7

WIND ENERGY

7.1 INTRODUCTION

Wind is air in motion and it derives energy from solar radiation. About 2% of the total solar flux that reaches the earth's surface is transformed into wind energy due to uneven heating of the atmosphere. During daytime, the air over the land mass heats up faster than the air over the oceans. Hot air expands and rises while cool air from oceans rushes to fill the space, creating local winds. At night the process is reversed as the air cools more rapidly over land than water over off-shore land, causing breeze, as shown in Figure 7.1. On a global scale low pressure exists near the Equator due to greater heating, causing winds to blow from subtropical belts towards the Equator. Also, the axial rotation of the earth induces a centrifugal force which throws equatorial air masses to the upper atmosphere, causing deflection of winds.

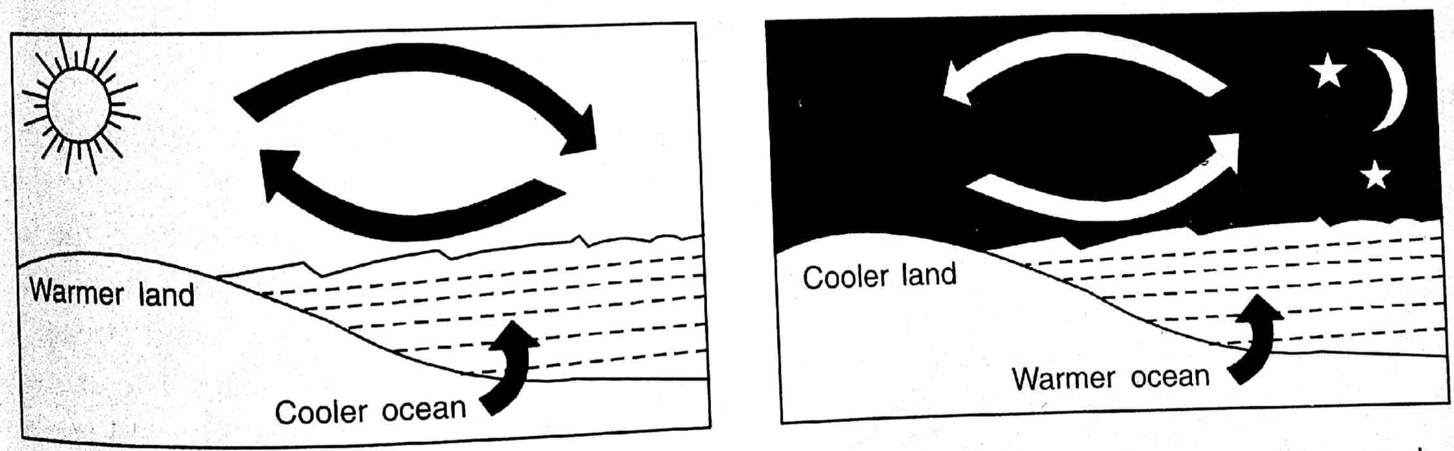


Figure 7.1 (a) Wind from ocean to land during daytime, and (b) wind from land to ocean during night.

7.2 HISTORICAL DEVELOPMENT

The concept of harnessing wind energy dates back to 4000 BC, when Egyptians used wind power to sail their boats in the Nile river. By the tenth century the wind mills were being used to grind grains in Iran and Afghanistan. Skilful technicians of Iran introduced the windmills to China where they gained popularity and were used to raise water for irrigation and sea water for production of salt.

The technology to harness wind energy reached western Europe via the Arabs. Wind machines became popular because the energy can be used in a number of ways. In 1854, Daniel Halladay in US introduced a wind pump. Windmills were in use for draining lakes, raising water for irrigation, industrial uses like sawing timber, extracting oil from oil seeds, and polishing stones. In West Indies, windmills were used for crushing sugarcane.

It was P. La'cour (Denmark), who in 1880 for the first time used the windmill as a source of electricity. A new era began after the First World War when experiments were carried out with windmills having sails of aerofoil section. A French engineer Darreius built an aerogenerator at Bourget in 1929 that had a tower 20 metres high with blades of the same diameter. In the late 1950s, Danish electrical companies successfully tested a 200 kW wind turbine with an asynchronous generator.

After the sudden price rise of fossil fuel in 1973, a number of countries were stimulated towards the development and use of renewable energy sources. In 1974, NASA constructed and operated a wind generator of 100 kW capacity with 38-m diameter rotor installed over a 30 m high tower. Success encouraged the US firms to manufacture a 2.5 MW generator in 1987. After 1990, the European and the Asian countries like Denmark, Germany, China and India encouraged private and cooperative sectors to install wind generators in capacities of 200 kW, and 500 kW to 1.5 MW.

The wind power programme in India is working quite satisfactorily. Provision of incentives instituted by the Ministry of New and Renewable Energy (MNRE), has made wind electricity competitive. As a result, wind electricity has emerged as an option for quality power. As on 31st December, 2004, India is ranked 5th in the world after Germany, USA, Spain and Denmark in terms of wind power generation. Most of the capacity addition has been achieved through commercial projects by private investors.

7.3 CLASSIFICATION OF WIND TURBINES

Wind turbines are classified as horizontal-axis turbines or vertical-axis turbines depending upon the orientation of the axis of rotation of their rotors. A wind turbine operates by slowing down the wind and extracting a part of its energy in the process. For a horizontal-axis turbine, the rotor axis is kept horizontal and aligned parallel in the direction of the wind stream. In a vertical-axis turbine, the rotor axis is vertical and fixed, and remains perpendicular to the wind stream.

In general, wind turbines have blades, sails or buckets fixed to a central shaft. The extracted energy causes the shaft to rotate. This rotating shaft is used to drive a pump, to grind seeds or to generate electric power. Wind turbines are further classified into 'lift' and 'drag' type.

7.3.1 Lift Type and Drag Type Wind Turbines

Two important aerodynamic principles are used in wind turbine operations, i.e., lift and drag. Wind can rotate the rotor of a wind turbine either by lifting (lift) the blades or by simply passing against the blades (drag). Wind turbines can be identified based on their geometry and the manner in which the wind passes over the blades.

Slow-speed turbines are mainly driven by the drag forces acting on the rotor. The torque at the rotor shaft is comparatively high which is of prime importance for mechanical applications such as water pumps. For slower turbines, a greater blade area is required, so the fabrication of blades is undertaken using curved plates.

