6
Wind Energy

6.1. Introduction

Chapter 5 dealt with the conversion of solar energy into thermal energy or electrical energy. We now deal with an indirect solar electric technology, *wind power*.

Wind results from air in motion. Air in motion arises from a pressure gradient. On a global basis one primary forcing function causing surface winds from the poles toward the equator is convective circulation. Solar radiation heats the air near the equator, and this low density heated air is buoyed up. At the surface it is displaced by cooler more dense higher pressure air flowing from the poles. In the upper atmosphere near the equator the air thus tend to flow back toward the poles and away from the equator. The net results is a global convective circulation with surface winds from north to south in the northern hemisphere.

It is clear from the above over simplified model that the wind is basically caused by the solar energy irradiating the earth. This is why wind utilization is considered a part of solar technology.

In actuality the wind is much more complex. The above model ignores the earth's rotation which causes a coriolis force resulting in an easterly wind velocity component in the northern hemisphere.

There is the further complication of boundary layer frictional effects between the moving air and the earth's rough surface. Mountains, trees, buildings, and similar obstructions impair stream line air flow. Turbulence results, and the wind velocity in a horizontal direction markedly increases with altitude near the surface.

Then there is the obvious fact of land and water with their unequal solar absorptivities and thermal time constants. During day light the land heats up rapidly compared to nearby sea or water bodies, and there tends to be a surface wind flow from the water to the land. At night the wind reverses, because the land surface cools faster than the water.

Local winds are caused by two mechanisms. The first is differential heating of land and water. Solar insolation during the day is readily converted to sensible energy of the land surface but is partly absorbed in layers below the water surface and partly consumed in evaporating some of that water. The land mass becomes hotter than the water, which causes the air above the land to heat up and become warmer than the air above water. The warmer lighter air above the land rises, and the cooler heavier air above the water moves into replace it. This is the mechanism of shore breezes. At night, the direction of the breezes is reversed because the land mass cools to the sky more rapidly than the water, assuming a clear sky. The second mechanism of local winds is caused by *hills* and *mountain sides*. The air above the slopes heats up during the day and cools down at night, more rapidly than the air above the low lands. This causes heated air the day to rise along the slopes and relatively cool heavy air to flow down at night.

It has been estimated that 2 per cent of all solar radiation falling on the face of the earth is converted to kinetic energy in the atmosphere and that 30 per cent of this kinetic energy occurs in the lowest 1000 m of elevation. It is thus said that the total kinetic energy of the wind in this lowest kilometer, if harnessed, can satisfy several times the energy demand of a country. It is also claimed that the wind power is pollution free and that its source of energy is free. Such are the seemingly compelling arguments for wind power, not unlike those for solar power. Although solar energy is cyclic and predictable, and even dependable in some parts of the globe, wind energy, however, is erratic, unsteady, and often not reliable, except in very few areas. It does, however, have a place in the total energy picture, particularly for those areas with more, or less steady winds, especially those that are far removed from central power grids, and for small, remote domestic and farm needs.

Conversion of the kinetic energy (*i.e.*, energy of motion) of the wind into mechanical energy that can be utilized to perform useful work, or to generate electricity. Most machines for converting wind energy into mechanical energy consist basically of a number of sails, vanes, or blades radiating from a hub or central axis. The axis may be horizontal, as in the more familiar windmills, or vertical, as it is in some cases. When the wind blows against the vanes or sails they rotate about the axis and the rotational motion can be made to perform useful work. Wind energy conversion devices are commonly known as *Wind turbines* because they convert the energy of the windstream into energy of rotation : the component which rotates is called the *rotor*. The terms turbine and rotor are, however, often regarded as being synonymous.

Because wind turbines produce rotational motion, wind energy is readily converted into electrical energy by connecting the turbine to an *electric generator*. The combination of wind turbine and generator is sometimes referred to as an *aero generator*. A step-up transmission is usually required to match the relatively slow speed of the wind rotor to the higher speed of an electric generator.

Although windmills have been used for more than a dozen centuries for grinding grain and pumping water, interest in large scale electric power generation has developed over the past 50 yrs. A largest wind generator built in recent times was the 800 kWe unit operated in France from 1958-1960. The flexible 3 blades propeller was about 35 m in diameter and produced the rated power in a 60 km/hour wind with a rotation speed of 47 rpm. The maximum power developed was 12 MWe.

Wind energy is one of America's greatest natural resources. The U.S. government could plan for installation of wind turbine generators with a total capacity of 1 GW by 1985. Windmills have been used for several centuries in countries like Netherland and Denmark where high velocity wind is available in abundent quantity. Nearly, 30,000 house mills capable of producing 100 MW and 3000 industrial windmills generating another 100 MW were operating in Denmark at the turn of this century.

In India the interest in the windmills was shown in the last fifties and early sixties. Apart from importing a few from outside, new designs were also developed, but it was not sustained. It is only in the last few years that development work is going on in many institutions. An important reason for this lack of interest in wind energy must be that wind, in India are relatively low and vary appreciably with the seasons. Data quoted by some scientists that for India wind speed value lies between 5 km/hr to 15-20 km/hr. These low and seasonal winds imply a high cost of exploitation of wind energy. Calculations based on the performance of a typical windmill have indicated that a unit of energy derived from a windmill will be at least several times more expensive than energy derivable from electric distribution lines at the standard rates, provided such electrical energy is at all available at the windmill site.

The above argument is not fully applicable in rural areas for several reasons. First electric power is not and will not be available in many such areas due to the high cost of generation and distribution to small dispersed users. Secondly there is possibility of reducing the cost of the windmills by suitable design. Lastly, on small scales, the total first cost for serving a felt need and low maintenance costs are more important than the unit cost of energy. The last point is illustrated easily : dry cells provide energy at the astronomical cost of about

Rs. 300 per kWh and yet they are in common use in both rural and urban areas. This raises the question of that the felt needs are that a windmill might satisfy while large scale energy production at some favourable sites in India is a possibility that needs to be explored, there appears to be a definite need for small sources of mechanical energy in rural areas. For example, even casual polls among villagers quickly reveal that their first concern is invariably water for drinking, washing and irrigation ; and lifting water is a task which a windmill can perform. For such a task, a windmill should produce about 100 W, considering that a pair of bullocks, often used for lifting water in villages, typically provides about 250 W power. Many projects on windmill systems for water pumping and for production of small amount of electrical power have been taken up by various organisers, such as National aeronautical laboratory Banglore, central salt and Marine Chemicals Research Institute Bhavnagar, Central Arid Zone Research Institute (CAZRI) Jodhpur etc.

Wind energy offers another source for pumping as well as electric power generation. India has potential of over 20,000 MW for power generation and ranks as one of the promising countries for tapping this source. The cost of power generation from *wind farms* has now become lower than diesel power and comparable to thermal power in several areas of our country especially near the coasts. Wind power projects of aggregate capacity of 8 MW including 7 wind farms projects of capacity 6.85 MW have been established in different parts of the country of which 3 MW capacity has been completed in 1989 by DNES. Wind farms are operating successfully and have already fed over 150 lakh units of electricity to the respective state grids. Over 25 MW of additional power capacity from wind is under implementation. Under demonstration programme 271 wind pumps have been installed upto February 1989. Sixty small wind battery chargers of capacities 300 watts to 4 kW are under installation. Likewise to stand-alone wind electric generators of 10 to 25 kW are under installation.

6.2. Basic Principles of Wind Energy Conversion

6.2.1. The Nature of the Wind

The circulation of air in the atmosphere is caused by the non-uniform heating of the earth's surface by the sun. The air immediately above a warm area expands, it is forced upwards by cool, denser air which flows in from surrounding areas causing a wind. The nature of the terrain, the degree of cloud cover and the angle of the sun in the sky are all factors which influence this process. In general, during the day the air above the land mass tends to heat up more rapidly than the air over water. In coastal regions this manifests itself in a strong onshore wind. At night the process is reversed because the air cools down more rapidly over the land and the breeze therefore blows off shore.

The main planetary winds are caused in much the same way: Cool surface air sweeps down from the poles forcing the warm air over the tropics to rise. But the direction of these massive air movements is affected by the rotation of the earth and the net effect is a large countries-clockwise circulation of air around low pressure areas in the northern hemisphere, and clockwise circulation in the southern hemisphere. The strength and direction of these planetary winds change with the seasons as the solar input varies.

Despite the wind's intermittent nature, wind patterns at any particular site remain remarkably constant year by year. Average wind speeds are greater in hilly and coastal areas than they are well inland. The winds also tend to blow more consistently and with greater strength over the surface of the water where there is a less surface drag.

Wind speeds increase with height. They have traditionally been measured at a standard height of ten metres where they are found to be 20—25% greater than close to the surface. At a height of 60 m they may be 30—60% higher because of the reduction in the drag effect of the earth's surface.

6.2.2. The power in the Wind

Wind possesses energy by virtue of its motion. Any device capable of slowing down the mass of moving air, like a sail or propeller, can extract part of the energy and convert is into useful work. Three factors determine the output from a wind energy converter:

(i) the wind speed ;

(ii) the cross-section of wind swept by rotor ; and

(iii) the overall conversion efficiency of the rotor, transmission system and generator or pump.

No device, however well-designed, can extract *all* of the wind's energy because the wind would have to be brought to a halt and this would prevent the passage of more air through the rotor. The most that is possible is for the rotor to decelerate the whole horizontal column of intercepted air to about one-third of its free velocity. A 100% efficient aerogenerator would therefore only be able to convert up to a maximum of around 60% of the available energy in wind into mechanical energy. Well-designed blades will typically extract 70% of the theretical maximum, but losses incurred in the gearbox, transmission system and generator or pump could decrease overall wind turbine efficiency to 35% or less.

The power in the wind can be computed by using the concept of kinetics. The wind mill works on the principle of converting kinetic energy of the wind to mechanical energy. We know that power is equal to energy per unit time. The energy available is the kinetic energy of the wind. The kinetic energy of any particle is equal to one half its mass times the square of its velocity, or $\frac{1}{2} mV^2$. The amount of air passing in unit time, through an area A, with velocity V, is $A.V$, and its mass m is equal to its volume multiplied by its density ρ of air, or

$$m = \rho AV \qquad \text{...(6.2.1)}$$

(m is the mass of air transversing the area A swept by the rotating blades of a wind mill type generator).

Substituting this value of the mass in the expression for the kinetic energy, we obtain, kinetic energy $= \frac{1}{2} \rho AV.V^2$ watts

$$K.E = \frac{1}{2} \rho AV^3 \text{ watts} \qquad \text{...(6.2.2)}$$

Equation (6.2.2) tells us that the maximum wind available the actual amount will be somewhat less because all the available energy is not extractable—is proportional to the cube of the wind speed. It is thus evident that small increase in wind speed can have a marked effect on the power in the wind.

Equation (6.2.2) also tell us that the power available is proportional to air density (1.225 kg/m^3 at sea level). It may vary 10-15 per cent during the year because of pressure and temperature change. It changes negligibly with water content. Equation also tells us that the wind power is proportional to the intercept area. Thus an aeroturbine with a large swept area has higher power than a smaller area machine; but there are added implications. Since the area is normally circular of diameter D in *horizontal axis* aeroturbines, then $A = \frac{\pi}{4} D^2$, (sq. m), which when put in equation (6.2.2) gives,

$$\text{Available wind power } P_a = \frac{1}{2} \rho \frac{\pi}{4} D^2 V^3 \text{ watts}$$

$$= \frac{1}{8} \rho \pi D^2 V^3 \qquad \text{...(6.2.3)}$$

The equation tells us that the maximum power available from the wind varies according to the square of the diameter of the intercept area (or square of the rotor diameter), normally taken to be swept area of the aeroturbine. Thus doubting the diameter of the rotor will result in a four-fold increase in the available wind power. Equation (6.2.3) gives us in sight into why the designer of an aeroturbine for wind electric use would place such great emphasis on the turbine diameter. The combined effects of wind speed and rotor diameter variations are shown in Fig. 6.2.1. *Wind machines intended for generating substantial* *amounts of power should have large rotors and be located in areas of high wind speeds.* Where low or moderate powers are adequate, these requirements can be relaxed.

