3- Renewable energy generation by Wind turbines

1. History of Wind-Mills

The wind is a by-product of solar energy. Approximately 2% of the sun's energy reaching the earth is converted into wind energy. The surface of the earth heats and cools unevenly, creating atmospheric pressure zones that make air flow from high- to low-pressure areas.

The wind has played an important role in the history of human civilization. The first known use of wind dates back 5,000 years to Egypt, where boats used sails to travel from shore to shore. The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C. in ancient Babylon. By the 10th century A.D., windmills with wind-catching surfaces having 16 feet length and 30 feet height were grinding grain in the areas in eastern Iran and Afghanistan.

The earliest written references to working wind machines in western world date from the 12th century. These too were used for milling grain. It was not until a few hundred years later that windmills were modified to pump water and reclaim much of Holland from the sea.

The multi-vane "farm windmill" of the American Midwest and West was invented in the United States during the latter half of the 19th century. In 1889 there were 77 windmill factories in the United States, and by the turn of the century, windmills had become a major American export. Until the diesel engine came along, many transcontinental rail routes in the U.S. depended on large multi-vane windmills to pump water for steam locomotives.

Farm windmills are still being produced and used, though in reduced numbers. They are best suited for pumping ground water in small quantities to livestock water tanks. In the 1930s and 1940s, hundreds of thousands of electricity producing wind turbines were built in the U.S. They had two or three thin blades which rotated at high speeds to drive electrical generators. These wind turbines provided electricity to farms beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers and power a light bulb. By the early 1950s, however, the extension of the central power grid to nearly every American household, via the Rural Electrification Administration, eliminated the market for these machines. Wind turbine development lay nearly dormant for the next 20 years.

A typical modern windmill looks as shown in the following figure. The wind-mill contains three blades about a horizontal axis installed on a tower. A turbine connected to a generator is fixed about the horizontal axis.

Wind Characteristics

1. Wind speed increases roughly as the 1/7th power of height. Typical tower heights are about 20–30 m.
2. *Energy-pattern factor*: It is the ratio of actual energy in varying wind to energy calculated from the cube of mean wind speed. This factor is always greater than unity which means that energy estimates based on mean (hourly) speed are pessimistic.

Utilisation Aspects There are three broad categories of utilisation of wind energy:

1. Isolated continuous duty systems which need suitable energy storage and reconversion systems.
2. Fuel-supplement systems in conjunction with power grid or isolated conventional generating units.
3. Small rural systems which can use energy when wind is available.

Category 2 is the most predominant in use as it saves fuel and is fast growing particularly in energy deficient grids. Category 3 has application in developing countries with large isolated rural areas.

2. Classification of Wind-mills

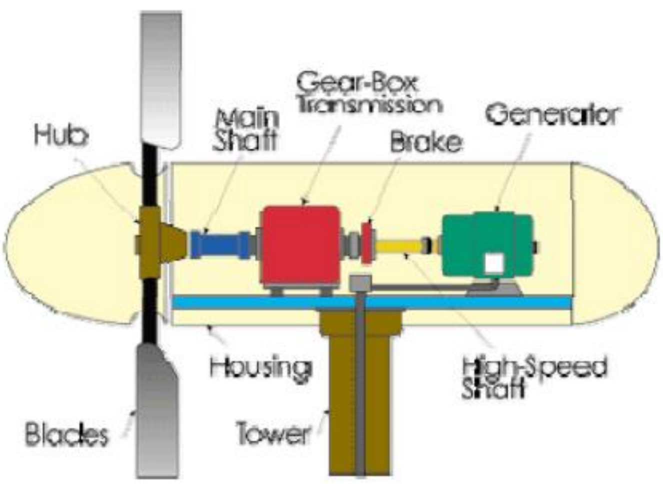
Wind turbines are classified into two general types: Horizontal axis and Vertical axis. A horizontal axis machine has its blades rotating on an axis parallel to the ground as shown in the above figure. A vertical axis machine has its blades rotating on an axis perpendicular to the ground. There are a number of available designs for both and each type has certain advantages and disadvantages. However, compared with the horizontal axis type, very few vertical axis machines are available commercially.

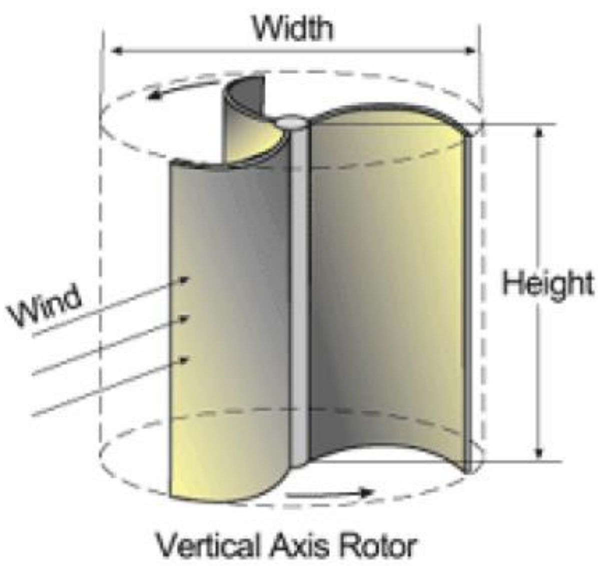
Horizontal Axis

This is the most common wind turbine design. In addition to being parallel to the ground, the axis of blade rotation is parallel to the wind flow. Some machines are designed to operate in an upwind mode, with the blades upwind of the tower. In this case, a tail vane is usually used to keep the blades facing into the wind. Other designs operate in a downwind mode so that the wind passes the tower before striking the blades. Without a tail vane, the machine rotor naturally tracks the wind in a downwind mode. Some very large wind turbines use a motor-driven mechanism that turns the machine in response to a wind direction sensor mounted on the tower. Commonly found horizontal axis wind mills are aero-turbine mill with 35% efficiency and farm mills with 15% efficiency.

