Chapter 6

Wind Energy

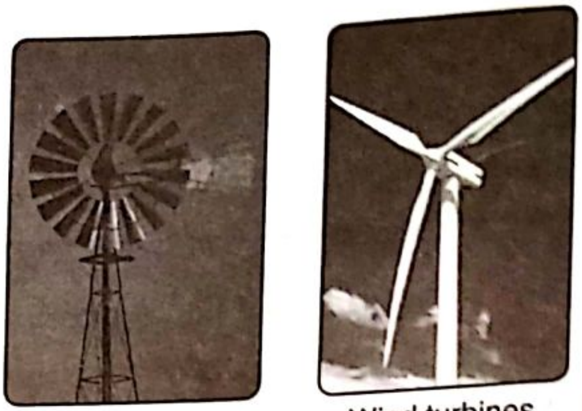
Sun is the main source of wind, and hence, wind is considered a form of solar energy. Winds are caused by the uneven heating of the atmosphere by the sun, the irregularities of the earth's surface, and rotation of the earth. Wind flow patterns are modified by the earth's terrain, water bodies, and vegetative cover. The wind flow or motion energy is 'harvested' by modern wind turbines. Wind power has been utilized for several centuries. The invention of sail boats are the first and most important example of driving them by using wind energy. The earliest known wind-powered grain mills and water pumps were used by the Persians, the Indians, and the Chinese. Wind turbines convert the kinetic energy of the wind into mechanical power. This mechanical power can be used for specific tasks (such as grinding grain or pumping water) or imparting motion to an electric generator that converts mechanical power into electricity.

Windmills have been used for many centuries for pumping water and milling grain. The discovery of the internal combustion engine and the development of electrical grids caused many windmills to disappear in the early part of this century. However, in recent years, there has been a revival of interest in wind energy and attempts are underway all over the world to introduce cost-effective wind energy conversion systems for this renewable and environmentally friendly energy source. In developing countries, wind power can play a useful role for water supply and irrigation (wind pumps) and electrical generation (wind generators). These two variants of windmill technology are discussed in separate technical briefs. This brief gives a general overview of the resource and of the technology for extracting energy from the wind.

KEY CONCEPTS

- Energy availability in the wind
- Wind energy scenario in india and worldwide
- Wind turbine site selection
- Wind turbine power output variation with steady wind speed
- Different parts of wind turbines
- Classification and description of wind machines
- Vertical axis and horizontal axis wind rotors
- Principles of wind energy conversion (aerodynamics)
- Simple wind turbine theory (betz theory of momentum)
- Characteristics of windmill rotors (rotor design)
- Types of electrical generators used with wind turbines
- Applications of wind turbines

If the mechanical energy is used directly by machinery, such as for a pump or grinding stones, the machine is usually called a windmill.



Wind mills Wind turbines

6.2 WIND TURBINES

Wind turbines deliver their power through a revealing shaft, and in this respect, they are similar to other prime movers such as diesel engine and stream turbines. A generator can be coupled to this shaft and the electrical power delivered can be used to serve the multitude of different purposes for which electricity is required today.

In practice, an important difference between the wind turbine and the power delivered by engines and stream turbines is that the power delivered by wind turbines to the same extent uncontrolled and unpredictable over very short periods of time. In most applications for electricity, power is normally required on demand and not whenever available. Therefore, it is important to have some storage or reserve supply. This requirement has been one of the main limitations. If the mechanical energy is then converted to electricity, the machine is called a wind generator.

6.3 ENERGY AVAILABILITY IN THE WIND

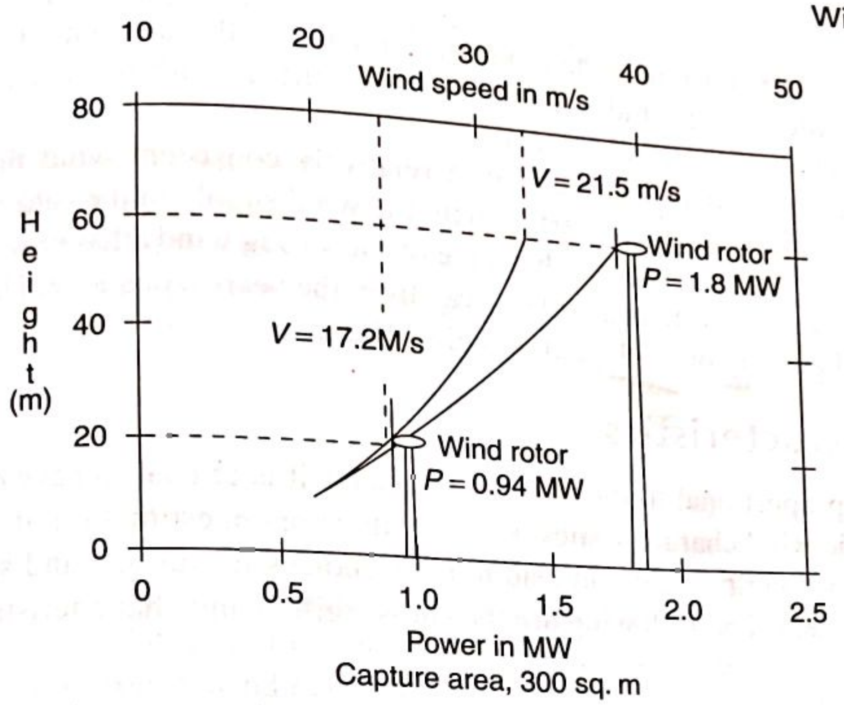


Figure 6.1 Relationship between wind speed, power, and height

varies over a wide range from 0.1 to 0.6 depending on the atmospheric conditions and the terrain near the wind turbine, but a value of 0.2 is common for wind turbine analysis.

For the example shown in Figure 6.1, the wind speed at 10 m height is 15 m/s wind speed.

At 20 m height, the wind speed is 17.2 m/s. Further, there is 0.94 MW of power available in the wind, for a 300 m^2 capture area (1 MW = 1 megawatts = 10^6 watts).

At 60 m, the wind speed is about 25% higher, but the power is almost doubled (≈1.8 MW). Due to physical limits (e.g., Betz limit) as well as inefficiencies in the rotor, generator, and gear-boxes, not all of this power can be captured by a wind turbine.

6.3.1 Wind Potential

In order for a wind energy system to be feasible, there must be an adequate wind supply. A wind energy system usually requires an average annual wind speed of at least 15 km/h. Table 6.1 represents a guideline of different wind speeds and their potential in producing electricity.

A wind generator will produce lesser power in summer than in winter at the same wind speed as air has lower density in summer than in winter. Similarly, a wind generator will produce lesser power in higher altitudes—as air pressure as well as density is lower—than at lower altitudes.

Table 6.1 Wind Turbine Performance with Wind Speed

Average Wind Speed Suitability (km/h)	Wind Turbine Performance
Up to 15	Extremely poor
18	Poor
22	Moderate
25	Good
29	Excellent

Scanned by CamScanner

which increases the output of the wind system.

In order for a wind system to be effective, a relatively consistent wind flow is required. Obstructions such as trees or hills can interfere with the wind supply to the rotors. To avoid this, rotors are placed on top of towers to take advantage of the strong winds that blow high above the ground. The towers are generally placed 100 m away from the nearest obstacle. The middle of the rotor is placed 10 m above any obstacle that is within 100 m.