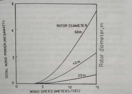


Fig. 6.2.1. Dependence of wind-rotor power on wind speed and rotor diameter.

The physical conditions in a wind turbine are such that only a fraction of the available wind power can be converted into useful power. As the free wind stream encounters and passes through a rotor, the wind transfer some of its energy to the rotor and its speed decreases to a minimum in the rotor wake. Subsequently, the wind stream regains energy from the surrounding air and at a sufficient distance from the rotor the free wind speed is restored (Fig. 6.2.2 upper curve). While the

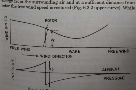


Fig. 6.2.2. Conditions in traversing a wind rotor.

wind speed is decreasing, as just described, the air pressure in the windstream changes in a different manner (Fig. 6.2.2, lower curve). It first increases as the wind approaches the rotor and then drops sharply by an amount Δp as it passes through and energy is transferred to the rotor. Finally the pressure increases to the ambient atmospheric pressure.

The power extracted by the rotor is equal to the product of the wind speed as it passes through the rotor (*i.e.* V_r in Fig. 6.2.2) and the pressure drop Δp. In order to maximize the rotor power it would therefore be desirable to have both wind speed and pressure drop as large as possible. However, as V is increased for a given value of the free wind speed (and air density), Δp increases at first, passes through a maximum, and then decreases. Hence for the specified free-wind speed, there is a maximum value of the rotor power.

The fraction of the free-flow wind power that can be extracted by a rotor is called the *power-coefficient* ; thus

$$\text{Power coefficient} = \frac{\text{Power of wind rotor}}{\text{Power available in the wind}}$$

where power available is calculated from the air density, rotor diameter, and free wind speed as shown above. The maximum theoretical power coefficient is equal to 16/27 or 0.593. This value cannot be exceeded by a rotor in a free-flow wind-stream. (It can be exceeded under specific conditions, as will be seen later).

As an ideal rotor, with propeller-type blades of proper areodynamic design, would have a power coefficient approaching 0.59. But such a rotor would not be strong enough to withstand the stresses to which it is subjected when rotating at a high rate in a high-speed wind stream. For the best practical rotors, the power coefficient is about 0.4 to 0.45, so that the rotors cannot use more than 40 to 45 percent of the available wind power. In the conversion into electric power, some of the rotor energy is lost and the overall electric power, coefficient of an aerogenerator (*i.e.* electric power generated/available wind power) in practice is about 0.35 (35 percent).

Returning to equation (6.2.2), but now recognizing that V, in actuality, is not constant but is represented by a statistically 'noisy' wind speed time curve, $V_{(t)}$, then the instantaneous power, in the wind would be

$$P_{a(t)} = \frac{1}{2}\rho A[V_{(t)}]^3 \text{ watts} \quad \text{...(6.2.4)}$$

Since we are normally more interested in average power, we must time average both sides of equation (6.2.4), signified by the bar below

$$\overline{P_{a(t)}} = \frac{1}{2}\rho A\,\overline{[V_{(t)}]^3} \text{ watts} \quad \text{...(6.2.5)}$$

Equation (6.2.5) tells us that for a non-steady state wind, it is necessary to cube the measured wind speeds and then take the average to find the average wind power available. It is immediately obvious that this non-steady state case is more complex than the simple steady state case, and it is why for the former case such great emphasis is placed on anemometry data at a proposed wind energy conversion system (WECS) site.

Transposing equation (6.2.5) results in

$$\frac{\overline{P_{a(t)}}}{A} = \frac{1}{2}\rho\,\overline{[V_{(t)}]^3}\ \text{watts/m}^2 \qquad \text{...(6.2.6)}$$

which says that the average available wind power per unit area is directly related to the average of the wind speed cubed. This is one useful method of characterizing the potential specific power in the wind over geographic area.

There are clear advantages in selecting sites with annual mean wind speeds and building larger rather than smaller wind generators since :

(*a*) the power available in the wind increases as *cube* of the wind speed : doubling the wind speed increases the power available by eight-fold ; and

(*b*) doubling the diameter of the turbine's rotor quadruples the swept area and hence the power output from the device (this law only applies to horizontal axis machines, for vertical axis machines the change in power output with diameter will be determined by the geometry of the rotor).

The way rotor diameter and wind speed affect power output can be seen in Fig. 6.2.1.

In practice a wind turbine's output will vary. There will be periods when there is insufficient wind for the machine to generate any power at all, and times when the wind speeds are so high that the machine has to be shut down to prevent damage.

Maximum Power. As stated above, that the total power can not be converted to mechanical power. Consider a horizontal-axis, propeller-type windmill, henceforth to be called a wind turbine, which is the most common type used today. Assume that the wheel of such a turbine has thickness $a\ b$, as shown in Fig. 6.2.3. Let p_i and V_i are the wind pressure and velocity at the upstream of the turbine, and P_e and V_e are pressure and velocity at downstream of the turbine. V_e is less than V_i because kinetic energy is extracted by the turbine.

Considering the incoming air between i and a as a thermodynamic system, and assuming that the air density remains constant (since changes in pressure and temperature are very small compared to ambient), that the potential energy is zero, and no heat or work are added or removed between i and a, the general energy equation reduces to the kinetic and flow energy-terms only :

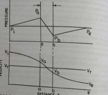


Fig. 6.2.3. Pressure and velocity profiles of wind moving through a horizontal-axis propeller-type wind turbine.

Thus
$$P_i v + \frac{V_i^2}{2g_c} = P_a v + \frac{V_a^2}{2g_c} \quad \text{...(6.2.7 a)}$$

[The general energy equation for steady state flow for unit mass (for a control volume) is :

$$Z_1 + \frac{V_1^2}{2g} + u + P_1 v_1 + \Delta q = Z_2 + \frac{V_2^2}{2g} + u_2 + P_2 v_2 + \Delta W_{sf}$$

where Z_1 = potential energy

$\frac{V^2}{2g}$ = kinetic energy

u = internal energy

Pv = flow energy

Δq = net heat added

ΔW_{sf} = net steady flow mechanical workdone of the system]

or
$$P_i + \rho \frac{V_i^2}{2g_c} = P_a + \rho \frac{V_a^2}{2g_c} \quad \text{...(6.2.7 b)}$$

where v and ρ are the specific volume and its reciprocal, the density, respectively, both considered to be constant.

Similarly for the exit region be,

$$P_e + \rho\frac{V_e^2}{2g_c} = P_b + \rho\frac{V_b^2}{2g_c} \quad ...(6.2.8)$$

The wind velocity across the turbine decreases from a to b since kinetic energy is converted to mechanical work there. The incoming velocity V_i does not decrease abruptly but gradually as it approaches the turbine to V_a and as it leaves it to V_e. The $V_i > V_a$ and $V_b > V_e$, and therefore, from equations (6.2.7) and (6.2.8), $P_a > P_i$ and $P_b > P_i$; that is, the wind pressure rises as it approaches, then as it leaves the wheel. Combining these equations,

$$P_a - P_b = \left(P_i + \rho\frac{V_i^2 - V_a^2}{2g_c}\right) - \left(P_e + \rho\frac{V_e^2 - V_b^2}{2g_c}\right) \quad ...(6.2.9)$$

It can be assumed that wind pressure at e can be assumed to ambient, *i.e.*,

$$P_e = P_i \quad ...(6.2.10)$$

As the blade width $a \cdot b$ is very thin as compared to total distance considered, it can be assumed that velocity within the turbine does not change much.

$$V_a \simeq V_t \simeq V_b \quad ...(6.2.11)$$

Combining equation (6.2.9) to (6.2.11) yields,

$$P_a - P_b = \rho\left(\frac{V_i^2 - V_e^2}{2g_c}\right) \quad ...(6.2.12)$$

The axial force F_a, in the direction of wind stream, on a turbine wheel with projected area, perpendicular to the stream A, is given by

$$F_a = (P_a - P_b)A = \rho A\left(\frac{V_i^2 - V_e^2}{2g_c}\right) \quad ...(6.2.13)$$

This force is also equal to change in momentum of the wind (from Newton's second law).

$$F_a = \Delta(\dot{m}V)/g_c$$

where $\dot{m}$ = mass flow rate = $\rho A V_t$

Thus

$$F_a = \frac{1}{g_c}\rho A V_t (V_i - V_e) \quad ...(6.2.14)$$

Equating equations (6.2.13) and (6.2.14),

$$\rho A\frac{(V_i^2 - V_e^2)}{2g_c} = \frac{1}{g_c}\rho A V_t (V_i - V_e)$$

$$V_t = \frac{1}{2}(V_i + V_e) \quad ...(6.2.15)$$

Considering the total thermodynamic system bounded by i and e, there are no changes in potential energy, the internal energy is there from T_i to T_e, and flow energy change is there from $P_i v$ to $P_e v$. In the system no heat is added or rejected *i.e.* adiabatic flow. The general energy equation how reduces to the steady flow work W and kinetic energy terms,

$$W = kE_i - kE_e = \frac{V_i^2 - V_e^2}{2g_c} \quad ...(6.2.16)$$

The power P is defined as the rate of work, from mass flow rate equation

$$P = m\frac{V_i^2 - V_e^2}{2g_c} = \frac{1}{2g_c}\rho A V_i (V_i^2 - V_e^2) \quad ...(6.2.17)$$

Combining this with equation (6.2.15),

$$P = \frac{1}{4g_c}\rho A (V_i + V_e)(V_i^2 - V_e^2) \quad ...(6.2.18)$$

Equation (6.2.17) reverts to equation (6.2.2) for P_{total} when $V_i = V_0$ and $V_e = 0$; that is, the wind velocity reduces to zero after leaving the turbine. This is not possible because the wind can not accumulate at turbine exit. It can be seen from equation (6.2.18), where V_e is positive in one term and negative in other, that too low or too high a value for V_e results in reduced power. There thus is an optimum exit velocity V_e opt, that results in maximum power P_{max}, which can be obtained by differenting P, and equating the derivative to zero *i.e.*

$$\frac{dp}{dV_e} = 0$$

or

$$\frac{dp}{dV_e} = 3V_e^2 + 2V_i V_e - V_i^2 = 0$$

This is solved for a positive V_e to give V_e opt. (The quadric has two solutions, *i.e.* $V_e = V_i$ and $V_e = \frac{1}{3}V_i$, only second solution is physically acceptable).

Thus $$\boxed{V_e \text{ opt} = \frac{1}{3}V_i} \quad ...(6.2.19)$$

Using the equation (6.2.18), for an ideal wind machine, with horizontal axis,

$$\boxed{P_{max} = \frac{8}{27g_c}\rho A V_i^3} \quad ...(6.2.20\text{ a})$$

$$= \frac{16}{27g_c} \frac{1}{2} \rho A V_i^3 = 0.593 \left(\frac{1}{2} \cdot \frac{\rho V A_i^3}{g_c} \right)$$

$$= 0.595 \, P_{total} \qquad \ldots(6.2.20\ b)$$

The *ideal, or maximum, theoretical efficiency* η_{max} (also called the *power coefficient*) of a wind turbine is the ratio of the maximum power obtained from the wind, to the total power available in the wind. The factor 0.593 is known as the Betz coefficient (from the name of the man who first derived it). It is the maximum fraction of the power in a wind stream that can be extract.

$$\text{Power coefficient} = C_p = \frac{\text{Power output from wind machine}}{\text{Power available in wind}}$$

Thus C_p can not exceed 0.593 for a horizontal axis wind machine.