High-speed turbines utilise lift forces to move the blades, which phenomenon is similar to what acts on the wings of an aeroplane. Faster turbines require aerofoil-type blades to minimize the adverse effect of the drag forces. The blades are fabricated from aerofoil sections with a high thickness-to-chord ratio in order to produce a high lift relative to drag.

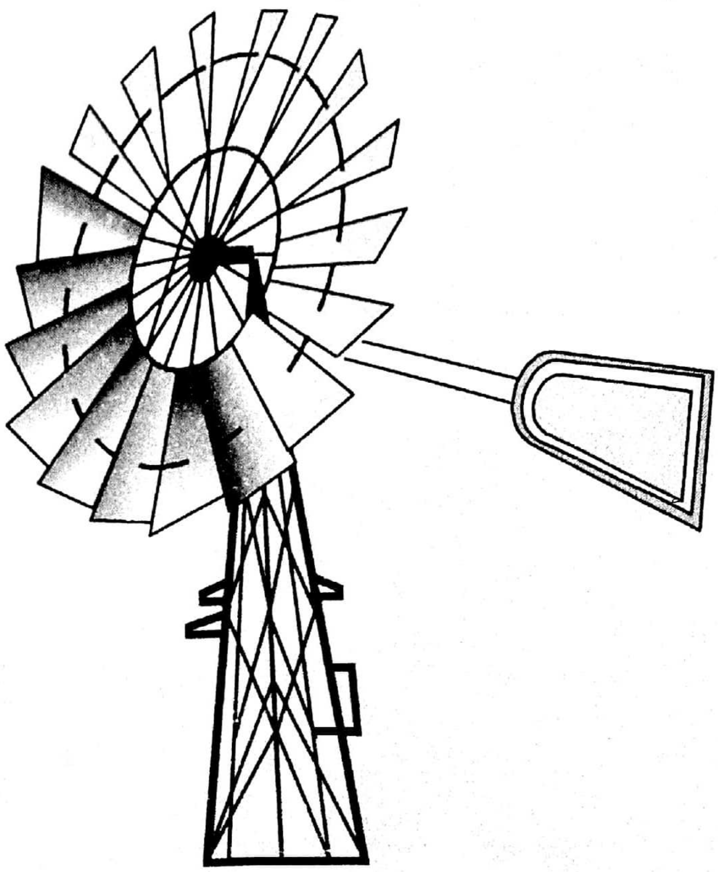
For electric power generation, the shaft of the generator requires to be driven at a high speed. For the same swept area, the energy extracted by a wind turbine operating on lift forces is several times greater than the energy from the drag-type turbine. Thus, the lift-type turbines are more suitable compared to drag-type turbines for electric power generation.

7.4 TYPES OF ROTORS

Different types of rotors used in wind turbines are: (i) multiblade type, (ii) propeller type, (iii) Savonious type, and (iv) Darrieus type. The first two are installed in horizontal-axis turbines, while the last two in vertical-axis turbines.

7.4.1 Multiblade Rotor

The multiblade rotor is fabricated from curved sheet metal blades. The width of blades increases outwards from the centre. Blades are fixed at their inner ends on a circular rim. They are also welded near their outer edge to another rim to provide a stable support. The number of blades used ranges from 12 to 18, as shown in Figure 7.2.



7.4.2 Propeller Rotor

The propeller rotor comprises two or three aerodynamic blades made from strong but lightweigh material such as fibre glass reinforced plastic. The diameter of the rotor ranges from 2 m to 25 m as detailed in Figure 7.3. The blade slope is designed by using the same aerodynamic theory as for aircraft.

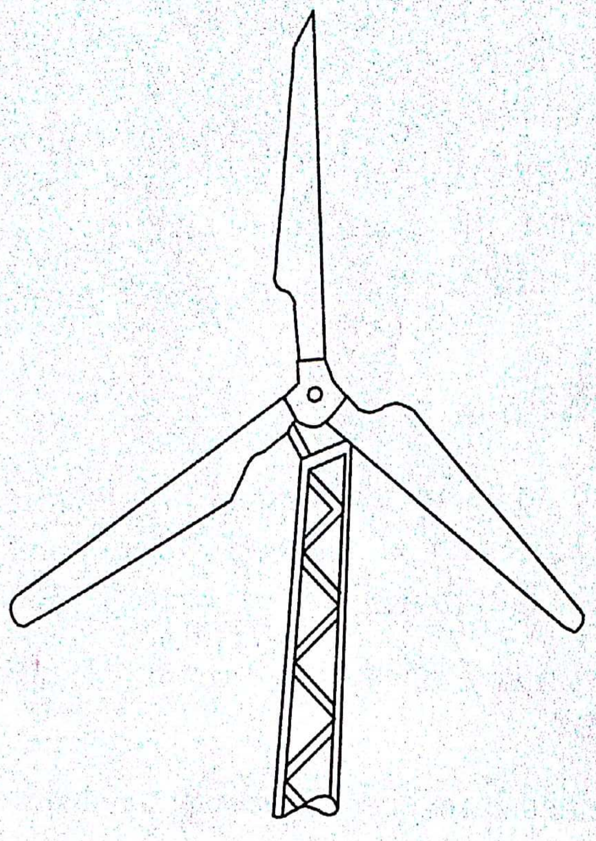


Figure 7.3 Propeller rotor installed on a tower.

7.4.3 Savonious Rotor

The Savonious rotor comprises two identical hollow semi-cylinders fixed to a vertical axis. The inner side of two half-cylinders face each other to have an S shaped cross section as detailed in Figure 7.4.

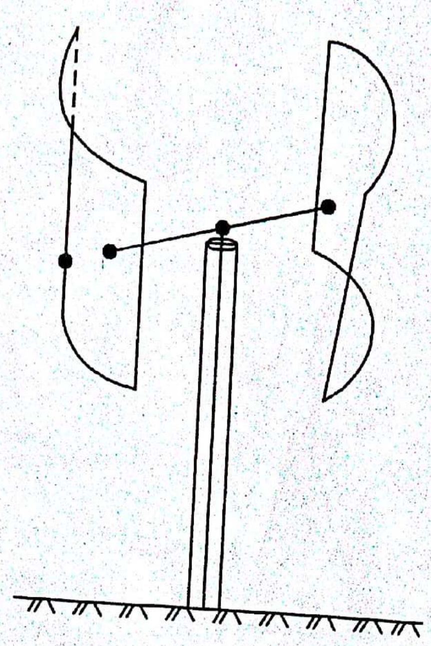


Figure 7.4 S

Irrespective of wind direction, the rotor rotates due to pressure difference between the two sides. This vertical axis rotor was developed by an engineer Savonious of Finland in the year 1920. It is self starting and the driving force is mainly of drag type. The rotor possesses high solidity so as to produce a high starting torque and hence this rotor is suitable for water pumping.