Vertical Axis

Although vertical axis wind turbines have existed for centuries, they are not as common as their horizontal counterparts. The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines. The basic vertical axis designs are the Darrieus, which has curved blades and efficiency of 35%, the Giromill, which has straight blades, and efficiency of 35%, and the Savonius, which uses scoops to catch the wind and the efficiency of 30%. A vertical axis machine need not be oriented with respect to wind direction. Because the shaft is vertical, the transmission and generator can be mounted at ground level allowing easier servicing and a lighter weight, lower cost tower. Although vertical axis wind turbines have these advantages, their designs are not as





Main components of Wind Turbine/Mills

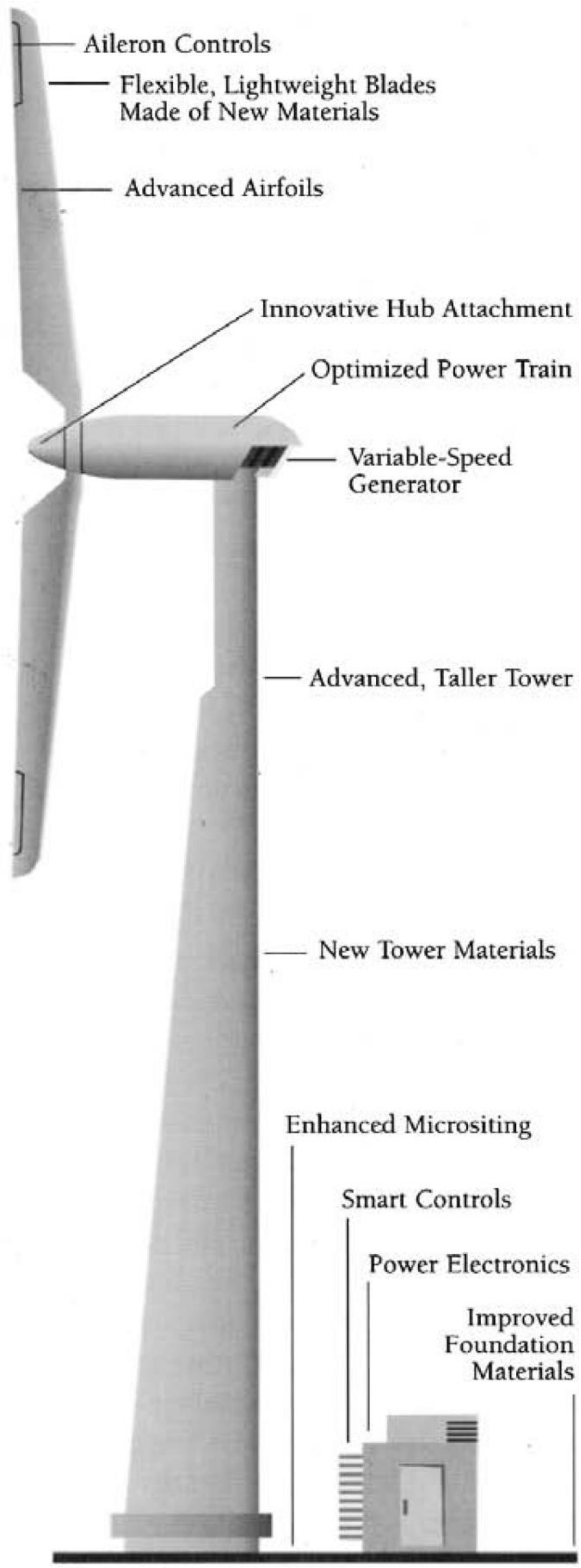


FIGURE 2-1
Modern wind turbine for utility scale power generation.

The wind power system is comprised of one or more units, operating electrically in parallel, having the following components:

- the tower.
- the wind turbine with two or three blades.
- the yaw mechanism such as the tail vane.
- the mechanical gear.
- the electrical generator.
- the speed sensors and control.

The modern system often has the following additional components:

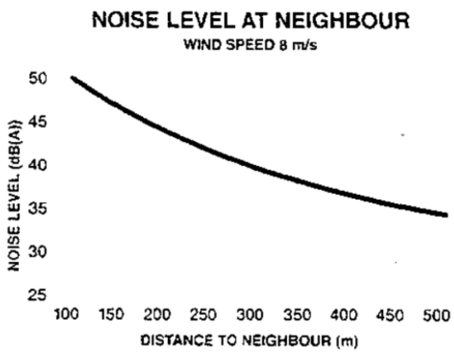
- the power electronics.
- the control electronics, usually incorporating a computer.
- the battery for improving the load availability in stand-alone mode.
- the transmission link connecting to the area grid.

Because of the large moment of inertia of the rotor, the design challenges include the starting, the speed control during the power producing operation, and stopping the turbine when required. The eddy current or other type of brake is used to halt the turbine when needed for emergency or for routine maintenance. In the multiple tower wind farm, each turbine must

have their own control system from a remote location.

Wind to Electric Energy Conversion The choice of electrical system for an aeroturbine is guided by three factors:

1. *Type of electrical output*–DC, variable-frequency AC, constant-frequency AC.
2. *Aeroturbine rotational speed*–constant speed with variable blade pitch, nearly constant speed with simpler pitch-changing mechanism or variable speed with fixed pitch blades.
3. *Utilisation of electrical energy output*–in conjunction with battery or other form of storage, or interconnection with power grid.



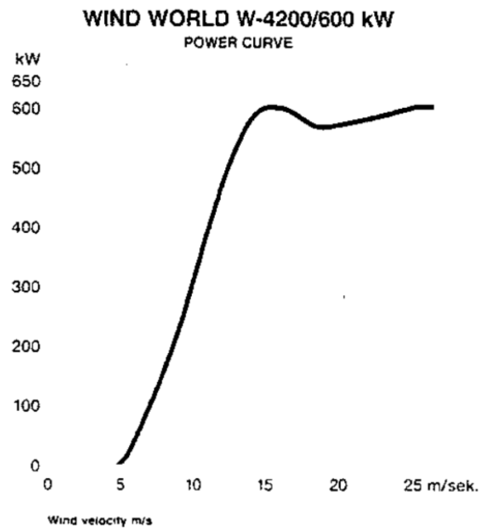
Annual Production:
Average wind velocity 8 m/s:
1.880.000 kWh.