6.2.3. Forces on the Blades and Thrust on Turbines

As stated earlier, here blades of propeller-type wind turbine is considered. There are two types of forces which are acting on the blades. One is *circumferential force* acting in the direction of wheel rotation that provides the torque and other is the *axial force* acting in the direction of the wind stream that provides an *axial thrust* that must be counteracted by proper mechanical design.

The *Circumferential force, or torque T* can be obtained from

$$T = \frac{P}{\omega} = \frac{P}{\pi D N} \qquad \ldots(6.2.21)$$

where T = torque *kgf* or *Newton (N)*

ω = angular velocity of turbine wheel, m/s

D = diameter of turbine wheel

$$= \sqrt{\frac{4}{\pi}} \, . A, \ m$$

N = wheel revolutions per unit time, s^{-1}

$\therefore$ The real efficiency $\eta = \dfrac{P}{P_{total}}$

or

$$P = \eta \, . \, P_{total} = \eta \cdot \frac{1}{2g_c} \rho A V_i^3$$

For a turbine operating at power P, the expression for torque becomes

$$T = \eta \frac{1 \, . \, \rho}{2g_c} \frac{A V_i^3}{\pi D N}$$

$$= \eta \frac{1}{2g_c} \frac{\rho \cdot \pi}{4} \frac{D^2 V_i^3}{\pi D N} = \eta \frac{1}{8g_c} \frac{\rho D V_i^3}{N}$$

$$= \eta \frac{1}{8g_c} \frac{\rho D V_i^3}{N} \quad ...(6.2.22)$$

At maximum efficiency $\left(\eta_{max} = \frac{16}{27} \right)$, the torque has maximum value T_{max} which is equal to

$$T_{max} = \frac{2}{27g_e} \frac{\rho D V_i^3}{N} \quad ...(6.2.23)$$

The axial force or thrust by equation (6.2.13)

$$F_x = \frac{1}{2g_c} \rho A (V_i^2 - V_e^2)$$

$$= \frac{\pi}{8g_c} \rho D^2 (V_i^2 - V_e^2) \quad ...(6.2.24)$$

The axial force on a turbine wheel operating at maximum efficiency where $V_e = \frac{1}{3} V_i$ is given by

$$F_{x,\,max} = \frac{4}{9g_c} \rho A V_i^2 = \frac{\pi}{9g_c} \rho A V_i^2$$

$$= \frac{\pi}{9g_c} \rho D^2 V_i^2 \quad ...(6.2.25)$$

We see that axial forces are proportional to the square of the diameter of the turbine wheel, this limits turbine wheel diameter of large size.

6.2.4. Wind Energy Conversion

Traditional windmills were used extensively in the Middle Ages to mill grain and lift water for land drainage and watering cattle. Wind energy converters are still used for these purposes today in some parts of the world, but the main focus of attention now lies with their use to generate electricity. There is also growing interest in generating heat from the wind for space and water heating and for glass-houses but the potential market is much smaller than for electricity generation.

The term "wind mill" is still widely used to describe wind energy conversion systems, however it is hardly an opt. description any more. Modern wind energy conversion systems are more correctly referred to as 'WECS', 'aerogenerators', 'wind turbine generators', or simply 'wind turbines'.

The fact that the wind is variable and intermittent source of energy is immaterial for some applications such as pumping water for land drainage—provided, of course, that there is a broad match between the energy supplied over any critical period and the energy required. If the wind blows, the job gets done ; if it does not, the job waits.

However, for many of the uses to which electricity is put, the interruption of supply may be highly inconvenient. Operators or users of wind turbines must ensure that there is some form of back-up to cover periods when there is insufficient (or too much) wind available. For small producers, back-up can take the form of :

(*i*) battery storage ;

(*ii*) connection with the local electricity distribution system ; or

(*iii*) a stand-by generator powered by liquid or gaseous fuels.

For utilities responsible for public supply, the integration of medium-sized and large wind turbines into their distribution net work could require some additional plant which is capable of responding quickly to meet fluctuating demand.

Small producers. Private citizens in several countries have won the right to operate wind generators and other renewable energy systems and to export power to the grid. For most small wind generators this requires that the output is 'conditioned' so that it conforms to the frequency and phase of the mains supply. Only a few small units are designed to maintain a constant rotational rate so that can be synchronized to the mains frequency and feed electricity directly into the grid. Most produce direct current (DC) or variable output alternating current (AC).

Power conditioning is readily achieved using an electronic black-box called a 'synchronous' inverter', and although this is an expensive item of equipment, it does eliminate the need for batteries and for conversion of home appliances to run on DC.

Where there is no grid connection, electricity that is surplus to immediately requirements must be stored on site using heavy duty batteries. It can be recovered later when the demand exceeds the supply. An alternative is to dump it (by generating and dissipating heat) or better, to convert it into heat that can be stored, for example as hot water in a well insulated tank.

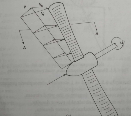
Large producers. Large and medium-sized wind generators are designed to give a stable and constant electrical output over a wide range of wind speeds and to feed current directly into the grid. They operate primarily as fuel savers, reducing the utility's total fuel burn.

The choice of generator type depends on the size of the local distribution grid and its associated generating capacity. An *induction generator* would normally be used where there is a significant amount of other generating capacity (which could provide the necessary reactive power for excitation). Induction generators are robust and reliable and require minimal control equipment. For isolated networks where other local generating capacity is limited, and where a high degree of autonomous control is required, a *synchronous* generator is more appropriate. Synchronous generators are more complex and therefore more expensive than induction machines.

Lift and drag : The basis for wind energy conversion. The extraction of power, and hence energy, from the wind depends on creating certain forces and applying them to rotate (or to translate) a mechanism. There are two primary mechanisms for producing forces from the wind ; *lift* and *drag*.

By definition lift forces act perpendicular to the air flow, while drag forces act in the direction of flow. Lift forces are produced by changing the velocity of the air stream flowing over either side of the lifting surface : speeding up the air flow causes the pressure to drop, while slowing the air stream down leads to increase in pressure. In other words, any change in velocity generates a pressure difference across the lifting surface. This pressure difference produces a force that begins to act on the high pressure side and moves towards the low pressure side of the lifting surface which is called an airfoil. A good airfoil has a high lift/drag ratio, in some cases it can generate lift forces perpendicular to the air stream direction that are 30 times as great as the drag force parallel to the flow. The lift increases as the angle formed at the junction of the airfoil and the air-stream (the angle of attack) becomes less and less actute, upto the point where the angle of the air flow on the low pressure side becomes excessive. When this happens, the air flow breaks away from the low pressure side. A lot of turbulence ensues, the lift decreases and the drag increases quite substantially ; this phenomenon is known as *stalling*. For efficient operation, a wind turbine blade needs to function with as much lift and as little drag as possible because drag dissipates energy. As lift does not involve anything more complex than deflecting the air flow, it is usually an efficient process. The design of each wind turbine specifies the angle at which the airfoil should be set to achieve the maximum lift to drag ratio.

In addition to airfoils, there are two other mechanisms for creating lift. One is the so-called *Magnus effect*, caused by spinning a cylinder in an air stream at a high-speed of rotation. The spinning slows down the air speed on the side where the cylinder is moving into wind and increases it on the other side; the result is similar to an airfoil. This principle has been put to practical use in one or two cases but is not generally employed. The second way is to blow air through narrow slots in a cylinder, so that it emerges tangentially; this is known as a *Thwaits slot*. This also creates a rotation (or circulation) of the air flow, which in turn generates lift. Because the lift drag ratio of airfoils is generally much better than those of rotating or slotted cylinders, the latter techniques probably have little practical potential.

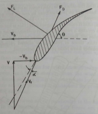


(a)

Symbols

V	Free wind velocity
V_b	velocity of airfoil element $(\mid V_b \mid = \omega_r)$
V_r	resultant wind as 'seen' by airfoil element
F_L	lift force (perpendicular to V_r)
F_D	drag force
θ	angle of twist
α	angle of incidence
ω	angular speed of rotor
r	distance of airfoil element from its axis of rotation.

The windmill blade 'sees' the resultant vector V_r. The blades need to be twisted because r varies in proportion to radius.



(b) Cross-section across A—A Fig. (a).

Fig. 6.2.1. Shape of a horizontal axis, wind turbine rotor blade.

Example 6.2.1. Wind at 1 standard atmospheric pressure and 15°C has velocity of 15 m/s calculate :

(i) the total power density in the wind stream,

(ii) the maximum obtainable power density,

(iii) a reasonally obtainable power density,

(iv) the total power, and

(v) the torque and axial thrust.

Given : turbine diameter = 120 m, and turbine operating speed = 4 r.p.m. at maximum efficiency. Propeller tyne wind turbine is considered.

Solution.

For air, the value of gas constant

$$R = 0.287 \text{ kJ/kg K}$$

$$1 \text{ atm.} = 1.01325 \times 10^5 \, P_a.$$

Air density $\rho = \dfrac{P}{RT}$

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

(i) Total power $P_{total} = \dfrac{\rho A V_i^3}{2g_c}$

Power density $= \dfrac{P_{total}}{A}$

$$= \frac{1}{2g_c} \cdot \rho\, V_i^3 = \frac{1}{2 \times 1} 1.226 \times 15^3$$

$$= \mathbf{2068.87\ W/m^2.\ Ans.}$$

(ii) Maximum power density

$$= \frac{P_{max}}{A} = \frac{8}{27g_c} \rho A V_i^3$$

$$= \frac{8}{27 \times 1} 1.226 \times 15^3$$

$$= 1226\ \text{W/m}^2.\ \textbf{Ans.}$$

(iii) Assuming $n = 35\%$

$$\because \quad \frac{P}{A} = n \frac{P_{total}}{A}$$

$$= 0.35 \times 2068.87 = 724\ \text{W/m}^2.\ \textbf{Ans.}$$

(iv) Total Power P = Power density × Area

$$= 724 \times \frac{\pi}{4} D^2 \text{ watt}$$

$$= 0.724 \times \frac{\pi}{4} \times 120^2 \text{ kW}$$

$$= \mathbf{8184\ kW.\ Ans.}$$

(v) Torque at maximum efficiency

$$T_{max} = \frac{2}{27g_c} \times \frac{\rho D V_i^3}{N}$$

$$= \frac{2}{27 \times 1} \times \frac{1.226 \times 120 \times 15^3}{40/60}$$

$$= 55170 \text{ Newton.}\ \textbf{Ans.}$$

and maximum axial thrust

$$F_{x\,max} = \frac{\pi}{9g_c} \rho D^2 V_i^2$$

$$= \frac{\pi}{9 \times 1} 1.226 \times 120^2 \times 15^2$$

$$= 1385{,}870 \text{ Newton.}\ \textbf{Ans.}$$

6.3. Wind Data and Energy Estimation

The seasonal as well as instantaneous changes in winds both with regard to magnitude and direction need to be well understood to make the best use of them in windmill designs. Winds are known to fluctuate by a factor of 2 or more within seconds (and thus causing the power to fluctuate by a factor of 8 or more). This calls for a proper recording and analysis of the wind characteristics.

There are various ways the data on wind behaviour is collected depending on the use it is intended to be put into. The hourly mean wind velocity as collected by the meteorological observations is the basic data used in a windmill designs. The hourly mean is the one averaged over a particular hour of the day, over the day, month, year and years. The factors which affect the *nature of the wind* close to the surface of the earth, they are :

(*i*) latitude of the place,

(*ii*) altitude of the place,

(*iii*) topography of the place,

(*iv*) scale of the hours, month or year.