7.4.4 Darrieus Rotor

This rotor has two or three thin curved blades of flexible metal strips. It looks like an egg beater and operates with the wind coming from any direction. Both the ends of the blades are attached to a vertical shaft as shown in Figure 7.5. It has an advantage that it can be installed close to the ground eliminating the cost of the tower structure.

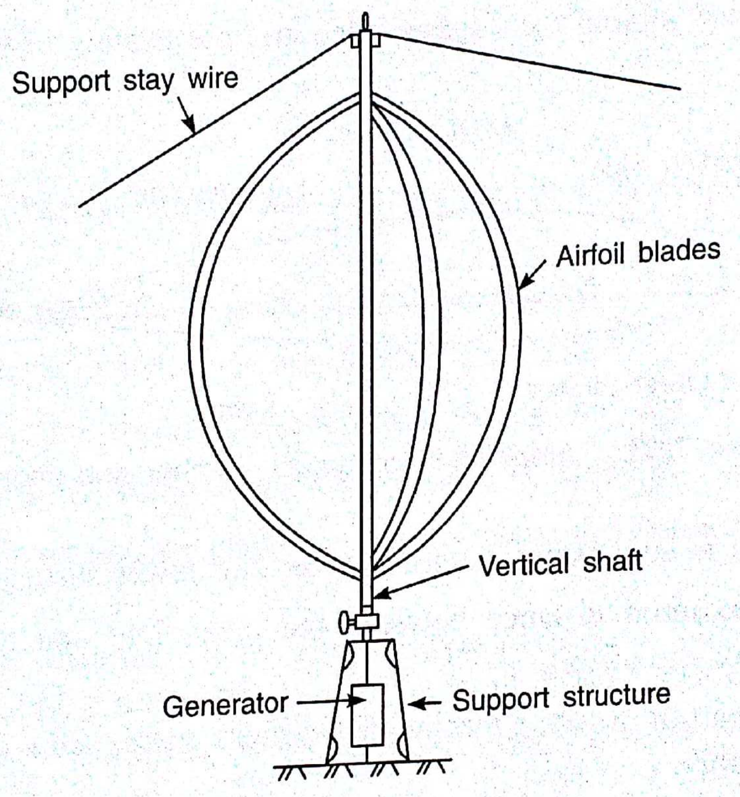


Figure 7.5 Darrieus rotor.

Lift is the driving force, creating maximum torque when the blade moves across the wind. This rotor was designed by a French engineer G.M. Darrieus in 1925. It is used for decentralized electricity generation.

7.5 TERMS USED IN WIND ENERGY

Airfoil (Aerofoil): A streamlined curved surface designed for air to flow around it in order to produce low drag and high lift forces.

Angle of attack: It is the angle between the relative air flow and the chord of the airfoil [Figure 7.6(a)].

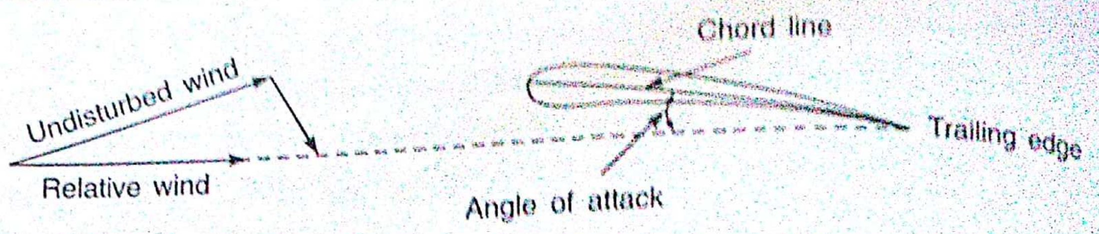


Figure 7.6(a) Angle of attack of a wind turbine airfoil.

Blade: An important part of a wind turbine that extracts wind energy.

Leading edge: It is the front edge of the blade that faces towards the direction of wind flow [Figure 7.6(b)].

Trailing edge: It is the rear edge of the blade that faces away from the direction of wind flow [Figure 7.6(b)].

Chord line: It is the line joining the leading edge and the trailing edge [Figure 7.6(b)].

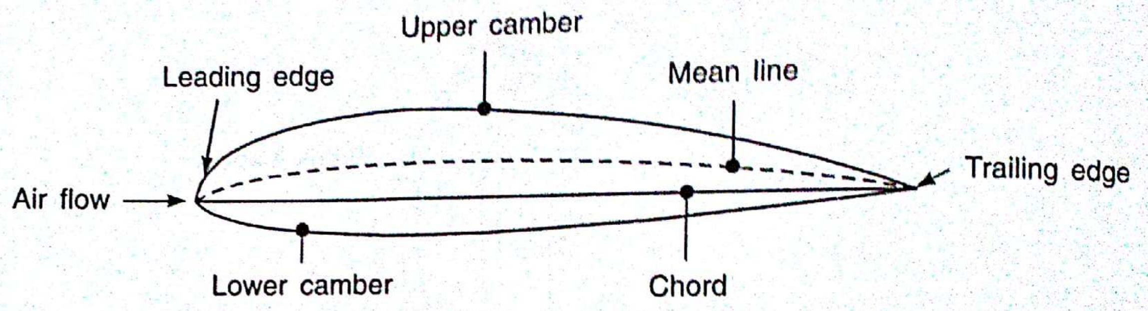


Figure 7.6(b) Airfoil showing edges, camber and chord.

Mean line: A line that is equidistant from the upper and lower surfaces of the airfoil.

Camber: It is the maximum distance between the mean line and the chord line, which measures the curvature of the airfoil.

Rotor: It is the prime part of the wind turbine that extracts energy from the wind. It constitutes the blade-and-hub assembly.

Hub: Blades are fixed to a hub which is a central solid part of the turbine.

Propeller: It is the turbine shaft that rotates with the hub and blades and is called the propeller. Blades are twisted as per design. The outer profile of the blades conforms to aerodynamic performance while the inner profile meets the structural requirements.

Tip speed ratio: It is the ratio of the speed of the outer blade tip to the undisturbed natural wind speed.

