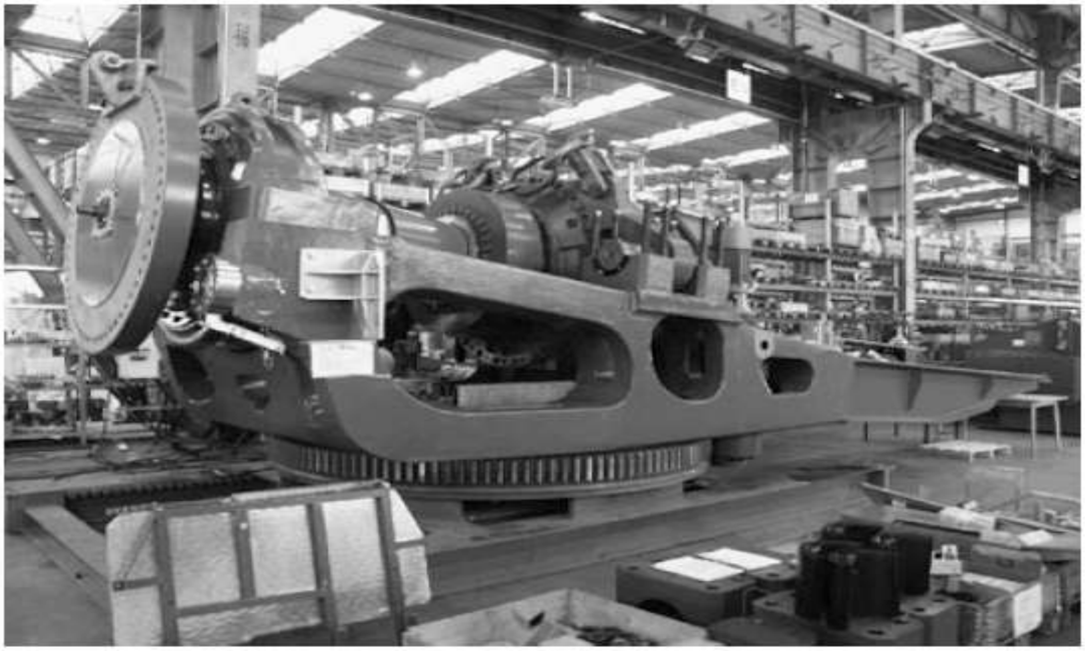


Fig.(1.11): Assembling of a wind turbine with gearbox by NORDEX company (Photo Nordex)

(b) Design without Gearbox

Some companies, e.g. the German company Enercon, designed another converter type without gearbox. The scheme of such a converter is shown in Fig. 1.12, where the main design aspects can be clearly seen. This design has just one stationary shaft.
The rotor blades and the generator are both mounted on this shaft.
The generator is in the form of a large spoked wheel with e.g. forty-two pole pairs around the outer circumference and stators mounted on a stationary arm around the wheel. The wheel is fixed to the blade apparatus, so it rotates slowly with the blades. Therefore, there is no need for a gearbox, rotating shafts or a disk brake.
This minimizing of rotating parts reduces maintenance and failure possibilities and simplifies the maintenance and production of the converter. The price for this advantages is a high nacelle mass caused by the high cupper content of multiple generator.

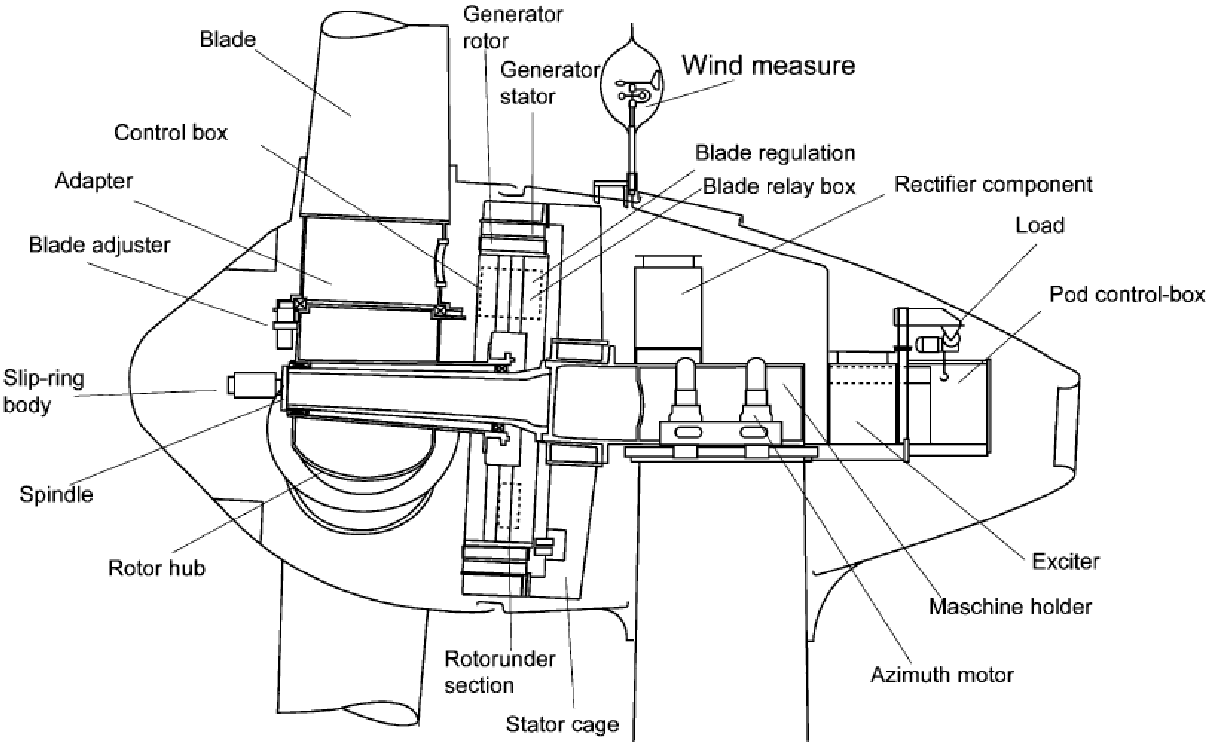


Fig.(1.12): Wind turbine without gearbox (Design of ENERCON company)