Average wind velocity 7 m/s:
1.467.000 kWh.

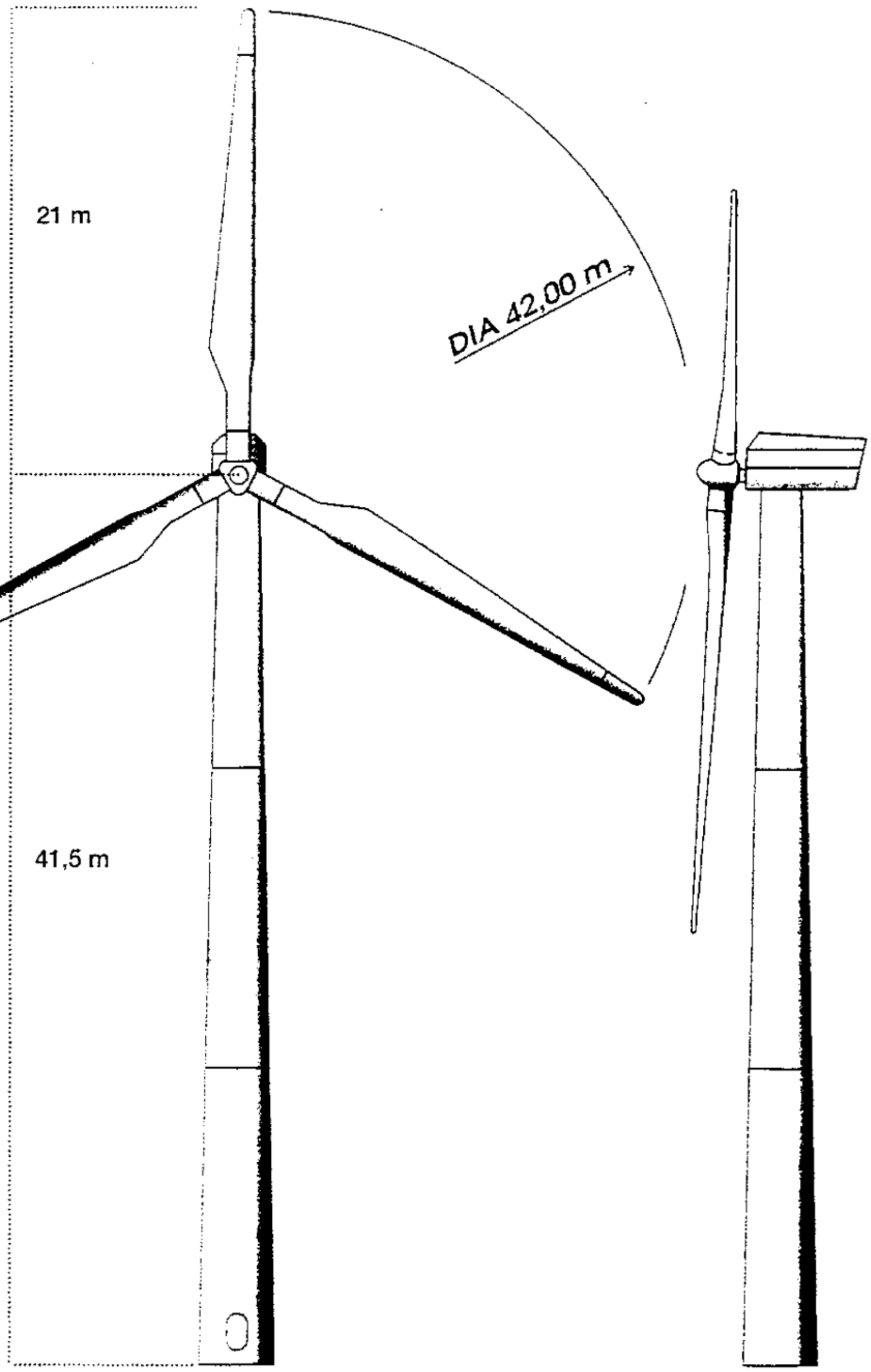
Average wind velocity 6 m/s:
1.020.000 kWh.

Average wind velocity 5 m/s:
596.000 kWh.

Calculations based on Weibull distribution
and shape parameter 2.0.
Wind speed in hubhight.



We reserve the right to make alterations.



Tower:
Type: Conical, tubular
Height: 43,5 m (alt. 40 m)

Generator:
Type: 600 kW, 4 pole, IP 54

Start wind: 4,5 m/s

Swept area: 1385 m^2

Weights:
Total system: 63.000 kg
Blades, hub: 11.400 kg
Tower: 29.200 kg
Nacelle (without rotor): 22.200 kg

Wind World A/S. Buttervej 60. DK-9990 Skagen. Denmark
Phone +45 98 44 40 11. Fax +45 98 44 57 56

FIGURE 5-4
A 600 kW wind turbine and tower dimensions with specifications. (Source: Wind World Cor-

3. Operating Characteristics of wind mills

All wind machines share certain operating characteristics, such as cut-in, rated and cut-out wind speeds.

Cut-in Speed

Cut-in speed is the minimum wind speed at which the blades will turn and generate usable power. This wind speed is typically between 10 and 16 kmph.