Pitch angle: It is the angle made between the blade chord and the plane of the blade rotation.

Pitch control of blades: A system where the pitch angle of the blades changes according to the wind speed for efficient operation [Figure 7.6(c)].

Stall-regulated system: When the turbine blades are fixed at an optimum angle and the machine is stalled during high winds either by mechanical or hydraulic systems.

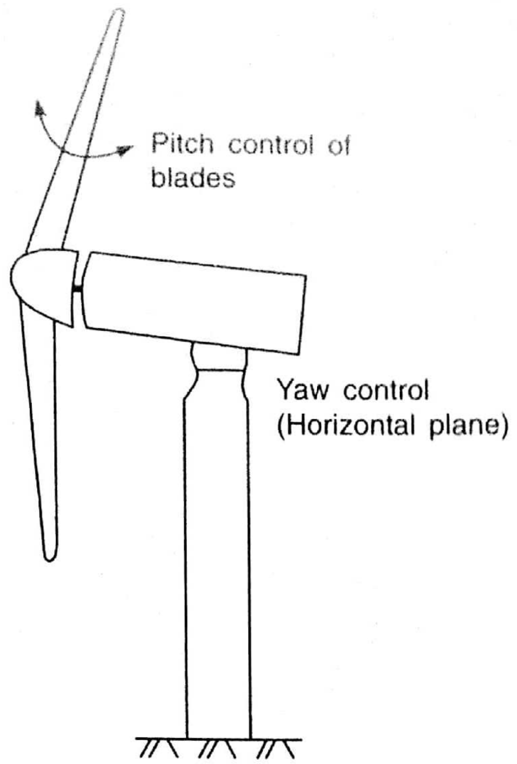


Figure 7.6(c) Pitch and yaw control of wind turbine.

Swept area: This is the area covered by the rotating rotor.

Solidity: It is the ratio of the blade area to the swept area.

Drag force: It is the force component which is in line with the velocity of wind.

Lift force: It is the force component perpendicular to drag force.

Nacelle: The nacelle houses the generator, the gear box, the hydraulic system and the yawing mechanism.

Yaw control: As the direction of the wind changes frequently, the yaw control is provided to steer the axis of the turbine in the direction of the wind. It keeps the turbine blades in the plane perpendicular to the wind, either in the upward wind direction or in the downward wind direction.

Cut-in speed: It is the wind speed at which a wind turbine starts to operate.

Rated wind speed: It is the wind speed at which the turbine attains its maximum output.

Cut-out speed: It is the wind speed at which a wind turbine is designed to be shut down to prevent damage from high winds. It is also called the *furling wind speed.*

Down wind: It is the opposite side of the direction from which the wind is blowing.

Up wind: It is the side of the direction from which the wind is blowing (in the path of the oncoming wind).

Wind rose: It is the pattern formed in a diagram illustrating vectors that represent wind velocities occurring from different directions.

Wind vane: A wind vane monitors the wind direction. It sends a signal to the controlling computer which activates the yaw mechanism to make the rotor face the wind direction.

7.6 AERODYNAMIC OPERATION OF WIND TURBINES

Aerodynamics deals with the movement of solid bodies through the air. In wind turbines, aerodynamics provides a method to explain the relative motion between airfoil and air. Airfoil is the cross-section of the wind turbine blade. When the wind passes over the surface of the rotor blade, it automatically passes over the longer or upper side of the blade, creating a low pressure area above the airfoil as shown in Figure 7.7(a).

The pressure difference between the top and the bottom surfaces results in a force called the aerodynamic lift that causes the airfoil to rise. As the blades can only move in a plane with the hub as their centre, the lift force causes rotation about the hub [Figure 7.7(b)]. The turbine thus extracts energy from the wind stream by converting the wind's linear kinetic energy into rotational motion. In addition to the lift force, a drag force perpendicular to the lift force also acts on the blade which impedes rotor rotation. The prime objective in wind turbine design is the desired lift-to-drag ratio of the blade (airfoil structure). The basic principles of lift and drag forces are dealt with in the next section.

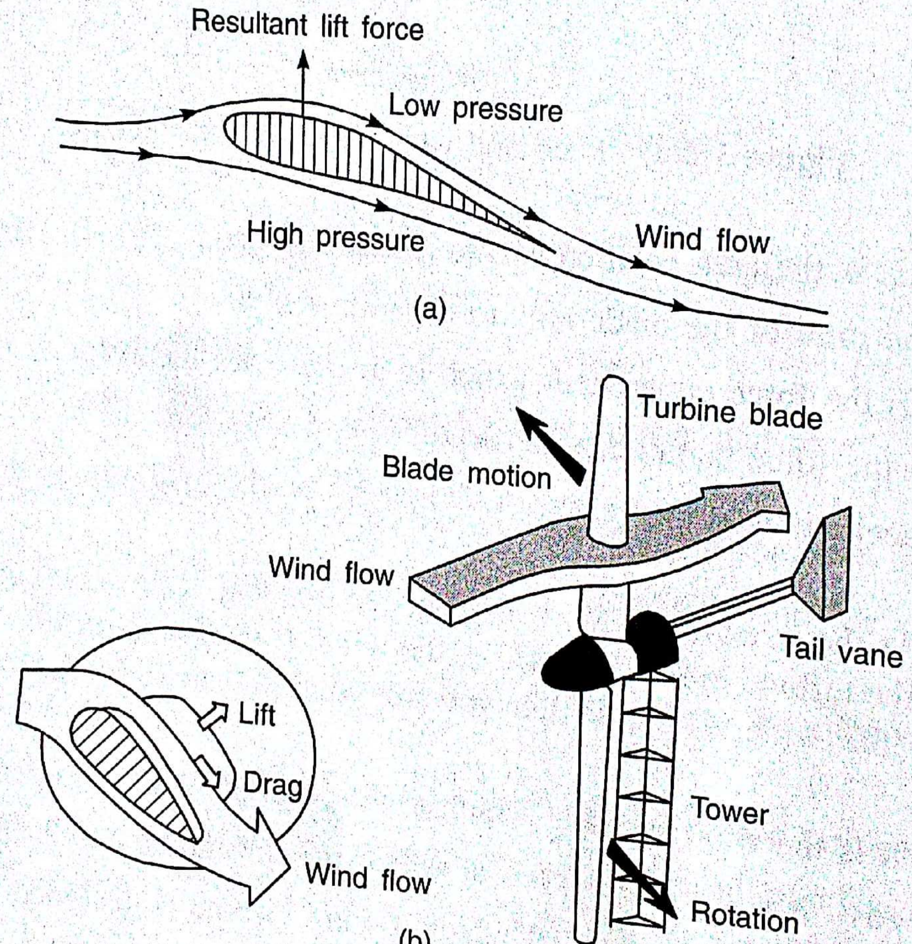


Figure 7.7 (a) Aerodynamic lift force on blade cross-section of wind turbine, and (b) the basic operating principle of wind turbine aerodynamic lift.