6.3.2 Wind Characteristics

As the wind power is proportional to the cubic wind speed, it is crucial to have detailed knowledge of the site-specific wind characteristics. Even small errors in estimation of wind speed can have large effects on the energy yield and lead to poor choices for turbine and site. An average wind speed is not sufficient. The following are the site-specific wind characteristics that are pertinent to wind turbines:

1. Mean wind speed: only interesting as a headline figure, but does not tell how often high wind speeds occur.
2. Wind speed distribution: diurnal, seasonal, annual patterns
3. Turbulence: short-term fluctuations
4. Long-term fluctuations
5. Distribution of wind direction
6. Wind shear (profile)

Information on those dimensions and tools for basic yield calculations is required. However, due to the sensitivities, no calculation can replace on-site wind measuring campaigns. The following are the main causes of high turbulence:

1. Inhomogeneous landscapes
2. Steep cliffs or mountain tops
3. Regions with many obstacles—buildings and others

Turbulence adversely affects the performance of wind machines. It includes

1. Reduced production of energy
2. Increased wear and tear shorten lifetime of the turbine
3. Increased dynamic loads on the blades

6.3.3 Wind into Electricity

Although the equation (6.1) gives the power in the wind, the actual power that can be extracted from the wind is significantly lesser than this figure suggested as above. The actual power will depend on the following several factors:

1. The type of machine and rotor used the sophistication of blade design
2. Friction losses

3. The losses in the pump or other equipment connected to the wind machine.
4. There are also physical limits to the amount of power that can be extracted realistically from the wind.

It is shown theoretically in succeeding section that any windmill can only possibly extract a maximum of 59.3% of the power from the wind (this is known as the Betz limit). In reality, this figure is usually around 45% (maximum) for a large electricity producing turbine and around 30%–40% for a wind pump. Therefore, modifying the formula for 'power in the wind', it can be said that the power that is produced by the wind machine can be given by the following formula:

$$P_M = \tfrac{1}{2} C_p \rho S V^3 \tag{6.3}$$

where P_M = power (in watts) available from the machine and C_p = coefficient of performance of the wind machine.

It is also worth bearing in mind that a wind machine will only operate at its maximum efficiency for a fraction of the time it is running, due to the variations in the wind speed. A rough estimate of the output from a wind machine can be obtained using the following equation:

$$P_A = 0.2\, S V^3 \tag{6.4}$$

where P_A = the average power output in watts over the year and V = the mean annual wind speed in m/s.

6.4 WIND RESOURCES

Unfortunately, the general availability and reliability of wind speed data is extremely poor in many regions of the world. Large areas of the world appear to have average annual wind speeds below 3 m/s and are unsuitable for wind power systems; further, almost equally large areas have wind speeds in the intermediate range (3–4.5 m/s), where wind power may or may not be an attractive option. In addition, significant land areas have mean annual wind speeds exceeding 4.5 m/s, where wind power would most certainly be economically competitive.

6.4.1 Worldwide Wind Energy Scenario in 2010

As per the World Wind Energy Report 2010, wind energy scenario in 2010 is summarized as follows:

1. Worldwide capacity reached 196,630 MW, out of which 37,642 MW were added in 2010, slightly less than the capacity in 2009.
2. Wind power showed a growth rate of 23.6%, the lowest growth since 2004 and the second lowest growth of the past decade. All wind turbines installed by the end of 2010 worldwide can generate 430 TWh per annum; this wind power is more than the total electricity demand of the United Kingdom, the sixth largest economy of the world, and equalling 2,5% of the global electricity consumption.
3. China became number one in total installed capacity and the centre of the international wind industry, and it added 18,928 MW within one year, accounting for more than 50% of the world's market for new wind turbines.

4. Major decrease in new installations can be observed in North America and USA lost its number one position in total capacity to China.
5. Many Western European countries are showing stagnation, whereas there is strong growth in the number of Eastern European countries.
6. Germany keeps its number one position in Europe with 27,215 MW, followed by Spain with 20,676 MW.
7. The highest shares of wind power can be found in three European countries: Denmark (21%), Portugal (18%), and Spain (16%).
8. Asia accounted for the largest share of new installations (54,6%), followed by Europe (27,0%) and North America (16,7%).
9. Latin America (1,2%) and Africa (0,4%) still played only a marginal role in new installations.
10. Africa: North Africa represents still lion share of installed capacity, while wind energy plays hardly a role yet in Sub-Saharan Africa.
11. Nuclear disaster in Japan and oil spill in Gulf of Mexico will have long-term impact on the prospects of wind energy. Governments need to urgently reinforce their wind energy policies.
12. WWEA sees a global capacity of 600,000 MW as possible by 2015 and more than 1,500,000 MW by 2020.

6.4.2 Wind Energy in India

The Indian wind energy sector has an installed capacity of 14,158.00 MW (as on March 31, 2011). In terms of wind power installed capacity, India is ranked fifth in the world. Today, India is a major player in the global wind energy market.

The potential is far from exhausted. Indian Wind Energy Association has estimated that with the current level of technology, the 'on-shore' potential for utilization of wind energy for electricity generation is of the order of 65,000 MW. The unexploited resource availability has the potential to sustain the growth of wind energy sector in India in the years to come.

Wind in India are influenced by the strong south-west summer monsoon, which starts in May–June, when cool, humid air moves towards the land; further, the weak north-east winter monsoon, which starts in October, when cool, dry air moves towards the ocean. During March–August, the winds are uniformly strong over the whole Indian Peninsula, except the eastern peninsular coast. Wind speeds during November–March are relatively weak, although high winds are available during a part of the period on the Tamil Nadu coastline. A notable feature of the Indian programme has been the interest among private investors or developers in setting up of commercial wind power projects. The gross potential is 48,561 MW (source C-wet) and a total of about 14,158.00 MW of commercial projects have been established until March 31, 2011. The break-up of projects implemented in prominent wind potential states (as on March 31, 2011) is as given in Table 6.2.

Wind power potential has been assessed assuming 1% of land availability for wind farms requiring at 12 hectare/MW in sites having wind power density in excess of 200 W/m^2 at 50 m hub-height.

Table 6.2 State-wise Wind Power Installed Capacity in India

State	Gross Potential (MW)	Total Capacity (MW) Till 31.03.2011
Andra Pradesh	8,968	200.2
Gujarat	10,645	2,175.6
Karnataka	11,531	1,730.1
Kerala	1,171	32.8
Madhya Pradesh	1,019	275.5
Maharashtra	4,584	2310.7
Orissa	255	–
Rajasthan	4,858	1,524.7
Tamil Nadu	5,530	5,904.4
Others		4
Total(All India)	48,561	14,158

6.5 WIND TURBINE SITE SELECTION

The selection of a wind farm site is complex and time consuming, and also it involves multiple disciplines working on parallel paths. Financing, government permits, meteorological studies, land use restrictions, and design have to be completed well along before a site is approved and before the construction can begin. However, it is imperative in all of the above-referenced steps that construction expertise be involved and consulted to achieve maximum use of the approved site. Generally, there are three principle sources of construction expertise participating in wind farm projects. They are the design team responsible for conceptual and eventual site design, the developer or construction manager of the project, and the wind turbine generator contractor.

Wind is the energy resource that drives a wind turbine. A windmill needs to be placed on a high tower located in wind area. Not just any wind will do, a wind turbine needs air that moves uniformly in the same direction. Eddies and swirls, 'turbulence' in short, does not make good resource for a wind turbine. The rotor cannot extract energy from turbulent wind, and the constantly changing wind direction due to turbulence causes excessive wear and premature failure of turbine. This means that turbine must be placed high enough to catch strong winds, and above turbulent air. Since the tower price goes up quickly with height, there is a limit to what is practical and affordable.