Winds being an unsteady phenomenon, the scale of the periods considered is an important set of data required in the design. The *hourly mean velocity* (for many years) provides the data for establishing the potential of the place for tapping the wind energy. The *scale of the month* is useful to indicate whether it is going to be useful during particular periods of the year and what storage if necessary is to be provided for. The *data based on scale of the hour* is useful for mechanical aspects of design.

Since the winds near the surface of the earth are derived from large scale movement of atmospheric winds, the location height above ground level at which the wind is measured and the nature of the surface on earth have an influence on the velocity of wind at any given time. The winds near the surface of the earth are interpreted in terms of boundary layer concept, keeping in mind the factors that influence its development. The wind velocity at a given height can be represented in terms of gradient height and velocity

$$\frac{V}{V_g} = \left(\frac{h}{h_g}\right)^n \text{ (refer Fig. 6.3.1)}$$

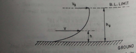


Fig. 6.3.1. Representation of gradient height and velocity

The values of V_g, h_g and n depends on the nature of the terrain, which are classified as

(i) Open terrain with few obstacles (open land, lake, shores, deserts, prairies, etc.)

(ii) Terrain with uniformly covered obstacles (wood lands, small towns, suburbs, etc.)

(iii) Terrain with large and irregular objects (large city centres, country with breaks of large trees etc.).

In as much as the height of the windmill rotor depends on the design wind velocity and cost of supporting structure. The above factors have a bearing on the design. Similarly, winds being an unsteady phenomenon, the scale of periods considered for this the temporal parameters (scale of hour, month and year) is an important set of data required in the design. While the hourly mean velocity (for many years) provides the data for establishing the potential of the place for tapping the wind energy. The scale of the month is useful to indicate whether it is going to be useful during particular periods of the year and what storage if necessary is to be provided for as already mentioned above. The data based on scale of the hour is useful for mechanical aspects of design. In addition to the data on the hourly mean velocity, two other informations required are :

—Spells of low wind speeds, and

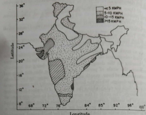
—gusts

The former again for providing storage or alternatives. The latter is required for structural design of the windmill as well as to provide safety measures against damage.

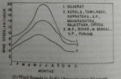
A number of criteria can be applied in estimating the importance of wind potential as a function of height and location. First of all careful siting is important because wind speed near the ground is greatly affected by houses, trees and similar features as stated above. Wind speed increases with height above ground, the if rate of increase being about the same at all locations. Therefore, if the wind speed at a given height is known, the speed at any other height may be calculated.

Surface wind data on a national or regional basis is usually presented in the forms of :

(i) *Isovents* or contours of constant average wind velocity (m/sec or km/hr.). The averaging period seen in the literature varies widely, but monthly, quarterly, and yearly averages are commonly seen. It is important to know what the data averaging period is when examining a given isovent contour map, for the winds change seasonally. Fig. (6.3.2) shows the wind map of India, in which the mean annual



(a)



(b) Wind Speeds in India (Average over 30 years).

Fig. 6.3.2. Wind map of India.

wind velocity zones are marked. It is seen that only some parts of the country have reasonably good velocity (*i.e.* from the point of view of wind mill operation). Even at other zones marked with low wind velocity one can always find 'spots high winds' depending on the topography.

(ii) *Isodynes* are contours of constant wind power (watts/m^2 of area perpendicular to the wind flow). Again it is important to know the averaging period. An example of this map is shown in Fig. (6.3.3).

Wind Surveys. Typical wind measurements at potential sites for wind machines usually require the following.

(1) Instrumentation :

3 cup anemometer and wind direction sensors.

Height of instruments ; 10 m (30 feet) for preliminary data ; 15 m to 45 m (50 to 150 feet) for long time data.

(2) Data recording systems ;

Strip chart

Magnetic tap

(3) Type of data

Wind speed and directional-hourly averages

(4) Data reporting

Wind frequency curves

Daily, weekly, monthly.

Fig. 6.3.3. A typical plot of available wind power (watts/m^2) yearly average.

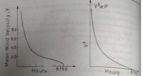
Energy Estimation. The basic wind data of hourly mean wind velocity is recast into—number of hours in the year for which the speed equals or exceeds each particular value.

—annual hours of duration of various wind speed.

The first of these plotted amongst the hours in the year is called the velocity—duration curve. The replot of this on V^3 basis is called the power duration curve (V^3 being proportional to P).

These curves are useful for establishing the wind energy potential of a place, and the design wind speed.

The plot of the second form of data of number of hours for which mean wind velocity of a particular value is available is called the frequency duration curve. (Fig. 6.3.5). This curve is useful in deciding



(a) Velocity duration curve (b) Power duration curve

Fig. 6.3.4

the design wind speed for a given site once the type of windmill is decided and its performance is known, the data is also useful in estimating the actual energy output of the plant.

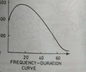


Fig. 6.3.5. Frequency duration curve.

The *three* speeds associated with the design of a windmill are:

V_c—cut in speed, the speed below which the wind mill does not operate.

V_d—design speed, the speed for which the rotor is designed.

V_f—furling speed, the speed at which the rotor is turned away from facing the wind or stopped otherwise with a view to protect the windmill.

All these speeds have a bearing on the mean wind velocity of the place. Another reference speed is the rated velocity V_{rat} at which the plant output is maximum.

The three speeds are marked on Fig. (6.3.6). The hatched area $a\ b\ c\ d\ e$, represents the annual energy output from an ideal plant. Area A B C D represents the output obtainable from an ideal plant, if the windmill were to operate at the design speed all the time. The ratio of areas $a\ b\ c\ d\ e$/A B C D is the annual load factor of the plant. In practice,

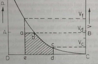


Fig. 6.3.6. Ideal plant output.

the actual output will be smaller than that represented by area $a\ b\ c\ d\ e$ due to the inability of the rotor to convert the entire kinetic energy available in the wind. This is represented by C_p, which varies as a function of velocity having the maximum value at the design wind speed. Fig. (6.3.7) shows a typical variation.

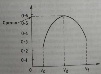


Fig. 6.3.7. Variation of C_p as a function of V.

Taking this into consideration, the annual output from a plant is given by

$$E = \int \eta_m\ C_p\ \rho A V^3 \delta_T \qquad ...(6.3.1)$$

where δ_T is the time increment since the data is usually available in the form of number of hours for which each mean wind velocity is available, the expression takes the form

$$E = \sum_{c}^{f} \eta_m C_p \rho A V^3_{c-f} \delta_T \quad ...(6.3.2)$$

As such the detailed knowledge of wind data, the type of windmill intended to be used and its performance characteristics are all required to establish the energy delivered by the plant at a given site.

6.4. Site Selection Considerations

The power available in the wind increases rapidly with the speed, hence wind energy conversion machines should be located preferable in areas where the winds are strong and persistent. Although daily winds at a given site may be highly variable, the monthly and especially annual average speeds are remarkably constant from year to year. The major contribution to the wind power available at a given site is actually made by winds with speeds above the average. Nevertheless, the most suitable sites for wind turbines would be found in areas where the annual average wind speeds are known to be moderately high or high.

The site choice for a single or a spatial array of WECS (wind energy conversion system) is an important matter when wind electric is looked at from the systems point of view of aeroturbine generators feeding power into a conventional electric grid. If the WECS sites are wrongly or poorly chosen the net wind electric generated energy per year may be sub optimal with resulting high capital cost for the WECS apparatus, high costs for wind generated electric energy, and low returns on investment. Even if the WECS is to be a small generator not tied to the electric grid, the siting must be carefully chosen if inordinately long break even times are to be avoided. Technical, economic, environmental, social, and other factors are examined before a decision is made to erect a generating plant on a specific site. Some of the main considerations are discussed below.

(1) *High annual average wind speed. A fundamental requirements* to the successful use of WECS, obviously, is an adequate supply of wind as stated above. The wind velocity is the critical parameter. The power in the wind P_w, through a given cross-sectional area for a uniform wind velocity V, is

$$P_w = KV^3$$

where K is a constant. It is evident, because of the cubic dependence on wind velocity that small increases in V markedly affect the power in the wind, *e.g.* doubling V, increases P_w by a factor of 8. It is obviously desirable to select a site for WECS with high wind velocity. Thus a high average wind velocity is the principal fundamental parameter of concern in initially appraising a WECS site. For a more detailed estimate value, one would like to have the average of the velocity cubed.

Anemometer data is normally based on wind speed measurements from a height of 10 m. For the most accurate assessment of wind power potential it is absolutely essential that anemometer data be obtained at the precise site and hub height for any proposed WECS.

Strategy for siting is generally recognized to consists of :

(*i*) Survey of historical wind data,

(*ii*) Contour maps of terrain and wind are consulted.

(*iii*) Potential sites are visited.

(*iv*) Best sites are instrumented for approximately one year.

(*v*) Choose optimal site.

(2) *Availability of anemometry data.* It is another important siting factor. The principal object is to measure the wind speed which basically determines the WECS output power, but there are many practical difficulties with the instrumentation and measurement methods. The anemometer height above ground, accuracy, linearity, location on the support tower, shadowing and inaccurate readings therefrom, icing inertia of rotor whether it measures the horizontal velocity component or vertical, and temperature effects are a few of the many difficulties encountered. The anemometry data should be available over some time period at the precise spot where any proposed WECS is to be built and that this should be accomplished before a siting decision is made.

(3) *Availability of wind $V_{(t)}$ curve at the proposed site.* This important curve determines the maximum energy in the wind and hence is the principal initially controlling factor in predicting the electrical output and hence revenue return of the WECS machine. It is desirable to have average wind speed V such that $V \geq 12 - 16$ km/hr (3.5 – 4.5 m/sec) which is about the lower limit at which present large scale WECS generators 'cut in' *i.e.* start turning. The $V_{(t)}$ curve also determines the reliability of the delivered WECS generator power, for if the $V_{(t)}$ curve goes to zero there will be no generated power during that time. If there are long periods of calm the WECS reliability will be lower than if the calm periods are short. In making such reliability estimates it is desirable to have measured $V_{(t)}$ curve over about a 5 year period for the highest confidence level in the reliability estimate.

(4) *Wind structure at the proposed site.* The ideal case for the WECS would be a site such that the $V_{(t)}$ curve was flat, *i.e.* a smooth steady wind that blows all the time ; but a typical site is always less than ideal. Wind specially near the ground is turbulent and gusty, and changes rapidly in direction and in velocity. This departure from

6.5. Basic Components of a WECS (Wind Energy Conversion System)

The main components of a WECS are shown in Fig. (6.5.1), in block diagram form. Summary of the system operation is as follows:

Aeroturbines convert energy in moving air to rotary mechanical energy. In general, they require pitch control and yaw control (only in

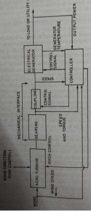


Fig. 6.5.1. Basic components of a Wind Electric System.

the case of horizontal or wind axis machines) for proper operation. A mechanical interface consisting of a step up gear and a suitable coupling transmits the rotary mechanical energy to an electrical generator. The output of this generator is connected to the load or power grid as the application warrants.

Yaw control. For localities with the prevailing wind in one direction, the design of a turbine can be greatly simplified. The rotor can be in a fixed orientation with the swept area perpendicular to the predominant wind direction. Such a machine is said to be *yaw fixed*. Most wind turbines, however, are *yaw active*, that is to say, as the wind direction changes, a motor rotates the turbine slowly about the vertical (or yaw) axis so as to face the blades into the wind. The area of the wind stream swept by the wind rotor is then a maximum.

In the small turbines, yaw action is controlled by a tail vane, similar to that in a typical pumping windmill. In larger machines, a servomechanism operated by a wind-direction sensor controls the yaw motor that keeps the turbine properly oriented.