When air flows over solid bodies, several physical phenomena are noticed such as drag force acting on objects like trees and electric towers, the lift force developed by airplane wings, the lift force experienced by dust particles in a wind storm and the blade motion developed by a turbine. Either the fluid moves over a stationary body or a body moves through a standstill fluid: aerodynamically both activities are the same. The approach is to study th between the fluid and the body.

7.6.1 Drag

It is the resistance which a body experiences when a fluid moves over it. Flood water washes away animals, vehicles and buildings. Wind storm and hurricane knocks down transmission towers, trees, sweeps away catamaran and ships. These are a few undesirable examples of drag forces. The force that a flowing fluid exerts on a body in the direction of flow is called 'drag force'. Drag may bring an undesirable effect of friction, such as burning of space vehicles on entering into the earth's atmosphere. Reduction of drag is the basic engineering approach, associated with the reduction in fuel consumption in automobiles, aircraft and submarines. However, in certain engineering activities the drag produces a useful effect. A meteor from outer space burns due to friction with the earth's atmosphere, saving the inhabitants on earth from catastrophic impact.

Friction acts to help us as a 'life saver' in brakes of automobiles. Similarly, the drag force is useful in safe landing with a parachute.

7.6.2 Lift

When a body is immersed in a standstill fluid, only the normal pressure force is exerted on it A flowing fluid in addition exerts tangential shear forces on the surface. Both these forces have two components, one is drag in the flow direction, the other is perpendicular to the fluid flow called 'lift'. It causes the body to move in the upward direction. The relative magnitudes of drag and lift forces depend completely on the shape of the object. Streamlined objects experience smaller drag force than that experienced by blunt objects. Generation of lift always creates certain amount of drag force.

Airfoils of a wind turbine are especially shaped to produce lift force on coming in contac with the moving air. It is achieved by fabricating the top surface of the airfoil as curved and th bottom surface nearly flat. Air flowing over the airfoil travels a longer distance to reach the ti end of airfoil, in contrast to air flowing under the foil (Figure 7.8). It creates a pressure differen that generates an upward force which tends to lift the airfoil causing rotation of the wind turbi rotor. Good airfoils can have lift 30 times greater than drag.

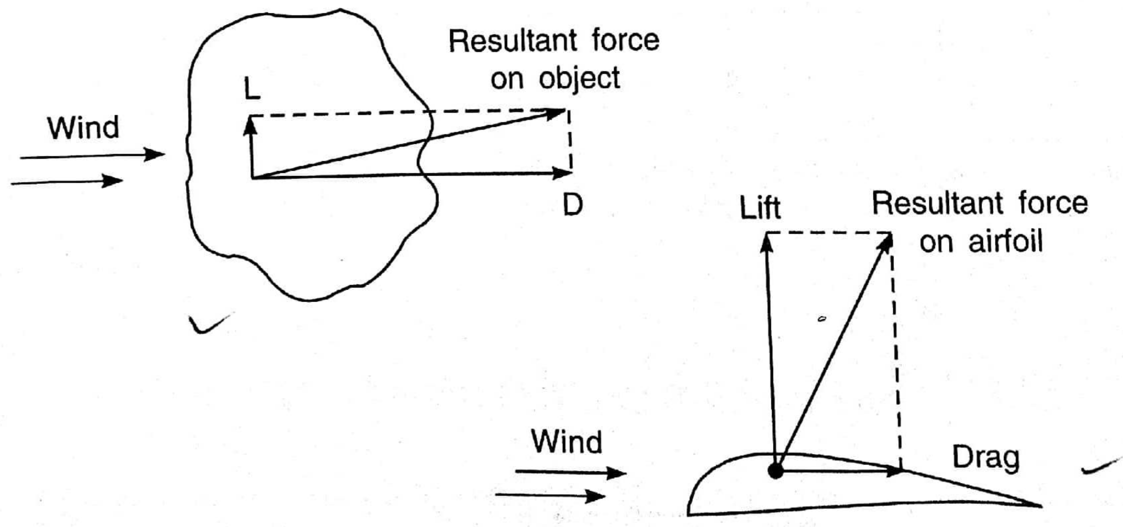


Figure 7.8 Relative magnitudes of lift and drag forces on a blunt object and a streamlined ai

7.7 WIND ENERGY EXTRACTION

Wind turbines extract energy from wind stream by converting the kinetic energy of the wind to rotational motion required to operate an electric generator. By virtue of the kinetic energy, the velocity of the flowing wind decreases. It is assumed that the mass of air which passes through rotor is only affected and remains separate from the air which does not pass through the rotor. Accordingly, a circular boundary surface is drawn showing the affected air mass and this boundary is extended upstream as well as downstream as detailed in Figure 7.9.

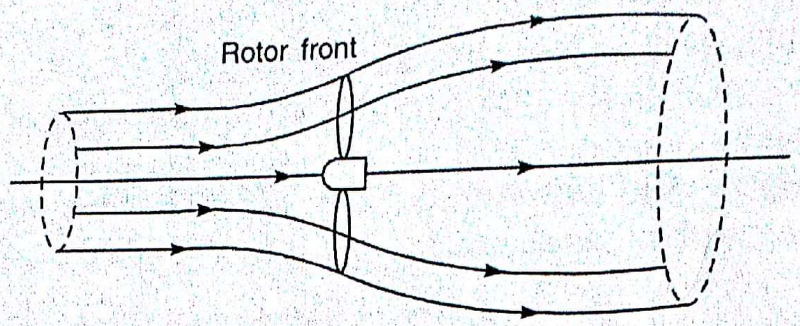


Figure 7.9 Representation of wind flow through turbine.

As the free wind (stream) interacts with the turbine rotor, the wind transfers part of its energy into the rotor and the speed of the wind decreases to a minimum leaving a trail of disturbed wind called **wake** [(Figure 7.10(a)]. The variation in velocity is considered to be smooth from far upstream to far downstream. However, the fall in static wind pressure is sharp as depicted in Figure 7.10(b). The wind leaving the rotor is below the atmospheric pressure (in wake region) but at far downstream it regains its value to reach the atmospheric level. The rise in static pressure is at the cost of kinetic energy, consequently further decreasing the wind speed.