Rated Speed

The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 40 kmph. Rated speed for most machines is in the range of 40 to 55 kmph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

Cut-out Speed

At very high wind speeds, typically between 72 and 128 kmph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

Betz Limit

It is the flow of air over the blades and through the rotor area that makes a wind turbine function. The wind turbine extracts energy by slowing the wind down. The theoretical maximum amount of energy in the wind that can be collected by a wind turbine's rotor is approximately 59%. This value is known as the Betz limit. If the blades were 100% efficient, a wind turbine would not work because the air, having given up all its energy, would entirely stop. In practice, the collection efficiency of a rotor is not as high as 59%. A more typical efficiency is 35% to 45%. A complete wind energy system, including rotor, transmission, generator, storage and other devices, which all have less than perfect efficiencies, will deliver between 10% and 30% of the original energy available in the wind.

Mathematical Expression Governing Wind Power

The wind power is generated due to the movement of wind. The energy associated with such movement is the kinetic energy and is given by the following expression:

$$Energy = KE = \frac{1}{2} \cdot m \cdot v^2$$ Where

m = Air mass in Kg = Volume (m^3) x Density (Kg/m^3) = Q x ρ

Q = Discharge

v = Velocity of air mass in m/s

Hence, the expression for power can be derived as follows:

$$Power = \frac{dE}{dt}$$

$$= \frac{1}{2} \cdot \frac{d}{dt} \{ m \cdot v^2 \}$$

$$= \frac{1}{2} \cdot \frac{d}{dt} \{ \rho \cdot Q \cdot v^2 \}$$

$$= \frac{1}{2} \cdot \rho \cdot \frac{dQ}{dt} \cdot v^2$$

Here, $\frac{dQ}{dt}$ = Rate of discharge (m^3/s) = A (m^2) • v (m/s)

Where, A = Area of cross section of blade movement.

$$Power = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

We know that for given length of blades, A is constant and so is the air mass density ρ. Hence we can say that wind power is directly proportional to (wind speed)^3.

At sea level, ρ = 1.2 Kg/m^3. Therefore,

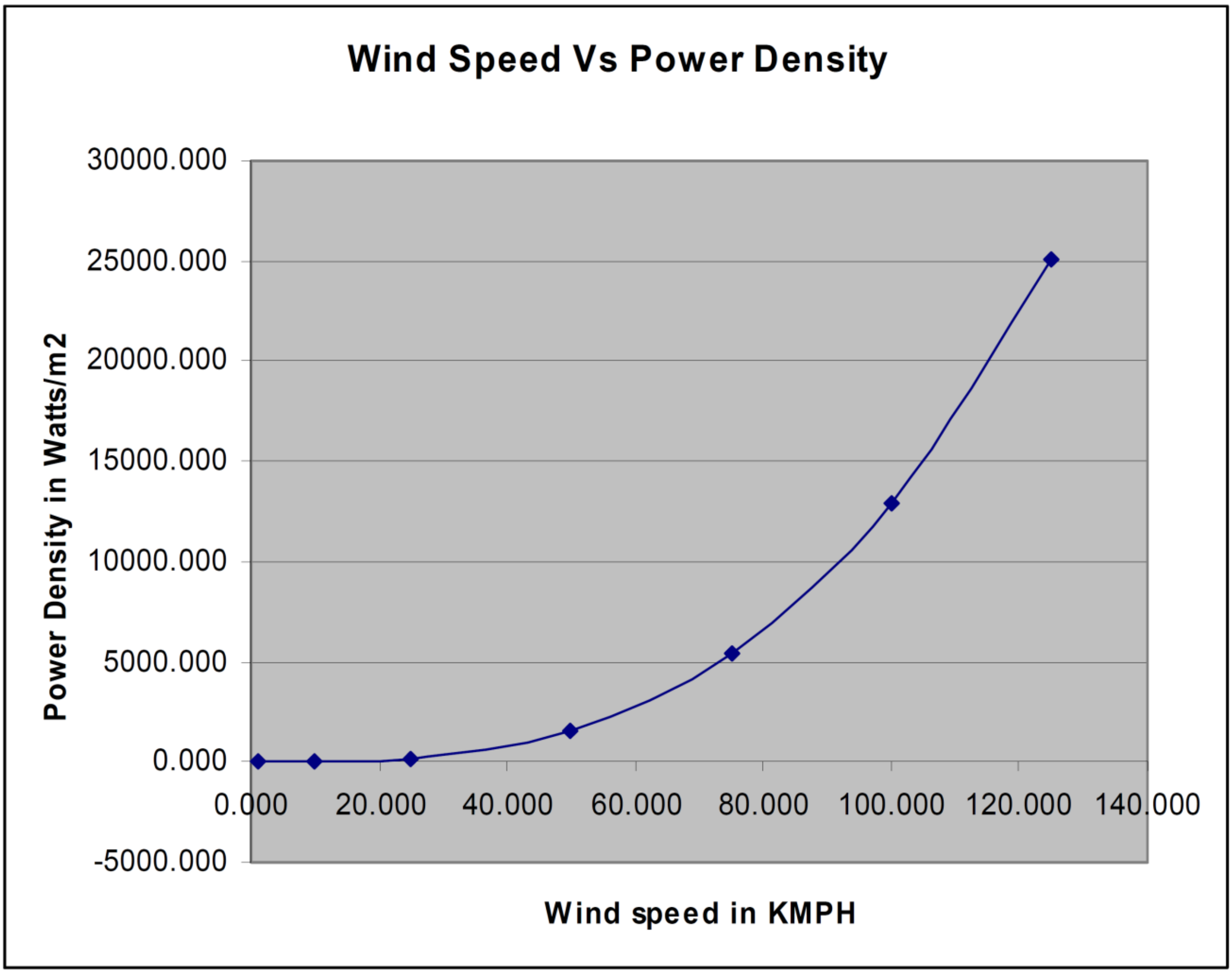
$$Power = \frac{1}{2} \cdot (1.2) \cdot A \cdot v^3$$

$$\frac{Power}{Area} = (0.6) \cdot v^3$$ = Power Density in watts/m^2

Let us construct a chart relating the wind speed to the power density and the output of the wind turbine assuming 30% efficiency of the turbine as shown in the following table.