The purpose of the controller is to sense wind speed, wind direction, shafts speeds and torques at one or more points, output power and generator temperature as necessary and appropriate control signals for matching the electrical output to the wind energy input and protect the system from extreme conditions brought upon by strong winds electrical faults, and the like.

The physical embodiment for such an areo-generator is shown in a generalized form in Fig. (6.5.2). The sub-components of the windmill are :

—wind turbine or rotor
—wind mill head
—transmission and control
and —Supporting structure

Such a machine typically is a large impressive structure.

Rotors

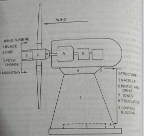
Rotors are mainly of two types :

(*i*) Horizontal axis rotor and

(*ii*) Vertical axis rotor.

One advantage of vertical-axis machines is that they operate in all wind directions and thus need no yaw adjustment.

The rotor is only one of the important components. For an effective utilization, all the components need to be properly designed and matched with the rest of the components.



A—*Transmission*
Speed Increaser
Driver Shaft add Bearing Brake
Clutch and Coulping.
B—*Electrical*
Generator
Control and indicators (at ground level)

Fig. 6.5.2. Physical embodiment of wind-electric generating station.

The windmill head supports the rotor, housing the rotor bearings. It also houses any control mechanism incorporated like changing the *pitch* of the blades for safety devices and tail vane to orient the rotor to face the wind. The latter is facilitated by mounting it on the top of the supporting structure on suitable bearings.

Transmissions. The rate of rotation of large wind turbine generators operating at rated capacity or below, is conveniently controlled by varying the pitch of the rotor blades, but it is low, about 40 to 50 revolutions per minute (rpm). Because optimum generator output requires much greater rates of rotation, such as 1800 rpm, it is necessary to increase greatly the low rotor rate of turning. Among the transmission options are mechanical systems involving fixed ratio gears, belts, and chains, singly or in combination or hydraulic systems involving fluid pumps and motors. Fixed ratio gears are recommended for top mounted equipment because of their high efficiency, known cost, and minimum system risk. For bottom mounted equipment which requires a right-angle drive, transmission costs might be reduced substantially by using large diameter bearings with ring gears mounted on the hub to serve as a transmission to increase rotor speed to generator speed. Such a combination offers a high degree of design flexibility as well as large potential savings.

Generator. Either constant or variable speed generators are a possibility, but variable speed units are expensive and/or unproved. Among the constant speed generator candidates for use are synchronous induction and permanent magnet types. The generator of choice is the synchronous unit for large aerogenerator systems because it is very versatile and has an extensive data base. Other electrical components and systems are, however, under development.

Controls. The modern large wind turbine generator requires a versatile and reliable control system to perform the following functions :

(1) the orientation of the rotor into the wind (azimuth of yaw) ;

(2) start up and cut-in of the equipment ;

(3) power control of the rotor by varying the pitch of the blades ;

(4) generator output monitoring—status, data computation, and storage ;

(5) shutdown and cut out owing to malfunction or very high winds ;

(6) protection for the generator, the utility accepting the power and the prime mover ;

(7) auxiliary and/ or emergency power ; and

(8) maintenance mode.

Many combinations are possible in terms of the control system and may involve the following components :

(1) sensor—mechanical, electrical, or pneumatic :

(2) decision elements—relays, logic modules, analog circuits, a microprocessor, a fluidics, units, or a mechanical unit ; and

(3) actuators—hydraulic, electric, or pneumatic. A recommended combination of electronic transducers feeding into a micro-processor which, in turn, signals electrical actuators and provides protection through electronic circuits, although a pneumatic slip clutch may be required.

Towers. Four types of supporting towers deserve consideration, these are :

(1) the reinforced concrete tower,

(2) the pole tower,

(3) the built up shell-tube tower, and

(4) the truss tower.

Among these, the truss tower is favoured because it is proved and widely adaptable, cost is low, parts are readily available, it is readily transported, and it is potentially stiff. Shell-tube towers also have attractive features and may prove to be competitive with truss towers.

The type of the supporting structure and its height is related to cost and the transmission system incorporated. It is designed to withstand the wind load during gusts (even if they occur frequently and for very short periods). Horizontal axis wind turbines are mounted on towers so as to be above the level of turbulence and other ground-related effects. The minimum tower height for a small WECS is about 10 m, and the maximum practical height is estimated to be roughly 60 m.

The turbine may be located either unwind or downwind of the tower. In the unwind location (*i.e.* the wind encounters the turbine before reaching the tower), the wake of the passing rotor blades causes repeated changes in the wind forces on the tower. As a result, the tower will tend to vibrate and may eventually be damaged. On the other hand, if the turbine is downwind from the tower as shown in figure, the tower vibrations are less but the blades are now subjected to severe alternating forces as they pass through the tower wake.

Both unwind and downwind locations have been used in WEC devices. Downwind rotors are generally preferred especially for the large aerogenerators. Although other forces acting on the blades of these large machines are significant, tower effects are still important and tower design is an essential aspect of the overall system design.

6.6. Classification of WEC Systems

1. First, there are two broad classifications :

(*i*) *Horizontal Axis Machines.* The axis of rotation is horizontal and the aeroturbine plane is vertical facing the wind.

(*ii*) *Vertical Axis Machines.* The axis of rotation is vertical. The sails or blades may also be vertical, as on the ancient Persian windmills or nearly so, as on the modern Darrievs rotor machine.

2. Then, they be classified *according to size* as determined by their useful electrical power output.

(*i*) *Small Scale* (upto 2 kW). These might be used on farms, remote applications, and other places requiring relatively low power

(ii) *Medium Size Machines* (2-100 kW). These wind turbines may be used to supply less than 100 kW rated capacity, to several residences or local use.

(iii) *Large Scale or Large Size Machines* (100 kW and up). Large wind turbines are those of 100 kW rated capacity or greater. They are used to generate power for distribution in central power grids. There are two sub classes :

(a) Single Generator at a single site.

(b) Multiple Generators sited at several places over an area.

3. As per the type of *output power*, wind aerogenerators are classified as :

(i) *DC output*

(a) DC generator

(b) Alternator rectifier

(ii) *AC output*

(a) Variable frequency, variable or constant voltage AC.

(b) Constant frequency, variable or constant voltage AC.

4. As per the *rotational speed* of the aeroturbines, these are classified as :

(i) *Constant Speed* with variable pitch blades. This mode implies use of a synchronous generator with its constant frequency output.

(ii) *Nearly Constant Speed* with fixed pitch blades. This mode implies an induction generator.

(iii) *Variable Speed with fixed pitch blades.* This mode could imply, for constant frequency output :

(a) Field modulated system

(b) AC-DC-AC link

(c) Double output induction generator

(d) AC Commutator generators

(e) Other variable speed constant frequency generating systems.

5. Wind turbines are also classified as per how the *utilization of output is made* :

(i) Battery storage.

(ii) Direct connection to an electromagnetic energy converter.

(iii) Other forms (thermal potential etc.) of storage.

(iv) Interconnection with conventional electric utility grids.

The system engineer seeking to integrate WECS will, naturally be most interested in the latter case but should be aware that WECS offer other options as well.

6.7. Advantages and Disadvantages of WECS

Advantages of wind energy are :

(*i*) It is a renewable source of energy.

(*ii*) Like all forms of solar energy, wind power systems are non-polluting, so it has no adverse influence on the environment.

(*iii*) Wind energy systems avoid fuel provision and transport.

(*iv*) On a small scale upto a few kilowatt system is less costly. On a large-scale costs can be competitive with conventional electricity and lower costs could be achieved by mass production.

Disadvantages of wind energy are :

(*i*) Wind energy available in dilute and fluctuating in nature.

(*ii*) Unlike water energy wind energy needs storage capacity because of its irregularity.

(*iii*) Wind energy systems are noisy in operation ; a large unit can be heard many kilometres away.

(*iv*) Wind power systems have a relatively high overall weight, because they involve the construction of a high tower and include also a gearbox, a hub and pitch changer, a generator coupling shaft etc. For large systems a weight of 110 kg/kW (rated) has been estimated.

(*v*) Large areas are needed, typically, propellers 1 to 3 m in diameter, deliver power in the 30 to 300 W range.

(*iv*) Present systems are neither maintenance free not-practically reliable. However, the fact that highly reliable propeller engines are built for aircraft suggest that the present troubles could be overcome by industrial development work.

6.8. Wind Energy Collectors

6.8.1. Introduction. A windmill is a machine for wind energy conversion. A wind turbine converts the kinetic energy of the wind's motion to mechanical energy transmitted-by the shaft. A generator further converts it to electrical energy, thereby generating electricity. The term 'windmill' which originally implied a mill for grinding grain becomes an obvious misnomer when applied to electric power generation. The term is still widely used however, *Aerogenerators* avoids this difficulty. Only in the last century have windmills been used to generate electric power.

Wind *aerogenerators* or wind turbine generators of WECS are generally classified as

—horizontal axis type, and

—vertical axis type

depending on their axis of rotation, relative to the wind stream.

Some authors refer to them also as wind axis rotors and cross wind axis rotors respectively. In the former types, the rotors are oriented normal to the direction of wind, while in the latter types, the effective surface of the rotor moves in the same direction as the wind.

Horizontal axis wind machines are further sub-classified as single bladed, multibladed and by-cycle multiblades type. Sail, wind, multibladed are example of horizontal axis wind machines, *Savonius* and *Darrius* rotor are example of vertical axis machines.

The vertical axis windmill or machine is again sub-divided into two major types :

(*i*) Savonius or 'S' type rotor mill (low velocity wind).

(*ii*) Darrieus type rotor mill (high velocity wind) based on the working speed of the machine and the velocity ranges required by the machine for operation.

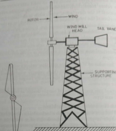
Vertical axis machines are of simple design as compared to the horizontal axis type.

6.8.2. Horizontal-Axial Machines

The common wind turbine with a horizontal (or almost horizontal) axis, is simple in principle, but the design of a complete system, especially a large one that will produce electric power economically, is complex. Not only must be individual components, such as the rotor, transmission, generator, and tower, be as efficient as possible, but these components must function effectively in combination. Some of the main design considerations will be considered later.

Some of the horizontal axis type wind machines are briefly described below :

1. *Horizontal axis using two aerodynamic blades*. In this type of design, rotor drives a generator through a step up gear box. The blade rotor is usually designed to be oriented *downwind* of the tower. The components are mounted on a bed plate which is attached on a pintle at the top of the tower. This arrangement is shown schematically in Fig. (6.8.1). The rotor blades are continuously flexed by unsteady aerodynamic, gravitational and inertia loads, when the machine is in operation. If the blades are made of metal, flexing reduces their fatigue life with rotor the tower is also subjected to above loads, which may cause serious damage. If the vibrational modes of the rotor happen to coincide with one of the natural mode of the vibration of the tower, the system may shake itself to pieces. Because of the high cost of the blade rotors with more than two blades are not recommended. Rotors with more than two, say 3 or 4 blades would have slightly higher power coefficient.



(a) TWO BLADE PRUFILE

(b) SCHEMATIC OF A HORIZANTAL AXIS TYPE WIND MILLS

Fig. 6.8.1

2. *Horizontal axis propeller type using single blade.* In this arrangement, a long blade is mounted on a rigid hub (Fig. 6.8.2). Induction generator and gear box are also shown. If extremely long blades (above say 60 m) are mounted on rigid hub, large blade root bending moments may occur due to tower shadow, gravity and sudden shifts in wind directions. To reduce rotor cost, use of low cost counter weight is recommended which balance long blade centrifugally.

Advantages of one bladed rotor :

(*i*) Simple blade controls
—lower blade weight and cost
—lower gear box cost

(*ii*) Counter weight costs less than a second blade.

(*iii*) Counter weight can be inclined to reduce blade coning.