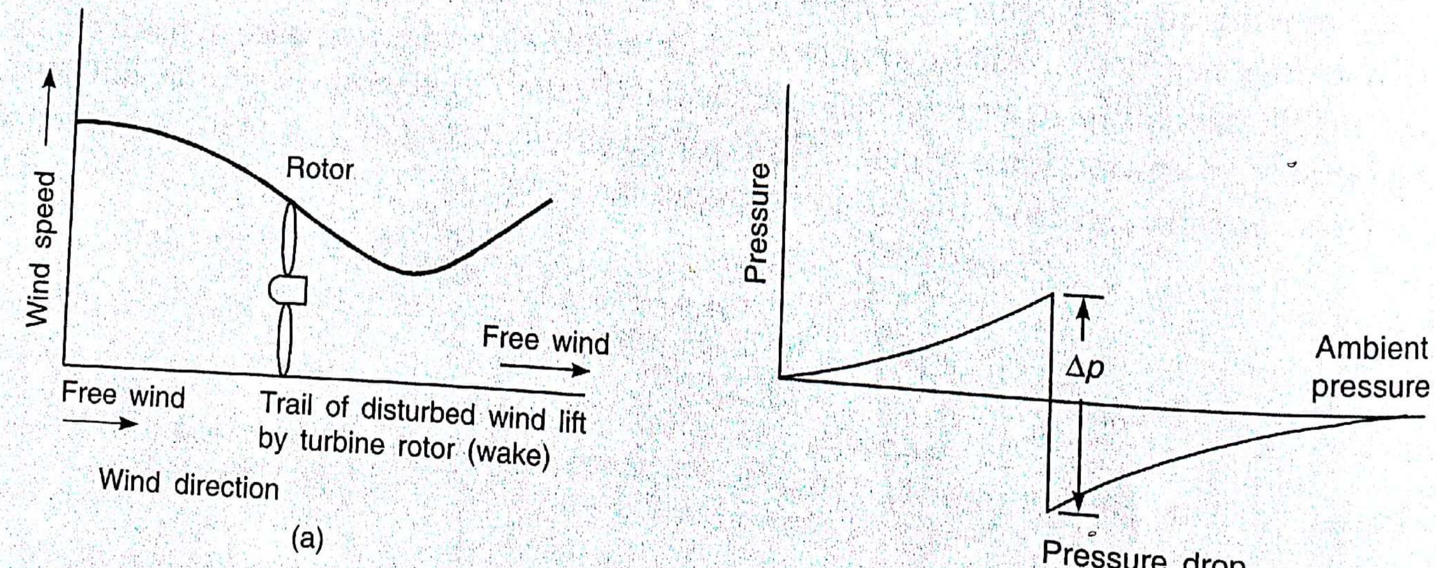


Figure 7.10 Change in wind speed and pressure in traversing the turbine rotor.

Wind flow is considered incompressible and hence the air stream flow diverges as it passes through the turbine. Also the mass flow rate of wind is assumed constant at far upstream, at the rotor and at far downstream. To compute the mathematical relationships, suppose:

P = atmospheric wind pressure
P_u = pressure on upstream of wind turbine
P_d = pressure on downstream of wind turbine
V = atmospheric wind velocity
V_u = velocity of wind upstream of wind turbine
V_b = velocity of wind at blades
V_d = velocity of wind downstream of wind turbine before the wind front reforms and regains the atmospheric level
A = area of blades
$\bar{M}$ = mass flow rate of wind
ρ = air density.

The kinetic energy of wind stream passing through the turbine rotor is

$$\text{KE} = \frac{1}{2}\bar{M}V_b^2$$

and

$$\bar{M} = \rho A V_b$$

Hence,

$$\text{KE} = \frac{1}{2}\rho A V_b^3 \tag{7.1}$$

The force on the disc of the rotor can be expressed as

$$F = (P_u - P_d)A \tag{7.2}$$

df/dt

Force on the rotor can be expressed as change of momentum per unit time from upstream to downstream winds, i.e.,

$$F = \bar{M}(V_u - V_d) \tag{7.3}$$

Applying the Bernaulli's equation to upstream and downstream sides,

$$P + \frac{1}{2}\rho V_u^2 = P_u + \frac{1}{2}\rho V_b^2 \tag{7.4}$$

$$P_d + \frac{1}{2}\rho V_b^2 = P + \frac{1}{2}\rho V_d^2 \tag{7.5}$$

Solving Eqs. (7.4) and (7.5), we get

$$P_u - P_d = \frac{1}{2}\rho(V_u^2 - V_d^2) \tag{7.6}$$

Equating Eqs. (7.2) and (7.3), we get

$$(P_u - P_d)A = \bar{M}(V_u - V_d) = \rho A V_b(V_u - V_d) \tag{7.7}$$

Solving Eqs. (7.6) and (7.7), we get

$$\frac{1}{2}\rho(V_u^2 - V_d^2) = \rho V_b (V_u - V_d)$$

or

$$V_b = \frac{V_u + V_d}{2} \tag{7.8}$$

In a wind turbine system "Steady Flow Work", W, is equal to the difference in kinetic energy between upstream and downstream of the turbine for unit massflow, $\bar{M} = 1$. Therefore,

$$W = (\mathrm{KE})_u - (\mathrm{KE})_d$$

$$= \frac{1}{2}(V_u^2 - V_d^2) \tag{7.9}$$

The power output P of wind turbine is the rate of work done, using the mass flow rate equation.

$$P = \bar{M}\left(\frac{V_u^2 - V_d^2}{2}\right)$$

$$= \rho A\left(\frac{V_u + V_d}{2}\right)\left(\frac{V_u^2 - V_d^2}{2}\right)$$

$$= \frac{1}{4}\rho A (V_u + V_d)(V_u^2 - V_d^2) \tag{7.10}$$

For maximum turbine output P, differentiate Eq. (7.10) with respect to V_d and equate to zero to obtain

$$\frac{dP}{dV_d} = 3V_d^2 + 2V_u V_d - V_u^2 = 0$$

The above quadratic equation has two solutions, i.e., $V_d = \frac{1}{3}V_u$ and $V_d = V_u$