Wind Speed kmph	Wind speed m/s	Power Density Watts/m^2	Turbine Output 30% efficiency
1	0.278	0.013	0.004
Wind Speed kmph	Wind speed m/s	Power Density Watts/m^2	Turbine Output 30% efficiency
10	2.778	12.860	3.858
25	6.944	200.939	60.282
50	13.889	1607.510	482.253
75	20.833	5425.347	1627.604
100	27.778	12860.082	3858.025
125	34.722	25117.348	7535.204

The following plot gives the relationship between wind speed in KMPH and the power density.



In the last column of the table, we have calculated the output of the turbine assuming that the efficiency of the turbine is 30%. However, we need to remember that the efficiency of the turbine is a function of wind speed. *It varies with wind speed.*

Now, let us try to calculate the wind speed required to generate power equivalent to 1 square meter PV panel with 12% efficiency. We know that solar insolation available at the PV panel is 1000 watts/m^2 at standard condition. Hence the output of the PV panel with 12% efficiency would be 120 watts. Now the speed required to generate this power by the turbine with 30% efficiency can be calculated as follows:

Turbine output required = 120 Watts/m^2

Power Density at the blades = 120/ (0.3) = 400 watts/m^2

Therefore, the wind speed required to generate equivalent power in m/s = $\left(\frac{400}{0.6}\right)^{1/3}$ = 8.735805 m/s = 31.4489 kmph.

We have seen that the theoretical power is given by the following expression:

$$P_{theoretical} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$$

However, there would be losses due to friction and hence, the actual power generated would be smaller. The co-efficient of power is defined as the ratio of actual power to the theoretical power. That is,

$$C_p = \frac{P_{actual}}{P_{theoretical}}$$

Another important ratio we need to know is the tip speed ratio. It is defined as the ratio of tip speed of blade to wind speed. That is,

$$T_R = \frac{Tip\_Speed\_of\_Blade}{Wind\_Speed} = \frac{\omega \cdot radius}{velocity} = \frac{(radians/second) \cdot meters}{(meters/second)}$$

In general, C_p is of the order of 0.4 to 0.6 and T_R is of the order of 0.8. Performance measure of a wind mill is given by a plot of T_R Vs C_p as shown in the following figure:

Example:

5.4 Variable-Speed Operation

At a given site, the wind speed can vary from zero to high gust. As discussed in Chapter 4, the Rayleigh statistical distribution is found to be the best approximation to represent the wind speed at most sites. It varies over a wide range. Earlier in Chapter 4, we defined the tip-speed ratio as follows:

$$TSR = \frac{\textit{Linear speed of the blade outer most tip}}{\textit{Free upstream wind velocity}} = \frac{\omega \cdot R}{V} \qquad (5\text{-}2)$$

where R and ω are the rotor radius and the angular speed, respectively.

For a given wind speed, the rotor efficiency C_p varies with TSR as shown in Figure 5-11. The maximum value of C_p occurs approximately at the same wind speed that gives peak power in the power distribution curve of Figure 5-10. To capture the high power at high wind, the rotor must also turn at high speed, keeping the TSR constant at the optimum level.

Three system performance attributes are related to the TSR:

- The centrifugal mechanical stress in the blade material is proportional to the TSR. The machine working at a higher TSR is stressed more. Therefore, if designed for the same power in the same wind speed, the machine operating at a higher TSR would have slimmer rotor blades.
- The ability of a wind turbine to start under load is inversely proportional to the design TSR. As this ratio increases, the starting torque produced by the blade decreases.
- As seen above, the TSR is also related to the operating point for extracting the maximum power. The maximum rotor efficiency C_p is achieved at a particular TSR, which is specific to the aerodynamic design of a given turbine. The TSR needed for the maximum power extraction ranges from nearly one for multiple-blade, slow-speed machines to nearly six for modern high-speed, two-blade machines.

control. The speed control methods fall into the following categories:

- no speed control whatsoever. In this method, the turbine, the electrical generator, and the entire system is designed to withstand the extreme speed under gusty wind.
- yaw and tilt control, in which the rotor axis is shifted out of the wind direction when the wind speed exceeds the design limit.
- pitch control, which changes the pitch of the blade with the changing wind speed to regulate the rotor speed.
- stall control. In this method of speed control, when the wind speed exceeds the safe limit on the system, the blades are shifted into a position such that they stall. The turbine has to be restarted after the gust has gone.

Advantages of Fixed and Variable Speed Systems

Fixed-Speed System	**Variable-Speed System**
Simple and inexpensive electrical system	Higher rotor efficiency, hence, higher energy capture per year
Fewer parts, hence higher reliability	Low transient torque
Lower probability of excitation of mechanical resonance of the structure	Fewer gear steps, hence inexpensive gear box
No frequency conversion, hence, no current harmonics present in the electrical system	Mechanical damping system not needed, the electrical system could provide damping if required
Lower capital cost	No synchronization problems
	Stiff electrical controls can reduce system voltage sags

The specific rated capacity (SRC) is often used as a comparative index of the wind turbine designs. It is defined as follows:

$$SRC = \frac{Generator\ electrical\ capacity}{Rotor\ swept\ area} \tag{5-1}$$

For the 300/30 wind turbine, the specific rated capacity is $300/\pi\ 15^2 = 0.42\ \mathrm{kW/m^2}$. The specific rated capacity increases with the diameter, giving a favorable economy of scale to large machine. It ranges from approximately $0.2\ \mathrm{kW/m^2}$ for 10-meter diameter rotor to $0.5\ \mathrm{kW/m^2}$ for 40-meter diameter