(*iv*) Pitch bearings do not carry centrifugal force.

(*v*) Blade root spar can be large diameter *i.e.* more rugged.

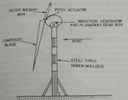


Fig. 6.8.2. Horizontal axis single blade wind mill.

Disadvantages :

(*i*) Vibration produced, due to aerodynamic torque.

(*ii*) Unconventional appearance.

(*iii*) Large blade root bending moment.

(*iv*) Starting-torque reduced by ground boundary layer.

(*v*) One-per-rev coriolis torque produced, due to flapping.

3. *Horizontal axis multibladed type*. This type of design for multiblades as shown in Fig. (6.8.3), made from sheet metal or

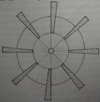


Fig. 6.8.3. Multiblade propeller.

aluminium. The rotors have high strength to weight ratios and have been known to service hours of freewheeling operation in 60 km/hr winds. They have good power coefficient, high starting torque and added advantage of simplicity and low cost.

4. *Horizontal axis wind mill-Dutch type*. It is shown in Fig. (6.8.4), is one of the oldest designs. The blade surfaces are made from an array of wooden slats which 'feather' at high wind speeds.

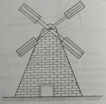


Fig. 6.8.4. Horizontal axis, Dutch type wind mill.

5. *Sail type*. It's blade are shown in Fig. (6.8.5). It is of recent origin. The blade surfaces is made from cloth, nylon or plastics arranged as mast and pole or sailwings. There is also variation in the number of sails used.

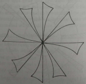


Fig. 6.8.5. Blades of sail type wind mill.

The horizontal axis types generally have better performance. They have been used for various applications, but the two major areas of interest are electric power generation, and pumping water. The latter introduces some complexity into the design as the mechanical energy has to be transmitted over a distance. Also in some cases the rotor motion has to be converted to reciprocating motion.

6.8.3. Design Consideration of Horizontal-Axis Machines

The common wind turbine with a horizontal (or almost horizontal) axis is simple in principle, but the design of a complete system, especially a large one that will produce electric power economically, is complex. Not only must the individual components, such as the rotor, transmission, generator, and tower, be as efficient as possible, but these components must function effectively in combination. Some of the main design considerations are outlined below.

Rotor. A wind turbine's rotor may have any number of blades which may be made from wood, metal, or composites of several materials including glass reinforced plastics. Future blades may use carbon fibre which combines light weight and flexibility with immense strength.

In the most common type of machine the rotor is mounted on a horizontal (or near horizontal) shaft and connected either to a generator or some mechanical device such as a water pump or heat generator. The whole assembly is mounted on a tower so that it turns clear of the ground and away from surface drag and interference. From a performance point of view, the taller the tower the better because wind speeds increase with height.

Many turbine designs have been built over the years. These have included machines with a single, counter balanced blade or with multiple rotors, and turbines with two or more sets of counter-rotating blades on the same shaft. Rotors have been constructed with cups, paddles, or sails rigged to rigid wooden spars as in the early type windmill. The rotor can be mounted upwind or down wind of the support tower.

Horizontal-axis rotors can be either lift or drag devices. Lift devices are generally preferred, since for a given swept area, high rotational speeds and more output power can be developed by lift than by drag forces. In general, a drag device can not move faster than the wind velocity, while a lift device can. Thus a lifting surface can obtain higher top to wind speeds and, consequently, a higher power output to weight ratio and, for many applications, a lower cost to power output ratio.

Lift devices use slender blades with an aerofoil section that generate *aerodynamic lift* when placed in an air current ; and drag devices are those, like the familiar multi-bladed farm wind pump, that rely essentially on *drag* forces to extract energy from the wind. Rotors that rely on lift are capable of turning at very high speeds as stated. Small rotors can spin at 400—500 revolutions per minute (rpm) with blade tip speeds of several hundred km per hour 8-10 times faster than the wind. Very large aerofoil rotors turn much more slowly, typically 20—40 rpm, but the blade tip speeds are comparable 65—110 m/s or 250—400 kmph.

Drag devices are less efficient wind energy converters and always turn more slowly than the wind. They work best in less windy inland locations. The faster they run the more they spill in the wind. Lift devices, on the other hand, are able to profit from the high power densities that are available at high wind speeds. The ratio of the power extracted by a lift device to that of a drag device is usually greater than 3 : 1 for the same swept area.

Drag devices are often capable of generating high torques (twisting forces) and are ideal for some uses such as water pumping. They are less suitable for electricity generation which requires very high rotational speeds (several thousand rpm). The reverse is generally true for lift devices. Small rotors can often rotate at such speeds that they can be connected directly to a generator. Larger rotors require step-up gearing.

One major disadvantage with rotors with slender aerofoil blades is that they will not start up without first being rotated to generate lift. They, therefore require some external source of power. Indeed, this is a general problem with rotors with a low 'solidity ratio' in which the blades occupy only a small part (10% or less) of the rotors swept area. The ratio of the projected area of the rotor (on a plane perpendicular to its axis of rotation) to the swept area of the rotor is known as the '*Solidity*' of the rotor. For multivane fan-type rotors such as the American farm wind mill, a typical-solidity is 0.7. For high speed lift type propellers, on the other hand, the solidity is usually much lower, *i.e.*, 0.1 to 0.01.

Lift type rotors often use tapered and/or twisted blades to reduce the bending strains on *the roots of the blades.*

All horizontal-axis rotors depend mainly on lift to rotate them. Maximum efficiency is achieved when the angle of incidence approaches the maximum possible angle of attack prior to stalling (*i.e.* when the lift drag ratio is as high as possible). Given that a rotor's tip travel faster than points nearer axis, the angle at which the wind meets the plane of rotation decreases in linear proportion to the radius. For this reason, an efficient wind rotor requires the blades to be twisted so that the optimum angle of incidence is obtained at all radii when the machine is running at its design speed. For the same reason, high-speed machines have blades set at a finer pitch than low-speed ones. The ratio of the speed of the rotor blade tips to the speed of the wind is called the tip-speed ratio. Every rotor has an optimum tip-speed ratio at which its maximum efficiency is achieved, and which also characterizes the rotor. The tip speed ratio computed numerically as :

$$\text{TSR (tip speed ratio)} = \frac{V_{tip}}{V}$$

where V_{tip} = speed of the rotor tip

and V = free wind speed.

The faster a rotor runs with respect to the wind speed, the less 'solidity' is required to intercept the entire stream-tube of wind passing through the rotor disc. In other words, a rotor with a high TSR needs less material and can have relatively slender blades. However, because it rotates at higher speeds and twist angles require only slight angles of attack at the tip, a high lift drag ratio is essential to produce a driving torque. Therefore high-speed low solidity wind rotors need good quality airfoils (similar to those used for aircraft). They must also be made with a good surface finish and the structural integrity necessary to withstand high rotational speeds. For this reason, the cost/m^2 of good, high-speed rotors is often greater than that of low-speed rotors, despite the reduced quantity of material. Conversely, low TSRs require rotor discs with relatively solid blades or sails so that wind energy will not be lost through the gaps between them. These blades need coarser pitch setting. Because lift is stronger in the plane of rotation and drag is weaker, the lift drag ratio is less critical. For this reason, wind mills with low TSRs tends to have many blades and the lifting surfaces can be much cruder without causing any serious loss of efficiency.

As the TSR increases, the number of blades decreases (see table 6.8.3.1). Solidity is normally defined as the fraction of the total circumferential (either at the tip or sometimes at two thirds of the tip radius) that contains blades. Numerically it can be expressed as :

$$S = NC/\pi D$$

where N is the number of blades,

C is the average breadth of a blade

and D is the diameter of the circle described by a blade.

Table 6.8.3.1 Blade number vs TSR

Tip speed ratio	*Number of blades*
1	6—20
2	4—12
3	3—8
4	3—5
5—8	2—4
8—15	1—2

It is usual to characterize a windmill rotor by comparing its curve of efficiency with its TSR. The efficiency is usually expressed as the C_p (power coefficient or performance coefficient). This is the fraction of wind energy passing through the rotor disc that is converted into shaft power *i.e.* (Eqn. 6.2.2)

$$C_p = 0.5\ \rho\ .\ AV^3$$

Every type of rotor has a unique C_p curve. The reason for the shape of the curve is that the optimum C_p occurs when the rotor blades are operating at their maximum LDR lift drag ratio (close to, but not quite, stalling). At lower TSR, the blades stall progressively and although they can generate a lot of lift, they also produce much more drag, which dissipates energy. At a higher than optimum TSR, they produce less than their maximum lift (and the lift forces act at a less favourable angle) because the angle of incidence decreases. At runaway speed, the angle of incidence approaches zero, and the lift and drag forces balance, so that no net shaft power is produced and the efficiency once again is zero. Windmills normally operate on the part of the curve to the right of the maximum C_p. They depend on an increasing wind speed to accelerate the rotor from rest through the peak C_p point.

Although the C_p—TSR curve is generally used to characterize wind rotors, in many ways the torque characteristic (the C_T—TSR curve) is of more interest (Figs. 6.10.1 and 6.10.2) to those concerned with system design. A wind turbine will always operate at a speed that produces enough torque to balance the load's torque requirement exactly. Hence, if the characteristics of both the load and the rotor torque speed are known, the system performance can be defined.

Torque coefficient C_T, is defined as

$$C_T = \frac{T}{T_{max}} \qquad ...(6.8.3.1)$$

where T = shaft torque, and

T_{max} = torque at maximum efficiency

The previous calculation (section 6.2.3) of thrust on a wind turbine provides a convenient opportunity to introduce definitions for the torque causing rotational shaft power. At this stage no attempt is made to analyze angular momentum exchange between the air and the turbine. However, it is obvious that if the turbine turns one ways the air must turn the other, and full analysis must eventually consider the vortices of air circulating down wind of the turbine.

The maximum conceivable torque T on a turbine rotor would occur if the maximum thrust could some how be applied at the blade tip furthest from the axis. For a propeller turbine of radius R

$$T_{max} = F_{max} R \qquad \text{...(6.8.3.2)}$$

and

$$F_{max} = \frac{1}{2} \rho A_1 V_i^2 \qquad \text{...(6.8.3.3)}$$

So

$$T_{max} = \frac{1}{2} \rho A_1 V_1^2 R \qquad \text{...(6.8.3.4)}$$

For a working machine producing a shaft torque T, the torque coefficient C_T is defined by Eqn. 6.8.3.1 *i.e.*

$$T = C_T T_{max}$$

We know the *tip speed ratio* λ is defined as the ratio of the outer blade tip speed V_t to the unperturbed wind speed V_i ;

$$\lambda = \frac{V_t}{V_i} = \frac{R\omega}{V_i} \qquad \text{...(6.8.3.5)}$$

where R is the outer blade radius and ω is the rotational frequency.

From equation (6.8.3.4) substituting for R

$$T_{max} = \frac{\rho A V_i^2 (V_i \lambda)}{2\omega}$$

$$= P_a \lambda / \omega \qquad \text{...(6.8.3.6)}$$

where P_a is the power in the wind from (6.2.2). The shaft power is the power derived from the turbine P_t, so

$$P_t = \tau \,.\, \omega \qquad \text{...(6.8.3.7)}$$

Now from equation $P_t = C_p P_a$, and thus using (6.8.3.1) and (6.8.3.6), equation (6.8.3.7) becomes

$$C_p P_a = C_T T_{max} \omega$$

$$C_p P_a = C_T P_a \lambda$$

$$C_p = \lambda C_T \qquad \text{...(6.8.3.8)}$$

Note that in practice power coefficient C_p and torque coefficient C_T will both be function of λ and are not constants.