6.5.1 Turbine Height

In general, wind turbines should be sited well above trees, buildings, and other obstacles. When the wind flows over an obstacle like a building or a tree, the wind is slowed down and turbulen

7. They require an additional yaw control mechanism ... wind.

6.7 PRINCIPLES OF WIND ENERGY CONVERSION (AERODYNAMICS)

The VAWT and HAWT use either lift or drag forces to harness the wind. Out of these types, the horizontal-axis lift device is the most commonly used. In fact, other than a few experimental machines, virtually all windmills come under this category.

There are two primary physical principles by which energy can be extracted from the wind. These are through the creation of either lift or drag force (or through a combination of the two), as shown in Figure 6.14.

Air flow over a stationary airfoil produces two forces, a lift force perpendicular to the air flow and a drag force in the direction of air flow, as shown in Figure 6.14. The existence of the lift force depends upon laminar flow over the airfoil, which means that the air flows smoothly over both sides of the airfoil. If turbulent flow exists rather than laminar flow, there will be little or no lift force. The air flowing over the top of the airfoil has to speed up because of a greater distance to travel and this increase in speed causes a slight decrease in pressure. This pressure difference across the airfoil yields the lift force, which is perpendicular to the direction of air flow. The air moving over the airfoil also produces a drag force in the direction of the air flow. This is a loss term and is minimized as much as possible in high-performance wind turbines

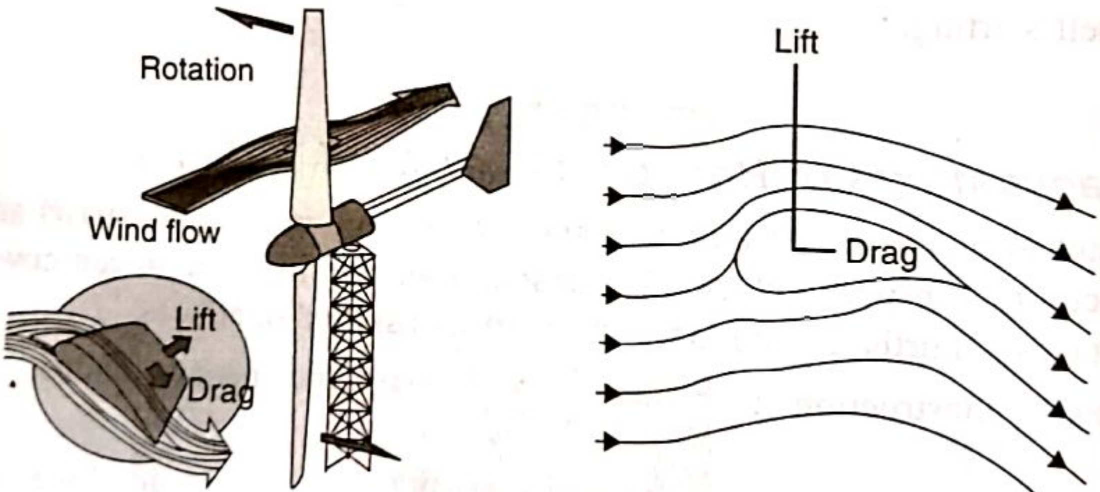


Figure 6.14 Principles of wind turbine aerodynamics

The basic features that characterize lift and drag are as follows:

1. Drag is in the direction of air flow.
2. Lift is perpendicular to the direction of air flow.
3. Generation of lift always causes a certain amount of drag to be developed.
4. With a good aerofoil, the lift produced can be 30 times greater than the drag
5. Lift devices are generally more efficient than drag devices.

The difference between the drag and the lift is illustrated by the difference between using a spinnaker sail, which fills like a parachute and pulls a sailing boat with the wind, and a Bermuda rig, the familiar triangular sail that deflects with wind and allows a sailing boat to travel across the wind or slightly into the wind.

Drag forces provide the most obvious means of propulsion and these being the forces felt by a person (or object) exposed to the wind. Lift forces are the most efficient means of propulsion, but being more subtle than drag forces are not so well understood.

6.7.1 Lift Force

The lift force (F_L) arises in a direction that is perpendicular to the airstream caused by Bernoulli's effect that lowers the pressure on the top of the airfoil when compared with the pressure on its bottom. The curvature on the top leads to a higher stream velocity than at the bottom and hence a lower pressure. Let (F_L) is the lift force in Newton, (S_L) is the cross-sectional area of airfoil in m^2, ρ is the air density in kg/m^2, and V is the wind speed in m/s^2. Then, lift coefficient (C_L) is defined as follows:

$$C_L = [F_L/S_L]/[(1/2)\rho V^2]$$

6.7.2 Drag Force

Similarly, drag force (F_D) is described as

$$C_D = [F_D/S_D]/[(1/2)\rho V^2]$$

where C_D = drag coefficient and S_D = effective area of airfoil in the direction of drag force.

The lift and drag force vary with the angle that rotor blade makes with the direction of wind stream. This angle is called as angle of attack. The resultant of drag and lift forces constitute the thrust force that effectively rotate the blade.

6.7.3 Capturing Wind Power

Just like an aeroplane wing, wind turbine blades work by generating lift due to their shape. The more curved side generates low air pressures, while high pressure air pushes on the other side of the aerofoil. The net result is a lift force perpendicular to the direction of the flow of the air.

The lift force increases as the blade is turned to present itself at a greater angle to the wind. This is called the angle of attack (see Fig. 6.15a). At very large angles of attack, the blade 'stalls' and the lift decreases again. Therefore, there is an optimum angle of attack to generate the maximum lift.

There is, unfortunately, also a retarding force on the blade, that is, the drag. This is the force parallel to the wind flow, and also increases with angle of attack. If the aerofoil shape is good, the lift force is much bigger than the drag, but at very high angles of attack, especially when the blade stalls, the drag increases dramatically. Therefore, at an angle slightly less than the maximum lift angle, the blade reaches its maximum lift or drag ratio. The best operating point will be between these two angles.

Both the lift and the drag are proportional to the air density, the area of the airfoil, and the square of the wind speed. Suppose now that we allow the airfoil to move in the direction of the lift force. This motion or translation will combine with the motion of the air to produce a relative wind direction, as shown in Figure 6.15(a). The airfoil has been reoriented to maintain a good lift to drag ratio. The lift is perpendicular to the relative wind, but it is not in the direction of airfoil translation.

The lift and drag forces can be split into components parallel and perpendicular to the direction of the undisturbed wind, and these components combined to form net force F_1 in the direction of translation and net force F_2 in the direction of the undisturbed wind. Force F_1 is available to do useful work. Force F_2 must be used in the design of the airfoil supports to assure structural integrity.

A practical way of using F_1 is to connect two such airfoils or blades to a central hub and allow them to rotate around a horizontal axis, as shown in Figure 6.15(b). Force F_1 causes a torque that drives some load connected to the propeller. The tower must be strong enough to withstand force F_2.

These forces and the overall performance of a wind turbine depend on the construction and orientation of the blades. One important parameter of a blade is the pitch angle, which is the angle between the chord line of the blade and the plane of rotation, as shown in Figure 6.15(c).