For power generation $V_d < V_u$, so we can have only $V_d = \frac{1}{3}V_u$ (7.10a)

Therefore,

$$P_{\max} = \frac{8}{27}\rho A V_u^3 \tag{7.11}$$

$$= \frac{16}{27}\left(\frac{1}{2}\rho A V_u^3\right)$$

$$= 0.593\left(\frac{1}{2}\rho A V_u^3\right)$$

Total power in wind stream is

$$P_{\text{total}} = \frac{1}{2}\rho A V_u^3 \tag{7.11a}$$

Therefore,

$$P_{\max} = 0.593 P_{\text{total}}$$

Maximum theoretical efficiency $\eta_{\max}$ (also called the power coefficient C_p) is the ratio of maximum output power to total power available in the wind, i.e.,

$$\text{Power coefficient, } C_p = \frac{P_{\max}}{P_{\text{total}}} = 0.593 \tag{7.12}$$

The factor 0.593 is known as the **Bitz limit** (After the name of the engineer who first derived this relationship).

Available efficiency

Theoretically, the maximum power extracted by a turbine rotor is 59.3% of the total wind energy in the area swept by the rotor. Considering the rotor efficiency to be 70%, bearing, vibrations, friction losses and generator efficiency 90%, the available efficiency η is 60% of C_p, i.e.,

$$\eta_a = 0.6 \times 0.593$$

$$= 35.5\%$$

7.8 EXTRACTION OF WIND TURBINE POWER

Equation [7.11(a)] can be expressed as $P_{\text{total}} = \frac{\rho}{2} \cdot \frac{\pi}{4} D^2 V_u^3$. Accordingly, for a given wind speed at a site, P_{total} would increase four times if the rotor diameter is doubled, The designer of a wind turbine always tries to increase the rotor diameter to optimize the extraction of the wind energy. The cumulative effect of wind speed and rotor diameter on the availability of wind power can be observed in Figure 7.11.

While selecting the wind turbine it is necessary to know the energy needs and the availability of wind speeds at the given site. Economically, it is known that the wind system cost varies according to the rotor size. Referring to Figure 7.11, if the rotor diameter of 40 m is selected in lieu of 20 m at the proposed site having wind speed of 10 m/s, the available power rises up to 1 MW from a low value of 0.25 MW, i.e., becomes four times more.

7.9 WIND CHARACTERISTICS

Power in the wind is proportional to the cube of the wind speed [Eq. (7.11)] and is highly site specific. It is necessary to carry out wind measurements if the performance of wind turbines is to be estimated accurately. The highest wind speed sites are on exposed hill tops, offshore

A straight coastline site where the 'windrose' is uniform or a land surface with a few wind breaks (roughness class I) are the favourable sites.

While analyzing the wind resource potential, it should be ensured that the prevalent wind is not turbulent. It should also be confirmed that the wind is not gusty.

7.16 CALCULATION FOR AIR DENSITY

Air density ρ varies directly with air pressure. Its value is inversely proportional to air temperature expressed in kelvin scale as

$$\rho = \frac{P}{RT}$$

where P is the air pressure in Pa, T is the air temperature in kelvin and R is the gas constant, 287 J/kg·K. The standard value of air pressure = 1.01325×10^5 Pa (at 1 atmosphere) and at 15°C. Therefore,

$$\rho = \frac{1.01325 \times 10^5}{287 \times 288} = 1.226 \text{ J/kg·K/m}^3$$

Air density is maximum at sea level and reduces gradually as one moves up to higher altitudes.

A Wind Energy Generator (WEG) is designed for a mean air density of 1.23 J/kg·K/m^3. The operational data and the power curves are given at this air density. If the mean air density differs from this value, the data and power curves will change accordingly.

EXAMPLE 7.1

Wind speed is 10 m/s at the standard atmospheric pressure. Calculate (i) the total power density in wind stream, (ii) the total power produced by a turbine of 100 m diameter with an efficiency of 40%. Air density = 1.226 J/kg·K/m^3.

Solution

(i) Total power density $= \dfrac{\text{Total power}}{A} = \dfrac{1}{2}\rho V^3$

$$= \frac{1}{2} \times 1.226 \times 10^3 = 613 \text{ W/m}^2$$

(ii) Total power produced = Efficiency × Power density × Area

$$= \frac{40}{100} \times 613 \times \frac{\pi}{4}(100)^2 \times \frac{1}{1000}$$

$$= 1924.8 \text{ kW}$$

7.17 VARIATION OF WIND SPEED WITH ELEVATION

The wind speed increases with height above the ground. Increase in wind speed with elevation h (above ground level) is called *wind shear*. The wind speed at the ground is friction between the ground surface and air. Increase in wind speed with height is due to temperature gradient and it depends on the type of terrain (ground roughness) over which the wind has blown and the atmospheric stability. Sites can be divided into four types with yearly output from 225 kW WEG.

1. More than 10 km offshore (roughness class zero) with yearly output of 779,000 kWh.
2. Open landscape with few wind breaks, also sea-shore sites (roughness class 1) with yearly output of 577,000 kWh.
3. Suburban areas with farms, gardens and with medium wind breaks (roughness class 2) with yearly output of 454,000 kWh.
4. Urban districts, high trees, buildings and structures with many wind breaks (roughness class 3) with yearly output of 301,000 kWh.

Based on the data from several locations, for sites of low ground roughness, the change in wind speed with height can be expressed by an equation

$$\frac{V_2}{V_1} = \left(\frac{H_2}{H_1}\right)^{\alpha} \tag{7.16}$$

where V_1 and V_2 are wind speeds at levels H_1 and H_2, respectively. This is known as power law index α which depends on the roughness of terrain. Its value taken as is 1/7 for open land and 0.10 for calm sea area. For a particular site, the value of power law index is obtained from the measured wind speed at two heights, i.e.,

$$\alpha = \frac{\log V_2 - \log V_1}{\log H_2 - \log H_1} \tag{7.17}$$

The ideal wind energy sites have a low value of α. Generally, wind measurements are carried out at an elevation of 10 m. However, modern wind turbines are installed at a hub height of 25 m to 50 m. Wind speed at the required height is extrapolated from Eq. (7.16) with $\alpha = 1/7$.