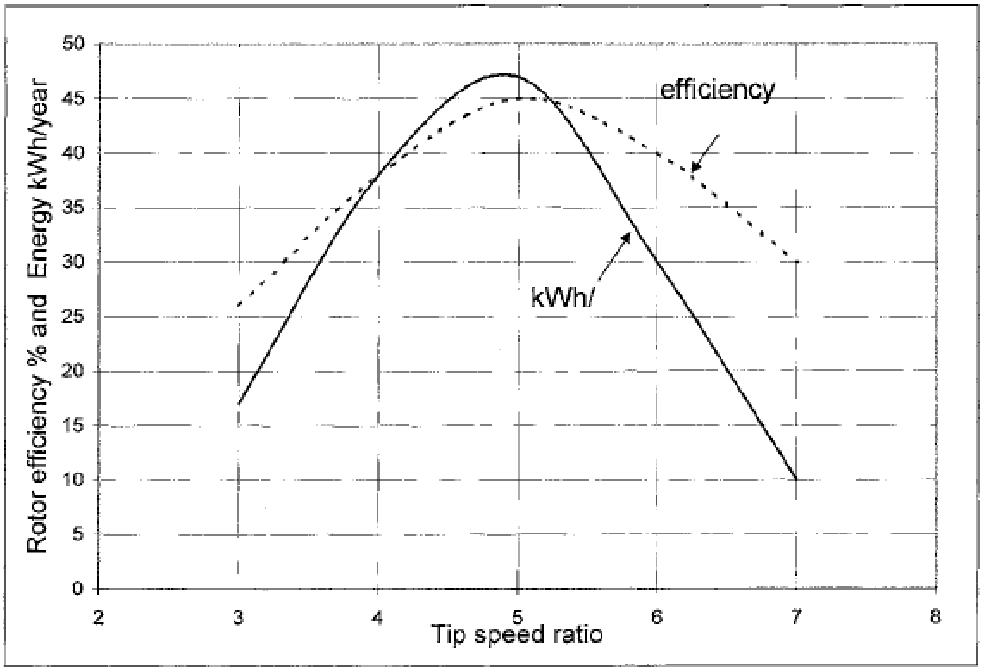


FIGURE 5-11
Rotor efficiency and annual energy production versus rotor tip-speed ratio.

5.5 System Design Features

The following additional design trade-offs are available to the system engineer:

5.5.1 Number of Blades

This is the first determination the design engineer must make. Wind machines have been built with the number of blades ranging from 2 to 40

or more. The high number of blades was used in old low, tip-speed ratio rotors for water pumping, the application which needs high starting torque. The modern high, tip-speeds ratio rotors for generating electrical power have two or three blades, many of them with just two. The major factors involved in deciding the number of blades are as follows:

- the effect on power coefficient.
- the design tip-speeds ratio.
- the cost.
- the nacelle weight.
- the structural dynamics.
- the means of limiting yaw rate to reduce gyroscopic fatigue.

Compared to the two-blade design, the three-blade machine has smoother power output and balanced gyroscopic force. There is no need to teeter the rotor, allowing the use of simple rigid hub. Three blades are more common in Europe, where large machines up to 1 MW are being developed using the three-blade configuration. The American practice, however, has been in the two blade designs. Adding the third blade increases the power coefficient only by about 5 percent, thus giving a diminished rate of return for the 50 percent more weight and cost. The two-blade rotor is also simpler to erect,

5.5.3 Horizontal Axis Versus Vertical Axis

Most wind turbines built at present have a horizontal axis. The vertical axis Darrieus machine has several advantages. First of all, it is omnidirectional and requires no yaw mechanism to continuously orient itself toward the wind direction. Secondly, its vertical drive shaft simplifies the installation of the gearbox and the electrical generator on the ground, making the structure much simpler. On the negative side, it normally requires guy wires attached to the top for support. This could limit its applications, particularly for the offshore sites. Overall, the vertical axis machine has not been widely used because its output power cannot be easily controlled in high winds simply by changing the blade pitch. With modern low-cost, variable-speed power electronics emerging in the wind power industry, the Darrieus configuration may revive, particularly for large capacity applications.

5.5.4 Spacing of the Towers

When installing a cluster of machines in a wind farm, certain spacing between the wind towers must be maintained to optimize the power cropping. The spacing depends on the terrain, the wind direction, the speed, and the turbine size. The optimum spacing is found in rows 8 to 12-rotor diameters apart in the wind direction, and 1.5 to 3-rotor diameters apart in the crosswind direction (Figure 5-12). A wind farm consisting of 20 towers rated at 500 kW each need 1 to 2 square kilometers of land area. Of this, only a couple of percent would actually occupy the tower and the access roads.

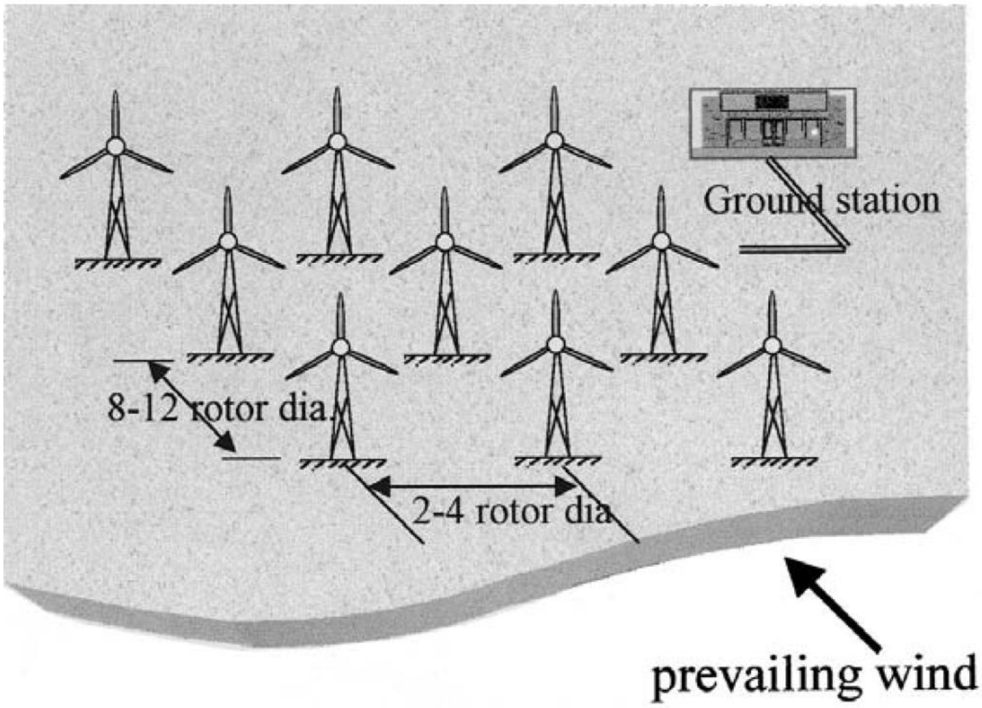


FIGURE 5-12
Optimum tower spacing in wind farms in flat terrain.