The chord line is the straight line connecting the leading and trailing edges of an airfoil. The plane of rotation is the plane in which the blade tips lie as they rotate. The blade tips actually

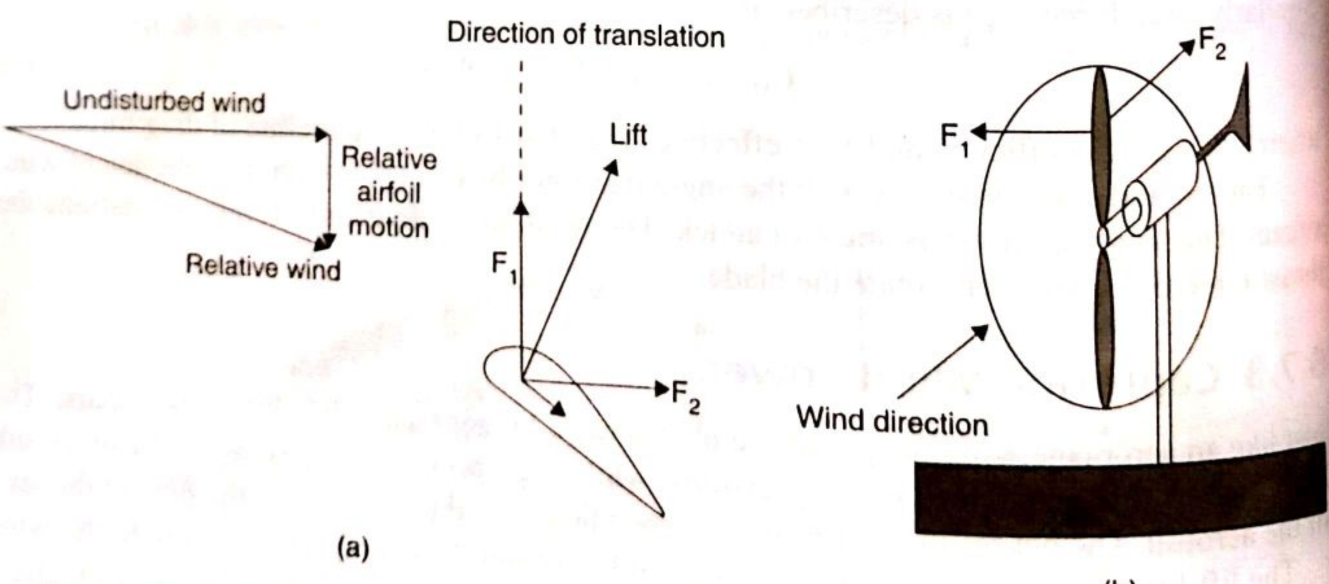
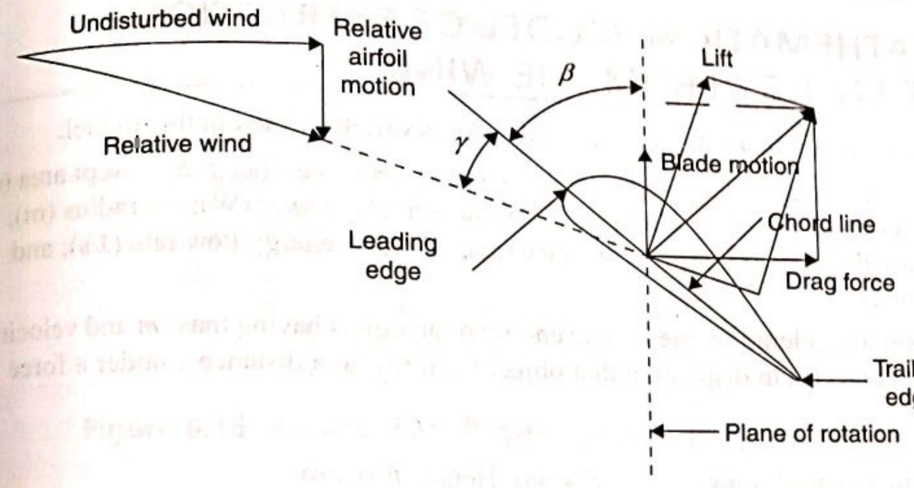


Figure 6.15 (a) Lift and drag on a translating airfoil (b) aerodynamic forces on a turbine blade



(c)

Figure 6.15 (c) Definition of pitch angle β and angle of attack γ

trace out a circle that lies on the plane of rotation. Full power output would normally be obtained when the wind direction is perpendicular to the plane of rotation. The pitch angle is a static angle, depending only on the orientation of the blade.

Another rtant blade parameter is the angle of attack, which is the angle γ between the chord line of the blade and the relative wind or the effective direction of air flow. It is a dynamic angle, depending on both the speed of the blade and the speed of the wind. The blade speed at a distance r from the hub and an angular velocity ω_m is $r\omega_m$.

A blade with twist will have a variation in angle of attack from hub to tip because of the variation of $r\omega_m$ with distance from the hub. The lift and drag have optimum values for a single angle of attack, so a blade without twist is less efficient than a blade with the proper twist to maintain a nearly constant angle of attack from hub to tip. Even the blades of the Old Dutch windmills were twisted to improve the efficiency. Most modern blades are twisted, but some are not for cost reasons. A straight blade is easy and cheap to build and the cost reduction may more than offset the loss in performance.

When the blade is twisted, the pitch angle will change from hub to tip. In this situation, the pitch angle measured three-fourths of the distance out from the hub is selected as the reference. Since the drag is in the downwind direction, it may seem that it would not matter for a wind turbine as the drag would be parallel to the turbine axis, so would not slow the rotor down. It would just create 'thrust', the force that acts parallel to the turbine axis; hence, it has no tendency to speed up or slow down the rotor. When the rotor is stationary (e.g. just before start-up), this is indeed the case. However, the blade's own movement through the air means that, as far as the blade is concerned, the wind is blowing from a different angle. This is called apparent wind. The apparent wind is stronger than the true wind but its angle is less favourable: it rotates the angles of the lift and drag to reduce the effect of lift force pulling the blade round and increase the effect of drag slowing it down. It also means that the lift force contributes to the thrust on the rotor. The result of this is that, to maintain a good angle of attack, the blade must be turned further from the true wind angle.

6.8 MATHEMATICAL MODEL OF EXTRACTION OF ENERGY FROM THE WIND

The following table shows the definition of various variables used in this model:

E = kinetic energy (J); ρ = density (kg/m^3); m = mass (kg); S = swept area (m^2);
v = wind speed (m/s); C_p = power coefficient; P = power (W); r = radius (m);
dm/dt = mass flow rate (kg/s); x = distance (m); dE/dt = energy flow rate (J/s); and
t = time (s).

Under constant acceleration, the kinetic energy of an object having mass m and velocity v is equal to the work done (W) in displacing that object from rest to a distance x under a force F, that is,

$$E = W = Fx$$

According to Newton's Law, $F = ma$. Hence, $E = max$ (6.5)

Using the third equation of motion, $V^2 = U^2 + 2ax$, it can be written that $a = (V^2 - U^2)/2x$.
Since the initial velocity of the object is zero, $u = 0$, and hence, $a = V^2/2x$
Substituting it in Equation (6.5), the kinetic energy of a mass in motions is

$$E = ½\, mV^2 \tag{6.6}$$

The power in the wind is given by the rate of change of energy:

$$P = \mathrm{d}E/\mathrm{d}t = ½\ \dot{m}\ V^2 \tag{6.7}$$

The mass flow rate is given by, $= \rho S\mathrm{d}x/\mathrm{d}t$ and the rate of change of distance is given by

$$V = \mathrm{d}x/\mathrm{d}t.\text{Thus}, = \rho SV.$$

Substituting the abovementioned expression in Equation (6.7) yields

$$P = 1/2\ \rho SV^3 \tag{6.8}$$

A German physicist Albert Betz concluded in 1919 that no wind turbine can convert more than 16/27 (59.3%) of the kinetic energy of the wind into mechanical energy turning a rotor. At present, this is known as the Betz limit or Betz' law. The theoretical maximum power efficiency of any design of wind turbine is 0.59 (i.e., no more than 59% of the energy carried by the wind can be extracted by a wind turbine). This is called the 'power coefficient' and is defined as:

$C_{pmax} = 0.59$ and is shown in Figure 6.16. Further, wind turbines cannot operate at this maximum limit. The C_p value is unique to each turbine type and is a function of wind speed that the turbine is operating in. Once we incorporate various engineering requirements of a wind turbine—strength and durability, in particular—the real world limit is well below the Betz limit with values of 0.35–0.45 common even in the best designed wind turbines.