Extrapolation of power density

If power density is to be extrapolated to a higher height, say 40 m above ground from the value at 20 m, it is found to vary logarithmically and expressed by an equation

$$\frac{P_{40}}{P_{20}} = \left(\frac{40}{20}\right)^{3\alpha} \tag{7.18}$$

7.18 ENERGY PATTERN FACTOR IN WIND POWER STUDIES

To design a wind energy system for a given site, it is necessary to know the characteristic of natural wind and estimate the wind resource. Wind power is expressed by the equation

7.20.3 Khals (Low Depressions)

Low depression saddles and water divides, having suitable aerodynamic conditions, are common sites in rural Garhwal Himalayas. These are known as *Khals* in local dialect. It is observed that river valleys, separated by a smaller water divide, have a change in their altitude and a change in air pressure. During the day, the air in these valleys is heated, after sunset the temperature decreases, consequently the pressure of the cool air on mountain summits becomes more and more. As a result, the cool air drains from summits to valleys during night. After sunrise the surface air of the valley again warms up. Typically, a temperature difference of 0.5°C produces winds of 5 m/s at 10 m above ground which is a good wind energy potential. Survey records indicate that about 135 Khals have been formed in between the Alaknanda catchment in the North and the Ramganga catchment in the South.

7.21 DESIGN OF WIND TURBINE ROTOR

There are two forces that operate on the blades of a propeller type wind turbine. One is the axial thrust which acts in the same direction as that of the flowing wind stream. The other is the circumferential force acting in the direction of wheel rotation that provides the torque.

7.21.1 Thrust on Turbine Rotor

A turbine extracts wind energy, causing the difference in momentum of air streams between the upstream and downstream sides as shown in Figure 7.17.

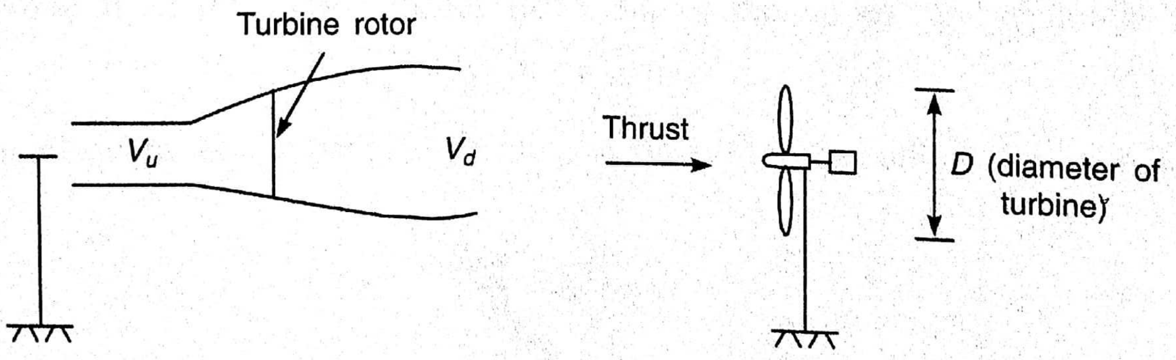


Figure 7.17 (a) Wind flow across turbine rotor, and (b) axial thrust on rotor.

$$F_x = \frac{1}{2}\rho A(V_u^2 - V_d^2)$$

$$= \frac{1}{2}\rho\frac{\pi}{4}D^2(V_u^2 - V_d^2)$$

$$= \frac{\pi}{8}\rho D^2(V_u^2 - V_d^2) \qquad (7.19)$$

where D is the rotor diameter.

For maximum output, $V_d = \frac{1}{3} V_u$ [Eq. 7.10(a)]

Therefore,

$$F_{x(\max)} = \frac{\pi}{8} \rho D^2 \left(V_u^2 - \frac{1}{9} V_u^2\right)$$

$$= \frac{\pi}{9} \rho D^2 V_u^2 \tag{7.20}$$

For designing a WEG, a large axial force can be obtained using large diameter turbines. The upper limit of the diameter needs to be optimized by matching structural design with economy.

7.21.2 Torque on Turbine Rotor

Maximum torque T on a turbine rotor would occur when maximum thrust can be applied at the blade tip farthest from the axis. A propeller turbine of radius R experiences

$$T_{\max} = F_{\max} \cdot R$$

From Eq. (7.19), F_x becomes maximum when $V_d = 0$. That is,

$$F_{\max} = \frac{1}{2} \rho A V_u^2$$

Hence,

$$T_{\max} = \frac{1}{2} \rho A V_u^2 R \tag{7.21}$$

For a wind turbine producing a shaft torque T, the torque coefficient C_T is defined by

$$T = C_T T_{\max} \tag{7.22}$$

The 'tip speed ratio λ' is the ratio of the blade's outer tip speed V_{tip} to the upstream (free) wind speed V_u, i.e.,

$$\lambda = \frac{V_{tip}}{V_u} = \frac{\omega R}{V_u} \tag{7.23}$$

where ω is the angular velocity of the rotor and R is the blade radius. Substituting the value of R in Eq. (7.21),

$$T_{\max} = \frac{1}{2} \rho A V_u^2 \left(\frac{V_u \lambda}{\omega}\right) = P_{total} \frac{\lambda}{\omega} \tag{7.24}$$

because, $\frac{1}{2} \rho A V_u^3 = P_{total}$ (wind power in upstream side).

Maximum shaft power, $P_{\max}$, is the power obtained from the turbine and is given as

$$P_{\max} = T \cdot \omega = C_T T_{\max} \omega \tag{7.25}$$

Equating Eqs. (7.12) and (7.25),

$$C_p\, P_{\text{total}} = C_T\, T_{\max}\, \omega = C_T\, P_{\text{total}} \frac{\lambda}{\omega} \cdot \omega$$

Therefore,

$$C_p = \lambda\, C_T \tag{7.26}$$

$C_p = 0.593$ as per Eq. (7.12), the Bitz limit.

So, ideally

$$(C_T)_{\max} = \frac{0.593}{\lambda} \tag{7.27}$$

7.21.3 Solidity

Solidity σ is defined as the ratio of the blade area to the circumference of the rotor. Solidity determines the quantity of blade material required to intercept a certain wind area. Hence,

$$\sigma = \frac{Nb}{2\pi R} \tag{7.28}$$

where N is the number of blades, b is the blade width and R is the blade radius.

For example, if a 3-metre radius rotor has 24 blades, each 0.35 m wide, the solidity is

$$\sigma = \frac{24 \times 0.35}{2\pi \times 3} \times 100 = 44.6\%$$

Solidity represents the fraction of the swept area of the rotor which is covered with metal.

Variation of solidity σ with tip speed ratio λ is shown in Figure 7.18.