If the land is very limited and expensive, the optimization of the wind turbines number, size, and location should consider the following objectives/factors:

- larger turbines cost less per MW capacity and occupy less land area.
- fewer large machines can reduce the MWh energy crop per year, as downtime of one machine would have larger impact on the energy output.
- the wind power fluctuations and electrical transients on fewer large machines would cost more in electrical filtering of the power and voltage fluctuations, or would degrade the quality of power, inviting penalty from the grid.

5.6.1 Constant Tip-Speed Ratio Scheme

This scheme is based on the fact that the maximum energy is extracted when the optimum tip-speed ratio is maintained constantly at all wind speeds. The optimum TSR is a characteristic of the given wind turbine. This optimum value is stored as the reference TSR in the control computer. The wind speed is continuously measured and compared with the blade tip speed. The error signal is then fed to the control system, which changes the turbine speed to minimize the error (Figure 5-14). At this time the rotor must be operating at the reference TSR generating the maximum power. This scheme has a disadvantage of requiring the local wind speed measurements, which could

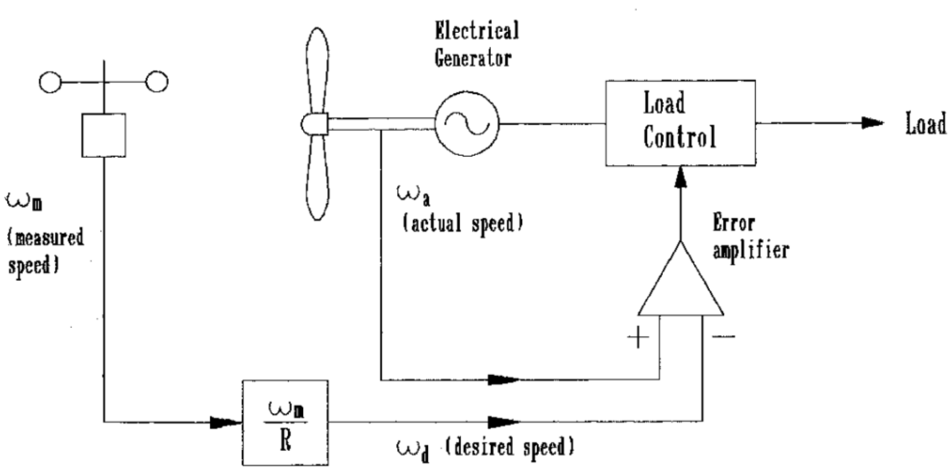


FIGURE 5-14
Maximum power operation using rotor tip-speed control scheme.

have significant error particularly in a large wind farm with shadow effects. Being sensitive to the changes in the blade surface, the optimum TSR gradually changes. The computer reference TSR must be changed accordingly many times over the life. This is expensive. Besides, it is difficult to determine the new optimum tip-speed ratio with changes that are not fully understood, nor easily measured.

With the advent of power switching technology (high power diodes and thyristors) and chip-based associated control circuitry, it has now become possible to use variable-speed constant-frequency (VSCF) systems. VSCF wind electrical systems (WES) and its associated *power conditioning* system operates is shown in Fig. 1.31.

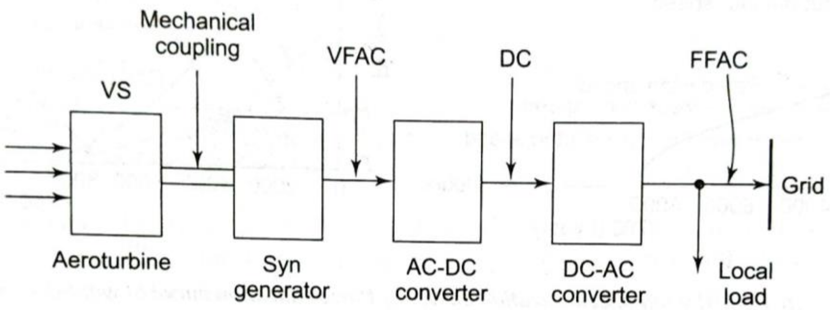


Fig. 1.31 *Block schematic of VSCF wind electrical system; VF (variable frequency), FF (fixed frequency)*

5.6.2 Peak Power Tracking Scheme

The power versus speed curve has a single well-defined peak. If we operate at the peak point, a small increase or decrease in the turbine speed would result in no change in the power output, as the peak point locally lies in a flat neighborhood. Therefore, a necessary condition for the speed to be at the maximum power point is as follows:

$$\frac{dP}{d\omega} = 0 \tag{5-3}$$

This principle is used in the control scheme (Figure 5-15). The speed is increased or decreased in small increments, the power is continuously measured, and $\Delta P/\Delta\omega$ is continuously evaluated. If this ratio is positive, meaning we get more power by increasing the speed, the speed is further increased. On the other hand, if the ratio is negative, the power generation will reduce