By the time one take into account the other factors in a complete wind turbine system—for example, the gearbox, bearings, generator, etc.—only 10%–30% of the power of the wind is ever actually converted into usable electricity.

Hence, the power coefficient needs to be factored in Equation (6.8) and the extractable power from the wind is given by

$$P_{\text{available}} = C_p\ (1/2\rho SV^3) \tag{6.9}$$

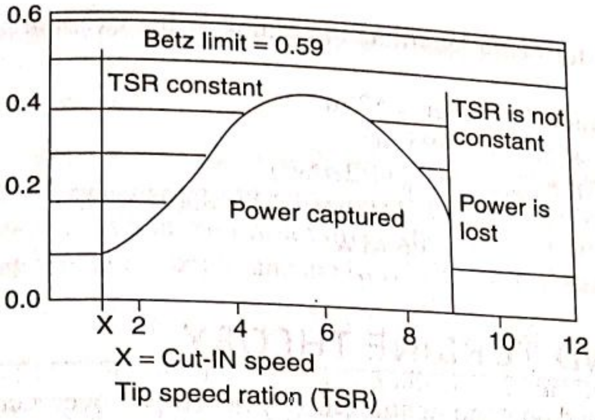


Figure 6.16 Variation of C_p with tip-speed ratio (TSR)

The swept area of the turbine can be calculated from the length of the turbine blades using the equation for the area of a circle:

$$S = \pi r^2 \tag{6.10}$$

where the radius is equal to the blade length as shown in Figure P6.1.

Example 6.1

A three-bladed wind rotor with blade length of 52 m is operating in a wind stream having wind velocity of 12 m/s. Air density is 1.23 kg/m^3 and power coefficient may be taken as 0.4. Calculate the extractable power from the wind.

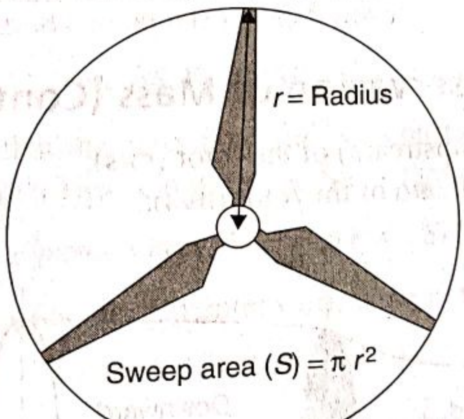


Figure P6.1 Three-bladed wind rotor

Solution Given data are as follows:

Blade length, $L = 52$ m; wind speed, $v = 12$ m/s; air density, $\rho = 1.23$ kg/m^3; power coefficient, $C_p = 0.4$.

Substituting the value for blade length as the radius of the swept area in Equation (6.10) we have:

Radius of blade = L = radius of blade = 52 m

A = swept area = $\pi r^2 = \pi(52)^2 = 8{,}495\ m^2$

Using the equation (6.9), $P_{available} = C_p\,(1/2\rho A v^3)$

$= 0.4 \times ½ \times 1.23 \times 8{,}495 \times (12)^3$

$= 3.6$ MW

6.9 SIMPLE WIND TURBINE THEORY

The simplest model is based on a momentum theory developed over a century ago to predict the performance of ship propellers. The adaptation of this early theory to wind turbines was undertaken by Betz (1927), and the turbine being represented by a uniform actuator disc that generates a discontinuity of pressure in the stream tube of air flowing through it. A simple representative showing the overall control volume is given in Figure 6.17.

6.9.1 Assumptions

1. The rotor does not possess a hub; this is an ideal rotor, with an infinite number of blades, which have no drag. Any resulting drag would only lower this idealized value.
2. The flow in and out of the rotor is axial. This is a control volume analysis, and to construct a solution, the control volume must contain all flow going in and out; however, failure to account for that flow would violate the conservation equations.
3. This is incompressible flow. The density remains constant, and there is no heat transfer from the rotor to the flow or vice versa.
4. The rotor is also mass less. Therefore, angular momentum imparted to either the rotor or the air flow behind the rotor is not considered, that is, wake effect was not taken into account.

6.9.2 Application of Conservation of Mass (Continuity Equation)

Let V_1 = the speed of wind in front (upstream) of the rotor (m/s);

V_2 = the speed of wind in downstream of the rotor (m/s);

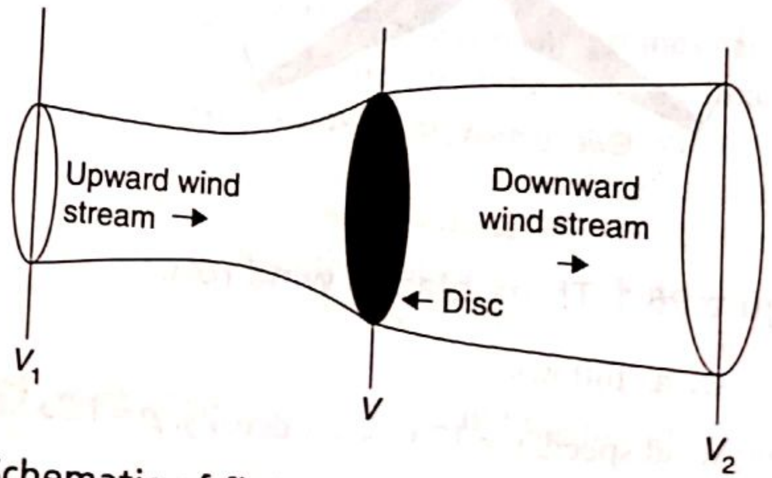


Figure 6.17 Schematic of fluid flow through a disk-shaped actuator

Example 6.2

Wind speed at a particular location is 10 m/s at 1atm and 15°C. Calculate density of air.

Solution $1 \text{ atm} = 1.01325 \times 10^5 \text{ Pa} = 1.01325 \times 10^2 \text{ kPa}$

Temperature in K = $15 + 273 = 288$ K

Using Equation (6.34), $\rho = 3.485\ p/T = 3.485 \times 1.01325 \times 10^2/288 = 1.226\ \text{kg/m}^3$.

In the diagram shown in Figure P6.2, the wind turbine converts 70% of the Betz Limit into electricity. Therefore, C_p of this wind turbine would be $0.7 \times 0.59 = 0.41$. Therefore, this wind turbine converts 41% of the available wind energy into electricity. This is actually a pretty good coefficient of power. Good wind turbines generally fall in the 35%–45% range.