By the Betz criterion the maximum value of C_p is 0.593, so in the 'ideal' case

$$C_{T\,max} = \frac{0.593}{\lambda} \qquad \text{...(6.8.3.9)}$$

The torque coefficient C_T is numerically equal to C_p/ω, where ω is the rotational speed radian/second. Machines with higher speeds have a slightly higher maximum C_p but a much lower C_T, particularly for starting. In fact, high solidity machines generally have higher starting than running torques, while the starting torques of low-solidity machines are even lower than their quite low running torques.

The choice of rotor is based mainly on the pump's load characteristics. A positive displacement pump, such as the piston pumps used in the bore holes, demands a higher starting than running torque and, therefore, a high solidity rotor is essential unless some method of unloading the rotor to help it start is included. However, electricity generators need little torque to start them turning and they should be driven at high speeds, so that a high-speed, low soliding rotor is generally used for this type of load.

Number of blades. Wind turbines have been built with upto six propellers type blades but two-and three-bladed propellers are most common. A one-bladed rotor with a balancing counterweight, has some advantages, including lower weight and cost and simpler controls, over the multi-blade tupe. However, starting requires high wind speeds, and vibration and other forces can be large.

Turbines with three blades have been used in several WEC machines in order to avoid the vibrations experienced with two-bladed rotors. These vibrations are related to the turning (or yawing) of the rotor in order to face it into the wind. It appears, however, that the problem can be overcome by controlling the yaw rate. Because they cost less to fabricate in large sizes and are capable of operating with a high tip speed ratio, two-bladed systems are receiving major attention.

Blade Design. Wind turbine blades have an airfoil-type cross section and a variable pitch (Fig. 6.8.6 *a*). They are slightly twisted from the outer tip to the root (*i.e.* where the blade is attached to the hub) to reduce the tendency for the rotor to stall. In a few devices, the blades had a constant chords length *i.e.* constant distance from edge to the other). As a general rule, however better performance is obtained with blades that are narrower at the tip than at the root (see Fig. 6.8.6 *a*).

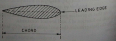


Fig. 6.8.6 (*a*). Cross-section of airfoil-type wind-rotor blade.

As shown in Fig. (6.8.6 *b*), we see that the force that propels the blades of a conventional wind mill comes from the chord of the airfoil, being tilted away from the direction of motion. The motion causing the

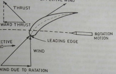


Fig. 6.8.6. (*b*). Wind mill blade as an airfoil.

"wind due to motion" is the rotation of the blades. At the tip of the blades of a modern wind turbine the velocity is about six times the wind velocity. This means that the blades are set rather flat at a small angle with the plane of the rotation and almost at right angles to the direction of wind so that the effective wind properly approach from ahead of the leading edge. At other parts of the blade, between the tip and the axle, the velocity and the ideal set of the airfoil is at a greater angle to the plane of rotation. Ideally the blade should be twisted, but because of construction difficulties this is not always achieved.

In the large two bladed wind turbines, the blades are inclined at a small angle called the *coming angles* to the vertical. This design decreases the bending load on the roots of the blades and lessens the danger of fouling the supporting tower under severe wind conditions. In the very large rotors consisting of a single piece mounted at the midpoint, there is no coning angle.

A fundamental problem in wind turbine design is to allow for the many forces to which the blades are subjected during normal operation. In addition to vibrational stresses resulting from rotation, there are several extraneous forces. There arise form wind turbulence, directional changes in the wind, variations of wind speed with height, wind gusts, gravitational forces, the pressure of the tower etc. The blades must be constructed and attached to the hub in such a manner as to with stand these forces. Consequently, aerodynamic performance is sacrificed to some extent in the design of a rotor with adequate strength.

Although the wind power of a rotor increases with the square of the swept diameter, there is a practical limit to the size. In the first place, the mass of a blade increases rapidly with its dimensions. As a result, the wind power available per unit mass decreases as the dimensions of the rotor are increased ; the tip speed ratio tends to decrease correspondingly. Further more, the wind drag forces generally increase with the blade size. The limiting dimensions depend on the design and constructional materials, but the maximum practical diameter of a two-blade rotor may perhaps be in the range of 90 to 110 m.

In order to provide both light weight and adequate strength aircraft industry techniques, as used, in connection with air place and helicopter propellers, have been drawn upon in the design and the construction of wind turbines. For small rotors in particular, the blades can be made of laminated wood, possibly covered with a thin skin of aluminium. Rotors upto 34 m in diameter have been fabricated from plastic reinforced with glass fibre. More conventional air-craft type blades are usually made from aluminium (or an aluminium alloy); they consist of a long central span with ribs at intervals, covered with an aluminium skin. The very largest rotor blades have been made of steel to provide adequate strength.

Yaw control. The area of the windstreams swept by the wind turbine is maximum, when blades face into the wind. This is achieved by control arrangement, is which when the wind direction changes, a motor rotates the turbine slowly about the vertical (or yaw) axis so as the face the blades into the wind.

For localities with the prevailing wind in one direction, the design of a turbine can be greatly simplified. The rotor can be in a fixed orientation with swept area perpendicular to the predominant wind director. Such a machine is said to be *yaw-fixed* i.e. it can not be rotated around a vertical axis perpendicular to the wind stream. Most wind turbines, however, are *yaw-active* ; that is to say, as the wind direction changes, they will "track" the changing direction of the wind. In this case, a motor rotates the turbine slowly about the vertical (or yaw) axis so as to face the blades into the wind. The area of the windstream swept by the wind in then a maximum.

In the smaller turbines, yaw action is controlled by a tail vane similar to that in the American pumping windmill. In larger machines a servomechanism operated by a wind-direction sensor controls the yaw motor that keeps the *turbine* properly oriented.

Wind stream variation. Wind speed variability must be considered, especially in the design of the larger WEC machines. For a given turbine there is a minimum wind speed called the *cut-in speed* at which rotation is allowed to start the cut-in wind speed and the rated wind speed, at which the generator produces its rated power, the rotation rate is maintained constant by varying the output of the generator. At wind speeds exceeding the rated value, the rotor speed is held constant by automatic adjustment of the pitch of the blades. At very high wind speeds the blades are feathered, as in aircraft, and rotation ceases. The wind speed at which this occurs is called the *cut-out speed* (or furling speed), the electric power output of the generator is essentially constant.

The variation of the generated power with the wind speed is shown (approximately) by the full lines in Fig. 6.8.7, the dashed curve represents the theoretical variation without any control of the rotation rate of the turbine (*i.e.* power proportional to the cube of the wind speeds. At wind speeds above the rated value, part of the available wind power is not used (or "spilled") as a consequence, of changing the pitch angle of the rotor. Consequently in this respect, the system is somewhat less efficient than one in which the rotor speed is allowed to increase with wind speed, within limits. However, machines of the letter type are less easily adapted to connection into an electric utility grid.

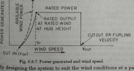


Fig. 6.8.7. Power generated and wind speed.

By designing the system to suit the wind conditions at a particular site, the wind power lost by spilling can be relatively small. At higher wind speeds, the speed of rotation of the blades (and of the hub to which they are attached) tends to increases. In fact, for a given wind speed, the rate of rotation must exceed a certain value if a stall, with loss of power, is to be avoided. However, a changing speed of rotation will generally not provide the optimum conditions for generating constant-frequency alternating current.

One solution to this problem is to allow the turbine speed to vary and to couple the hup with a mechanical or electrical system which can generate a current of constant frequency from a variable-speed input. For example, variable-frequency alternating current may be generated and rectified to produce direct current. The direct current can then be used to generate constant frequency alternating current by means of an inverted. If the electricity produced by the WEC machine is to be used for battery charging, a direct-current generator (upto about 20 kW) may be connected directly to the rotor hub ; the speed of rotation of the turbine is then immaterial provided it is not so low as to cause stalling.

Although it results in some loss of efficiency, an alternative solution, used in some aerogenerators, has been preferred. Between the cut-in wind speed and the rated wind speed, at which the generator produces its power, the rotation rate is maintained constant by varying the output of the genérator. At wind speeds exceeding the rated value the rotor speed is held constant by automatic adjustment of the pitch of the blades. At very high speed the blades are feathered, as in an aircraft, and rotation ceases. Over the range from the rated wind speed to the cut-out speed, the electric power out put of the generator as stated remains constant.

In order to take advantage of winds with speeds above average the rated wind speed should be greater than average value but not so high that the generator is often operating below the rated power. The ratio of rated to average wind speeds should be about 1.8 for an average speed of 5 m/sec. (17.5 kmph) decreasing to 1.5 for average speed of 10 m/sec (35 kmph). Over the years many ingenious techniques have been developed for preventing over-speeding and for dissipating the excess power that would otherwise be generated by the rotor in gale (strong winds). Over-speeding can literally tear the blades out by the roots. In comparatively small machines the tail vane can be hinged to turn the rotor out of the wind, thus effectively reducing the swept area. Alternatively, the whole assembly can be mounted slightly off-centre so that it swings aside when the thrust on the rotor exceeds a set rating. In very high winds the rotor can turn completely out of the wind. 'Spoilers' which unfold at high speed ; can be used to exert a drag on the rotor ; or the blases can be made from very flexible materials so that they bow back, twist and spill the wind. Most machines are fitted with a brake which can bring the rotor to full a stop.

In more sophisticated rotor designs the blades are 'Feathered' automatically—their pitch is changed in response to the wind speed. This approach is attractive since it permits the wind turbine to operate with virtually constant output over range of wind speeds and to continue to generate power even in a gale. In small machines 'feathering weights' can be placed on or near the hub, and these respond to centrifugal forces as the rotor's speed increases ; as they lean outwards they automatically alter the pitch of the blades. The performance of large rotors is generally controlled by a computer which senses changes in the wind speed or electrical power and alters the pitch of the blades accordingly. Sometimes just the tips of the blades move.

Wind turbines must be sufficiently robust to withstand cyclic gravity loads caused by the revolving blades and vibration caused by the buffeting of the wind. In poorly designed machines this can lead to increased wear, fretting and metal fatigue, and, in extreme cases, to blade or bearing failures or even complete structural collapse. One innovation that can reduce stress in large two-bladed rotors is the 'teetered hub' which allows the rotor to seesaw back and forth by a few degrees. This motion across the hub alleviates loads on both the blades and the tower and has enabled engineers to design much lighter, and hence cheaper structures.

Turbine Tower System. As stated earlier, the horizontal axis wind turbines are mounted on towers, and there are wind forces on the tower. Both upwind and downwind locations have been used so that tower design is an essential aspect of the overall system design.

6.8.4. Vertical-Axis Machines

Various types of vertical axis panemones have been developed in the past that use drag forces to turn rotors of different shapes. These include those panemones that use plates, cups, or turbines as the drag device, as well as the Savonius—S-shaped cross-section rotors which actually provide some lift force, but are still predominantly drag devices. Such devices have relatively high starting torques compared to lift devices because of their higher solidity, but have relatively low tip-to-wind speeds and lower power outputs per given rotor size, weight and cost.

As stated vertical-axis rotors can be either drag-or lift-based. The cup anemometer is an example of a drag-based, vertical axis wind device. The drag on a cup is greater when its concave side faces the wind which causes the device to rotate. Lift also plays a small part : the cups crossing the wind experience a small lift because their convex surfaces deflect the wind and causes a pressure reduction. The main virtue of the cup anemometer is that it tends to rotate within a narrow range of TSRS under all conditions, so its rotational speed is closely proportional to wind speed. However, it can not carry a load with any efficiency, it has never been constructed on a large scale for use as a wind turbine. The Savonius rotor works on a principle similar to that of the cup anemometer but is adoated to produce shaft power. It also takes advantage of the lift generated as the curved outer surfaces of its scoops cross the air flow. There are also a variety of so-called Panamones ; these are pure drag devices, in which one side of the rotor carries blades or sails square to the wind, while the other side produces reduced drag by shielding or furling the blades. Because drag devices tend to run at

TSR below unity (since their tips can not readily travel faster than the wind), they are inevitably less efficient than lift-dependent devices. In addition, their high solidity makes them more material-intensive in relation to the wind area 'seen' by the rotor.