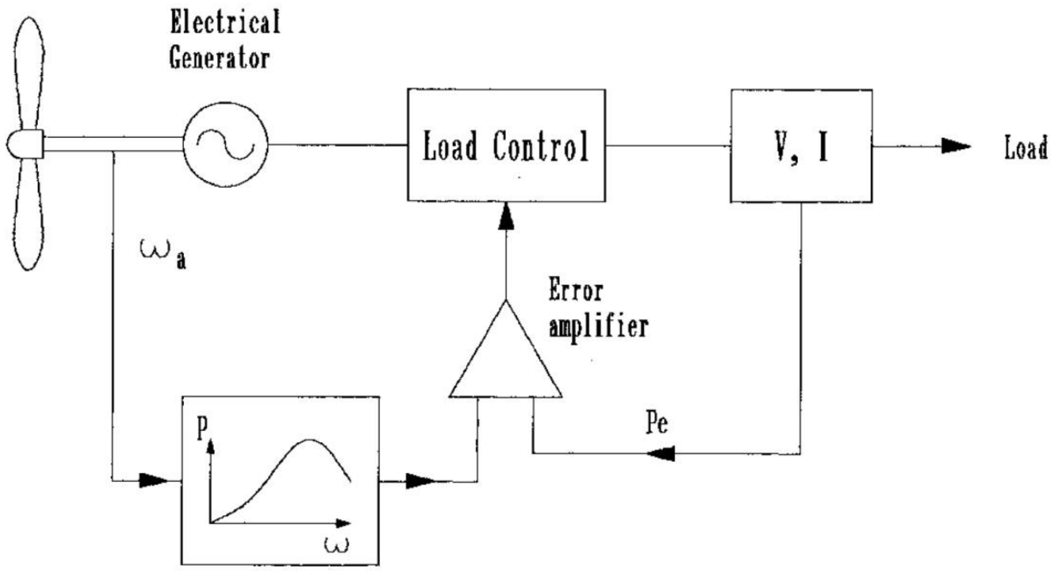


FIGURE 5-15
Maximum power operation using power control scheme.

5.7 System Control Requirements

5.7.1 Speed Control

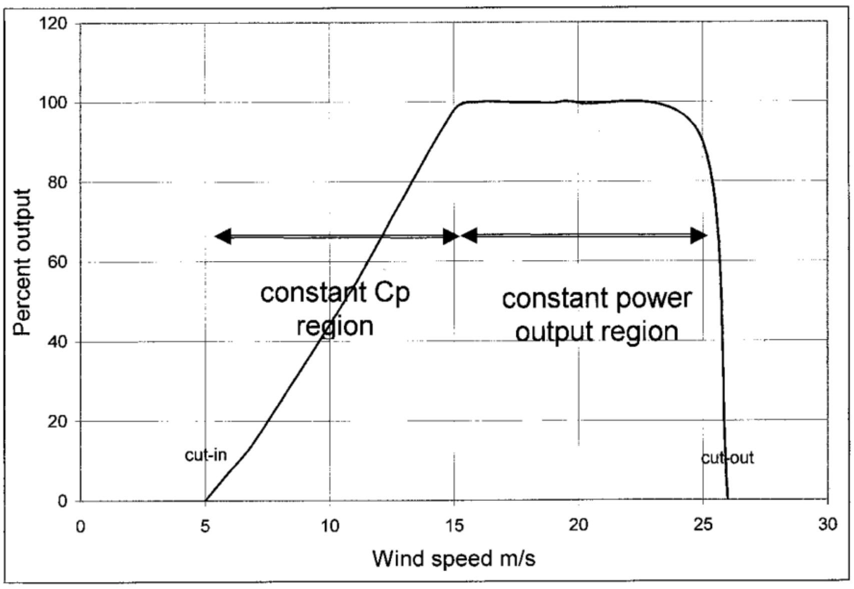
The rotor speed must be controlled for three reasons:

- to capture more energy, as seen above.
- to protect the rotor, the generator and the power electronic equipment from overloading at high wind.
- when the generator is disconnected accidentally or for a scheduled event, losing the electrical load. Under this condition, the rotor speed may run away, destroying it mechanically, if it is not controlled.

The speed control requirement of the rotor has five separate regions (Figure 5-16):

1. The cut-in speed at which the turbine starts producing power. Below this speed, it is not efficient to turn on the turbine.
2. The constant maximum C_p region where the rotor speed varies with the wind-speed variation to operate at the constant TSR corresponding to the maximum C_p value.
3. During high winds, the rotor speed is limited to an upper constant limit based on the design limit of the system components. In the constant speed region, the C_p is lower than the maximum C_p, and the power increases at a lower rate than that in the first region.
4. At still higher wind speeds, such as during a gust, the machine is operated at constant power to protect the generator and the power

5. The cutout speed. Beyond certain wind speed, the rotor is shut off producing power in order to protect the blades, the electrical generator, and other components of the systems.



5.7.2 Rate Control

The large rotor inertia of the blades must be taken into account in controlling the speed. The acceleration and deceleration must be controlled to limit the dynamic mechanical stress on the rotor blades and the hub, and the electrical load on the generator and the power electronics. The instantaneous difference between the mechanical power produced by the blades and the electrical power delivered by the generator will change the rotor speed as follows:

$$J \frac{d\omega}{dt} = \frac{P_m - P_e}{\omega} \tag{5-4}$$

where J = polar moment of inertia of the rotor
ω = angular speed of the rotor
P_m = mechanical power produced by the blades
P_e = electrical power delivered by the generator.

5.8 Environmental Aspects

5.8.1 Audible Noise

The wind turbine is generally quiet. It poses no objectionable noise disturbance in the surrounding area. The wind turbine manufacturers generally supply the machine noise level data in dB versus the distance from the tower. A typical 600 kW machine noise level is shown in Figure 5-8. This machine produces 55 dBA noise at a 50-meter distance from the turbine and 40 dBA at a 250-meter distance. Table 5-2 compares the turbine noise level with other generally known noise levels. The table indicates that the turbine at a 50-meter distance produces noise no higher than the average factory. This

TABLE 5-2

Noise Level of Some Commonly Known Sources Compared with Wind Turbine

Source	Noise level
Elevated train	100 dB
Noisy factory	90 dB
Average street	70 dB
Average factory	60 dB
Average office	50 dB
Quiet conversation	30 dB