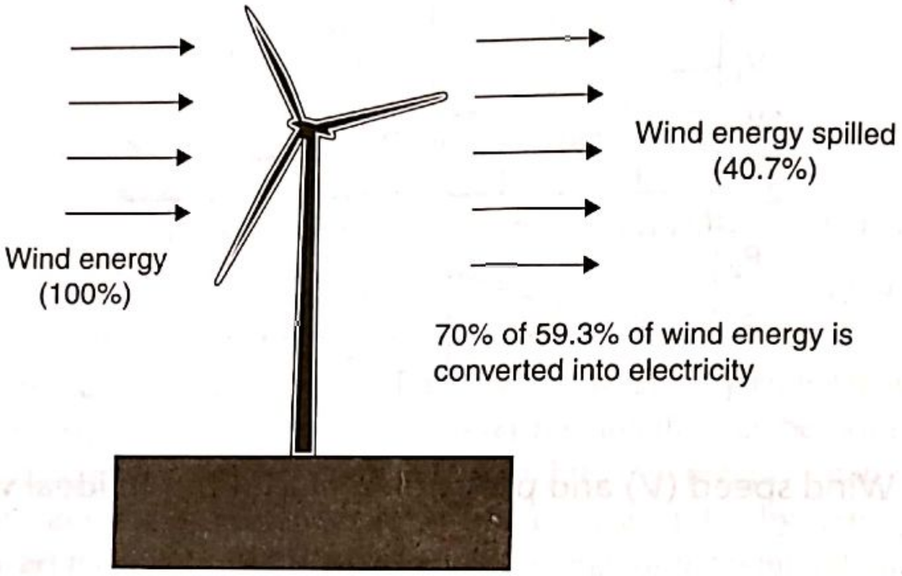


Figure P6.2 Wind energy conversion

6.10 CHARACTERISTICS OF WINDMILL ROTORS (ROTOR DESIGN)

In order to understand the effects of differences in rotor design, it is useful to describe how the blades of a rotor react to the wind, and to define some of the standard design parameters. Several technical parameters are discussed in the following sections.

6.10.1 Pitch

The blades of a rotor are curved so that they deflect the wind, as illustrated in Figure 6.20. The lift force created causes the rotor to rotate. In order to generate the maximum amount of lift, the blades must be set at an appropriate angle (β) to the wind called the pitch.

Since the tips of the blades travel faster than points near the axis, the angle of the wind 'seen' by the blade changes with the radius, as shown in Figure 6.20. The rotor is most efficient if this angle 'seen' by the blade is as large as possible without being so large than the rotor stalls. To make the angle large all the way along the blade, it must be twisted. For the same reason, a rotor designed to rotate fast, such as a two- or three-bladed wind turbine and has its blades set at a small pitch.

6.10.2 Tip-speed Ratio (TSR)

It is defined as the ratio of the speed of the extremities (see Fig. 6.21) of a windmill rotor to the speed of the free wind. It is a variable expressing the ratio between the peripheral blade speed and the wind speed denoted by TSR and computed as

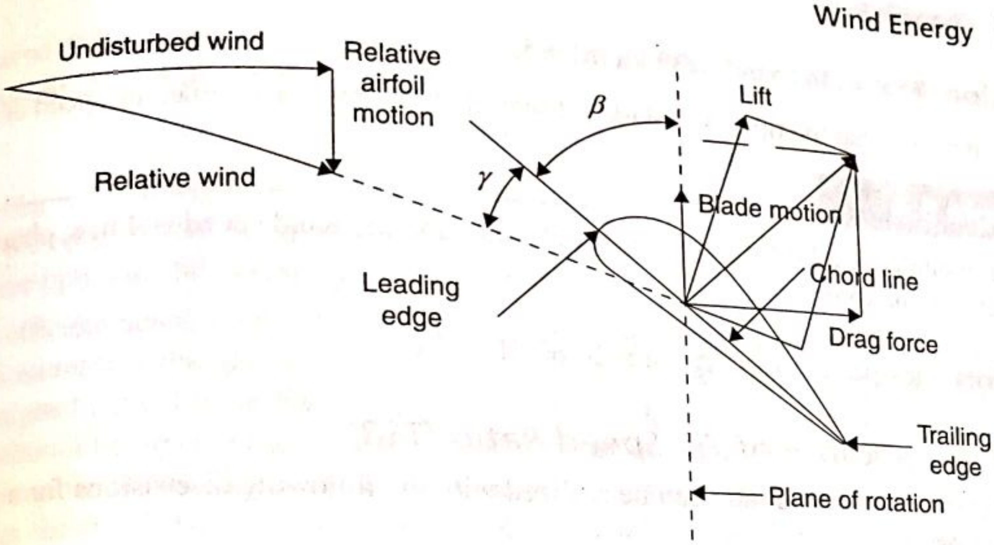


Figure 6.20 Definition of pitch angle β and angle of attack γ

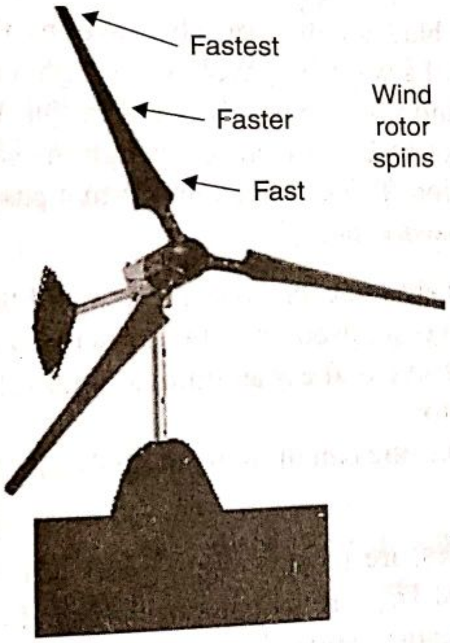


Figure 6.21 Wind speed spins at extremities

$$\text{TSR} = \text{blade tip speed/wind speed} = v_{RB}/V = (\pi DN/60)/V$$
$$= 0.052 \times \text{rotor diameter in m} \times \text{rotational speed in rpm/wind speed in m/s}$$

where L = rotor blade length (m); v_{RB} = rotor speed (m/s) = $R2\pi N/60$; V = wind speed (m/s); R = radius of wind rotor = rotor blade length $(L) = D/2$; D = wind rotor diameter (m); and N = wind rotor speed (rpm).

Speed movement along the rotor blade is shown in Figure 6.21.

Example 6.3

If the tip of a wind rotor blade is traveling at 100 miles/h (161 km/h or 45 m/s) and the wind speed is 20 miles/h (32 km/h or 9 m/s), obtain the tip-speed ratio.

Solution TSR = (161 km/h)/(32 km/h) = 5.

Simply, it means that the tip of the blade is traveling five times faster than the speed of the wind.

Example 6.4

If a 6 m diameter wind rotor is rotating at 20 rpm, and the wind speed is 4 m/s, obtain the tip-speed ratio of the rotor.

Solution Tip-speed ratio = $(\pi \times 6 \times 20/60)/4) = 1.6$

6.10.2.1 Significance of Tip-Speed Ratio (TSR)

The importance of tip-speed ratio can be realized with the following discussions for a particular wind generator:

1. If the blade set spins too slowly, then most of the wind will pass by the rotor without being captured by the blades.
2. If the blades spin too fast, then the blades will always be traveling through used or turbulent wind. This is because the blades will always be traveling through a location that the blade in front of it just travelled through (and used up all the wind in that location). It is important that enough time lapses between two blades traveling through the same location so that new or unused wind can enter this location. Thus, the next blade that passes through this location will be able to harness fresh or unused wind.

In short, if the blades are too slow, they are not capturing all the wind they could and if they are too fast, then the blades are spinning through used or turbulent wind. For this reason, TSRs are employed when designing wind turbines so that the maximum amount of energy can be extracted from the wind using a particular generator.

There are many important conclusions one can draw from analysing TSR. Following is a few of the most basic and important points:

1. Rotors with many blades (i.e., 11 blades) are generally not a good idea. An 11-bladed rotor would have an optimal TSR that is very low. This means that an 11-bladed rotor would operate most efficiently at extremely low rpms. Because nearly all generators (permanent magnet alternators) are not optimized for extremely low rpms, there is no advantage or reason to use a rotor with many blades. It should also be remembered that rotors with more number of blades are capturing used or turbulent wind at high TSR and are, thus, extremely inefficient if used as a high-rpm blade set. This is a very important point because many people intuitively think that more blades equal a faster and more efficient blade set. However, the laws of physics say that this is not true.
2. If one already has a generator or a motor and it requires high rpm to reach charging voltage, then the best choice is a two or three-bladed rotor. These rotors operate more efficiently at high rpm. Further, it is necessary keep the blades as short as pragmatically possible because shorter blades obviously spin faster than the longer blades.

6.10.2.2 Effect of the Number of Rotor Blades on the Tip-speed Tatio (TSR)

The optimal TSR depends on the number of rotor blades (n) of the wind turbine. The smaller the number of rotor blades, the faster the wind turbine must rotate to extract the maximum power from the wind. It has empirically been observed that for an n-bladed rotor, a figure Z is approximately equal to 50% of the rotor radius. Thus,

$$Z \approx 0.5r, \text{ and hence, } (\text{TSR})_{\text{OPT}} \approx (2\pi/n)/(r/Z) \approx 4\pi/n \tag{6.37}$$

Therefore, for $n = 2$, the optimal TSR is calculated to be 6.28.
For $n = 3$, the optimal TSR is reduced to be 6.28;
For $i = 4$, the optimal TSR further reduced to be 6.28.

Highly efficient aerofoil rotor blade design can increase these optimum values by as much as 25%–30% increasing the speed at which the rotor turns, and therefore, generating more power. A well-designed typical three-bladed rotor would have a tip-speed ratio of around 6 to 7.

The optimum tip-speed ratio depends on the number of blades in the wind turbine rotor. The fewer the number of blades, the faster the wind turbine rotor needs to turn to extract maximum power from the wind. Drag devices always have tip-speed ratios less than one and hence turn slowly, whereas lift devices can have high tip-speed ratios (up to 13:1) and hence turn quickly relative to the wind.

The following are the disadvantages of a high TSR:

1. Blade tips operating at 80 m/s or greater are subject to leading edge erosion from dust and sand particles and would require special leading edge treatments like helicopter blades to mitigate such damage;
2. Noise, both audible and inaudible, is generated;
3. Vibration, especially in two- or one-bladed rotors;
4. Reduced rotor efficiency due to drag and tip losses;
5. Higher speed rotors require much larger braking systems to prevent the rotor from reaching a runaway condition that can cause disintegration of the turbine rotor blades.

Example 6.5

An rpm of 450 at the tip of a 1 m blade using digital tachometer has been measured. How far does the tip of the blade travel in 1 h? If the wind is blowing at 20 miles/h, obtain the tip-speed ratio.

Solution Distance travelled by the blade in one revolution = $2\pi r = 2\pi 1$ m = 6.28 m.

Number of revolutions made by the blade in 1 h
= (450 r/min)(60 min/h) = 27,000 revolutions/h

Total distance travelled by the blade in 1 h
= (27,000 rotations) (6.28 m/rotation) = 169,560 m
= 169,560 m(1 mile)/(1,609 m) = 105 miles

Therefore, TSR = (blade tip speed)/(wind speed) = (105 mph)/ (20 mph) = 5.3

6.10.3 Solidity

Solidity is usually defined as the percentage of the circumference of the rotor that contains material rather than air. It is, in effect, the fraction of the swept area of the rotor, which is filled with metal.

The general equation of solidity is given by

% Solidity = [number of blades × blade width × blade length (or radius)/swept area]100

% Solidity = 31.8 × number of blades × blade width/rotor diameter

Example 6.6

If a 6 m diameter rotor has 24 blades, each 0.35 m wide, calculate its solidity.

Solution Solidity $= 24 \times 0.35 \times 100/\pi \times 6 = 45\%$

The greater the solidity of a rotor, the slower it needs to turn to intercept the wind. A two- or three-bladed wind turbine has a very low solidity, and therefore, it needs to rotate quickly to intercept the wind. Otherwise, a lot of wind energy would be lost through the large gaps between the blades.

High-solidity machines carry a lot of material and have coarse blade angles. They generate much higher starting torque than low-solidity machines but are inherently less efficient than low-solidity machines, as shown in Figure 6.22. The extra materials also cost more money. However, low-solidity machines need to be made with more precision that leads to little difference in costs.

6.10.4 Coefficient of Performance

It is the proportion of the power in the wind that the rotor can extract (it is also called power coefficient or efficiency; symbol C_p) and its variation as a function of tip-speed ratio is commonly used to characterize different types of rotor. It is physically impossible to extract all the energy from the wind, without bringing the air behind the rotor to a standstill. Consequently, there is a maximum value of C_p of 59.3% (known as the Betz limit), although in practice, real wind rotors have maximum C_p values in the range of 25%–45%.

The performance coefficient of a rotor is the fraction of wind energy passing through the rotor disc, which is converted into shaft power. This is a measure of the efficiency of the rotor and it varies with the tip-speed ratio. Typical performance coefficient versus tip-speed ratio curves for rotors of varying solidity is shown in Figure 6.22. Each type of rotor has a unique performance coefficient versus tip-speed ratio curve.

6.10.5 Torque

Torque is the turning force produced by the rotor. It depends on the solidity and tip-speed ratio of the rotor. Most wind turbines extract power from the wind in mechanical form and transmit it to the load by rotating shafts. These shafts must be properly designed to transmit this power. When power is being transmitted through a shaft, a torque T will be present. This torque is given by

$$T = P/\omega \text{ (N)} \tag{6.38}$$

ω = angular velocity in rad/sec.

$$= (\text{TSR} \times V)/r \tag{6.39}$$

The Torque equation of wind rotor is from eq(6.38) and (6.39)

$$T = (1/2)\, \rho . r . C_p S . V^2/\text{TSR} \tag{6.40}$$

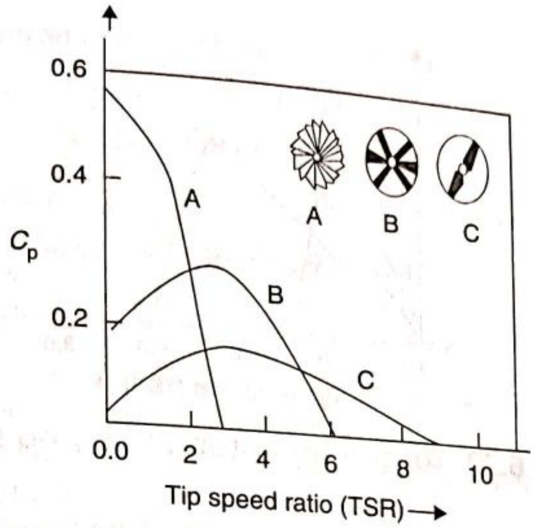


Figure 6.22 C_p versus TSR for rotor of varying solidity

where T = torque output (N); ρ = air density (kg/m²); C_p = power coefficient; S = swept area of wind rotor (m²); V = wind velocity (m/s);

$$TSR = v_{RB}/V = (\pi DN/60)/V \tag{6.40}$$

From Equation (6.22), the power that can be obtained in terms of upstream and downstream wind velocities is

$$P = (1/4)\,\rho\, S\,(V_1^2 - V_2^2)\,(V_1 + V_2) \tag{6.41}$$

The maximum power that can be extracted from the wind stream (under the condition $V_2 = (1/3)\,V_1$) is

$$P_{MAX} = 1/4\rho S\,(V_1^2 - [(1/3)\,V_1]^2\,)\,(V_1 + 1/3 \times V_1)$$
$$= 1/2 \times 16/27 \times \rho S V_1^3 \tag{6.42}$$

Since, swept area $S = \pi D^2/4$, $\quad P_{MAX} = 2/27 \times \rho\, \pi D^2 V_1^3$ (6.43)

Maximum torque

$T_{MAX} = P_{MAX}/v_{RB}$. Substituting from Equation (6.40)

$$T_{MAX} = (2/27)\,\rho \pi D^2 \times V_1^3/(\pi DN/60) = (2/27)\,\rho D V_1^3 \tag{6.44}$$

Rearranging Equation (6.44), we get

$$T_{MAX} = (2/27)\,\rho D \times V_1^3/TSR \tag{6.45}$$

High solidity rotors with low tip-speed ratios (like multibladed wind pump rotors) produce much more torque than low-solidity high-speed machines (like wind turbines). Figure 6.23 illustrates this.

The important features to note are that the high speed machine has a slightly high maximum performance coefficient, but a low starting torque. Conversely, the high solidity rotor produces a high starting torque but has a slightly low maximum performance coefficient.

The choice of rotor depends on the load characteristics. A positive displacement pump, like the piston pumps used in boreholes, demands a high starting torque than running torque, and therefore, a high-solidity rotor is almost essential unless some method of unloading the rotor to help it to start is included.

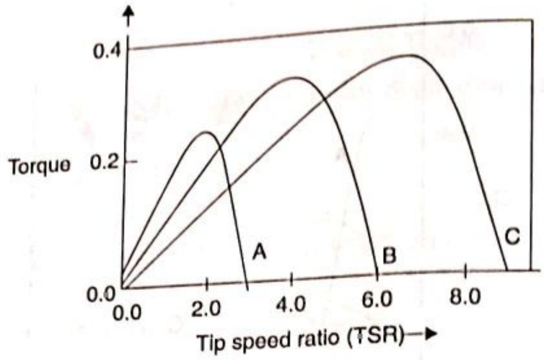


Figure 6.23 Torque for rotor of varying solidity

However, electricity generators need little torque to start them turning and they need to be driven at high speed, so generally a high-speed, low solidity rotor is used for this type of load. Positive displacement pumps that are invariably used with wind pumps need a fairly high torque to start, but will then continue to run with a low torque. The rotor of wind pump will always operate at a speed such that the torque produced exactly matches the torque required by the pump. For this reason, the torque characteristics of wind pump are important. In order to produce a high starting torque, a high solidity rotor is needed. This is why the wind pumps are almost always designed with high solidity multibladed rotors.

For a reciprocating positive displacement pump, approximately three as much torque is needed to start it than to keep it running. This means that even if a wind pump will operate at low wind speeds, it will need a gust of high wind speed to actually start it.

Example 6.7

The undisturbed wind speed at a place is 13.415 m/s. The wind speed at the turbine rotor and at exit is 6% and 30%, respectively, of the undisturbed wind. The rotor diameter is 9 m and air density is 1.293 kg/m^3. Calculate

1. Power available in the undisturbed wind
2. Power in the wind at exit
3. Power developed by the turbine rotor
4. Coefficient of performance

Solution 1. Power available in the undisturbed wind

Using Equation (6.1), $P_{un} = P =.½. (\rho SV^3) = (1/2) \times 1.293 \times [\pi \times (9)^2/4] \times (13.415)^3$
$= 41.128 \times 2{,}414.2 = 99.292$ kW

2. Power in the wind at exit

$$V = 60\% \text{ of } 13.415 = 8.049 \text{ and } V_2 = 30\% \text{ of } 13.415 = 4.0245. \text{ Therefore,}$$

$$P_E = (1/2) \times 1.293 \times [\pi \times (9)^2/4] \times 8.049 \times (4.0245)^2$$
$$= (1/2) \times 1.293 \times 63.617 \times 8.049 \times (4.0245)^2 = 5.381 \text{ kW}$$

3. Power developed by the turbine rotor, where $V_1 = 12.074$ m/s² (calculated)

   From Equation (6.23), $P_d = (1/4)\rho S(V_1^2 - V_2^2)(V_1 + V_2) = (1/2)\rho SV(V_1^2 - V_2^2)$

   $= 41.128 \times 8.049 \times (12.074^2 - 4.0245^2) = 42.897$ kW

4. Coefficient of performance

   $$C_p = P_d/P_{un} = 42.897/99.292 = 0.432$$

Example 6.8

Following data are given for a propeller-type HAWT:
Speed of wind = 10 m/s; air density = 1.226 kg/m³; rotor diameter = 120 m
Rotor speed = 40 rpm; coefficient of performance = 40%.
Calculate

1. Total power density in wind system,
2. Total power available in the wind, kW
3. Maximum extractable power
4. Maximum Torque and axial thrust

Solution

1. Using Equation (6.35), total power in the wind system $P = (1/2)\rho SV^3$

   Power density $(p_d) = P/S = (1/2)\,r\mathbf{V}^3 = 1/2 \times 1.226 \times (10)^3 = 613$ W/m²

2. Total power available in the wind = power density (p_d) × swept area of the wind turbine (S).

   Swept area of the wind turbine $(S) = \pi \times D^2/4 = \pi \times (120)^2/4 = 11{,}304$ m²

   Therefore, $P = p_d \times S = 613 \times 11{,}304 = 6{,}930$ kW.

3. Given that wind power coefficient $(C_p) = 40\%$,

   Maximum extractable power $= C_p \times P = 0.4 \times 6{,}930 \times 10^3 = 2{,}771$ kW.

4. Using Equation (6.21), the axial force $F = \rho SV(V_1 - V_2) = (½)\,\rho S(V_1^2 - V_2^2)$.

   The maximum axial force will occur at maximum efficiency when $V_2 = (1/3)\,V_1$

   Thus, $F_{max} = (\pi/9) \times \rho D^2 \times (V_1)^2 = (\pi/9) \times 1.226 \times (120)^2 \times (10)^2 = 619.95$ kN

   From Equation (6.44), $T_{MAX} = (2/27) \times \rho \times \pi \times D^2 \times V_1^3/(\pi DN/60) = (2/27) \times \rho \times D \times V_1^3$

   $= (2/27) \times 1.226 \times 120 \times (10)^3 = 10.897$ kN

6.11 TYPES OF GENERATORS USED WITH WIND TURBINES

The generator is the device inside the turbine that actually generates the electricity. It takes the kinetic energy generated by the wind rotor and translates it into electricity. Inside the generator, coils of copper wire called the armature are rotated in a magnetic field to produce electricity.

Wind generators are used for battery charging, AC utility, water or space heating, and direct motor drive for water pumping. A typical system would have the wind generator on a tall tower