Although only a few are available commercially, cross flow or Darrieus wind turbines have lately been attracting some attention.

Vertical-axis rotors have the great advantage of not having to be turned into the windstream as the wind direction changes, because their operation is independent of wind direction, vertical axis machines are called *panemones* (from Greek words meaning "all winds"). Until recent times, these devices received little attention for the generation of electric power, partly because vertical-axis rotors have lower power coefficients at high tip speed ratios (see Fig 6.10.1). In addition, vertical-axis turbines are said to be more difficult to control in strong winds. It is now realized, however, that the lower efficiency of panemones may be more than offset by the simpler design and consequent lower construction (and maintenance) costs. Elimination of the need for yawing into the wind, for example, results in decreased stresses on blades, bearing, and other components. Moreover, the transmission and generator are on (or near) the ground rather than at the top of a tall tower.

Hence following are the three distinct advantages of vertical axis wind turbines over horizontal axis ones :

(1) They will react to wind from any direction and therefore do not need yawing equipment to turn the rotor into the wind.

(2) They can require less structural support because heavy components (like gear box and generator) can be located at ground level. This configuration also eases installation and maintenance.

(3) Since the blades do not turn end over end, the rotor is not subjected to continuous cyclic gravity loads. (Fatigue induced by such action is a major consideration in the design of large horizontal axis machines).

Probably the single biggest disadvantage with vertical axis machines is that far less is known about them than horizontal axis ones. This handicap is rapidly being removed.

(a) *The Savonius Rotor*. Perhaps the simplest of the modern types of wind energy conversion systems is the Savonius rotor which works like a cup anemometer. This type was invented by S.J. Savonius in the year 1920. This machine has become popular since it requires relatively low velocity winds for operation.

It consists of two-half-cylinders facing opposite directions in such a way as to have almost an S-shaped cross section (refer Fig. 6.8.8

These two-semi circular drums are mounted on a vertical axis perpendicular to the wind direction with a gap at the axis between the two drums. Irrespective of the wind direction the rotor rotates such as to make the convex sides of the buckets head into the wind. From the rotor shaft we can tape power for use like water-pumping, battery charging, grain winnowing etc. However, instead of having two edges together to make an S-shaped they overlap to leave a wide space

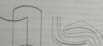


Fig. 6.8.8. The Savonius rotor and its stream flow.

between the two inner edges, so that each of these edges is near the central axis of the opposite half cylinder, as shown in the figure. The main action of the wind is very simple ; the force of the wind is greater on the cupped face than on the rounded face. In detail it is a bit more complicated. The wind curving around the back side of the cupped face exerts a reduced pressure much as the wind does over the top of an air-foil and this helps to drive the rotation. The wide slot between the two inner edges of the half cylinders, lets the air whip around inside the forward-moving cupped face, thus pushing both in the direction of the rotation.

The ratio of the height to the overall diameter (aspect ratio) of the machine can be varied, but it is generally less than three to one. The power coefficient of the S rotor is low, but it might possibly be improved by changes in the design, number, and arrangements of the vanes. These matters need to be investigated.

Characteristics of Savonius Rotor

(*i*) Self starting

(*ii*) Low speed

(*iii*) Low efficiency.

Advantages of Savonius Rotor

(1) A Savonius wind energy conversion system has a vertical axis which eliminates the expensive power transmission system from the rotor to the axis. Since it is a vertical axis machine it does not matters

much about the wind direction. The machine performs even at low-wind velocity ranges.

(2) It has its low *cut in speed* (the wind speed required for switching electric power into the line); it produces power effectively in winds as slow as 8 km/hour, where as most-propeller type wind mills or machines require about 16 km/hour, for effective operation and large wind mill still more. This means that it is useful more of the time and is thus less dependent on storage of supplementary power.

(3) In common with all vertical-axis machines, the Savonius rotor has the advantage that the weight of the electric generator may be carried at ground level without the use of level gears. This is, however not a very important advantage.

(4) *Cost* of vertical axis wind turbine may be significantly lower than that of standard wind turbines.

(5) It has *simple structure*, hence easy to manufacture.

(6) *Yaw and pitch controls* are not needed to bring it into the wind or operate in high winds. A constant speed vertical axis wind turbine, automatically stalls at high wind speeds.

(7) *Ground level mounting*, for the generator and gearing permits easy access and maintenance, and reduces tower costs.

(8) *Overall weight* of the turbine may be substantially less than that of conventional systems. This is because of the small amount of material involved in relation to the swept area which translates to lower cost.

Disadvantages: (*i*) This type of machine is too solid, having so much metal or other material surface compared with the amount of wind intercepted. This not only leads to excessive weight for a large installation but also leaves the machine of the mercy of severe storms since there is no way to reduce the effective area.

(*ii*) It is not useful for a very tall installation because a long drive shaft problems and also the bracing of the topmost bearing above the rotor of a very tall vertical-axis machine is awkward, requiring very long guy wires. In a conventional horizontal-axis wind electric machine with the generator a loft, the strength of the structure required to carry the added weight of the generator is small compared with that needed to servive a severe storm and the generator housing adds little to the area presented to the storm.

Areas of concern. The Savonius rotor has moderately good efficiency and a satisfactory starting characteristics, the latter being particularly important for use with a positive displacement pumps.

The rotor area requirement for getting the required amount of power is higher than any other systems. It is commonly, used for pumping, and to operate small agricultural machines like winnowers blowers, bird scarers, grinders etc. The another use of this type of wind energy conversion system is to use this machine along with Darrieus rotors for starting purposes.

(b) *The Darrieus type machines* (High velocity wind). This machine was invented originally and patented in 1925 by G.J.M. Darrieus, a French engineer and his concept has recently been given serious consideration once again. In India at BHEL, Hyderabad and NAL Bangalore research and development of the Darrieus wind energy conversion systems are in progress. This type of wind mills are already in use in Canada. As noted, a modern rapidly rotating propeller type windmill, by use of an efficient airfoil, effectively intercepts large area of wind with a small blade area. The Darrieus wind mill is a type of vertical axis machine that has the same advantage. An additional advantage is that it supports its blades in a way that minimizes bending stresses in normal operation.

It has two or three thin, curved (egg beater) blades with airfoil cross section and constant chord length (Fig. 6.8.9). Both ends of blades are attached to a vertical shaft. Thus the force in the blade due to rotation is pure tension. This provides a stiffness to help withstand the wind forces it experiences. The blades can thus be made lighter than in the propeller type. What happens in a serve storm is another question as yet un-answered. When rotating, these airfoil blades provide a torque about the central shaft in response to a wind stream. This shaft torque is being transmitted to a generator at the base of the central shaft for power generation.

Darrieus-type rotors are lift devices, characterized by curved blades with air foil cross-sections. They have relatively low solidity and low starting torques, but high tip to wind speeds and, therefore, relatively high power outputs per given rotor weight and cost. Various types of Darrieus rotor configurations have been conceived, including the Φ—Darrieus, Δ—Darrieus, the Y—Darrieus, and the □—Darrieus. Such Darrieus rotors can be designed to operate with one, two, three, or more blades.

Darrieus rotors can also be combined with various types of auxiliary rotors to increase their starting torques. However such additions increase the weight and cost of the system, so trade-offs in these characteristics must be considered in developing an optimum design for a given application.

Characteristics of Darrieus Rotor

(i) Note self starting

(ii) High speed

(iii) High efficiency

(iv) Potentially low capital cost.

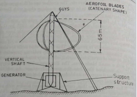


Fig. 6.8.9. Vertical axis wind mill.

As shown in Fig. 6.8.6 (*b*) we see that the force that propels the blades of a conventional wind mill comes from the chord of the airfoil being tilted away from the direction of motion, so that the thrust that is almost at right angles to the airfoil is tilted toward the forward direction and has a component in that direction, labelled "forward thrust". The remarkable thing about the Darrieus rotor is that it can

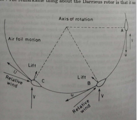


Fig. 6.8.10. Darrieus rotor principle.

not have the advantage of this tilt of the airfoil, and yet works without it, with the chord directly along the tangent to the circular path in the equatorial cross-section shown in Fig. 6.8.10. If the chord were tilted away from the tangent so as to tilt the thrust forward where the wind meets the airfoil on the wind ward side of the circle, as indicated by the broken lines in the figure then the other side of the circle, the wind would meet the other side of the aerofoil and the thrust would be filted backward to retard the motion.

The concept or Darrieus rotor principle (Fig. 6.8.10) is based on the principle by which a Bermuda-rigged sailing ship can sail across the wind at speeds greater than that of the wind, much like the blade of a horizontal-axis windmill. Lift causes a turning action stronger than the drag forces that impede it as long as the TSR is high enough to prevent the blades from stalling as they cross the wind. This concept patented by a Frenchman, Darrieus. Although modern Darrieus wind turbines usually cannot self-start under steady wind conditions, they do rotate slowly due to the drag difference between the rounded leading edges and the sharp trailing edges of the air-foils. If this is taking place when the wind speed drops below that of the rotor, the resulting increase in the TSR may be enough to unstall the blades. On one or two occasions when this possibility was not foreseen, the machines reached runaway speed with no load and accidentally destroyed themselves. However, there are ways to self-start a Darrieus wind turbine when desired, and methods of preventing over speed as well. There are also some types of high TSR, horizontal-axis turbines whose aerodynamics inhibit self- starting, these require either pitch changing or electrical motive power to run them up to a speed where the blades will unstall. The Darrieus turbine is usually shaped like an egg beater in profile, with blades curved in a form that minimizes the bending stresses caused by centrifugal forces—the so-called 'Troposkien' profile (Fig. 6.8.9).

Advantages. Advantages of such WEC system are :

(1) The major advantage of this design is that the rotor blades can accept the wind from any compass.

(2) Another added advantage is that the machine can be mounted on the ground eliminating tower structures and lifting of huge weight of machine assembly, *i.e.* it can be operated close to the ground level.

(3) Since this machine has vertical axis symmetry, it eliminates yaw control requirement for its rotor to capture wind energy. A dual purpose and relatively simple shaft axis support is anticipated as well as ground level power output delivery due to presence of vertical shaft. This may in turn, allow easier access and serviceability.

(4) Airfoil rotor fabrication costs are expected to be reduced over conventional rotor blade costs.

(5) The absence of pitch control requirements for synchronous operation may yield additional cost savings.

(6) The tip speed ratio and power coefficient are considerably better than those of the S-rotor but are still below the values for a modern horizontal-axis, two-bladed propeller rotor.

Disadvantages. (1) Although a Darrieus machine has many directional symmetry for wind energy capture, it requires external mechanical aid for start up. Tests indicate that, with small machines, the problem can be solved by attaching S-rotors at the top and bottom of the vertical (rotational) axis. This approach does not appear to be feasible with larger machines, but if the wind power system connected to a utility grid, the generator can serve as a motor to start the turbine. The (alternating-current) load can also provide a means for controlling the speed of the rotor regardless of the wind speed, so that variable-pitch blades are not required. At very high speeds, stalling occurs and the rotation stops automatically.

(2) Rotor power output efficiency of a Darrieus wind energy conversion system is also somewhat lower than that of a conventional horizontal rotor.

(3) Because a Darrieus rotor is generally situated near ground proximity, it may also experience lower velocity wind compared to a tower mounted conventional wind energy conversion system of comparable projected rotor disc area. This may yield less energy output.

(4) Because a Darrieus rotor encounters greatly varied local flow conditions per revolution, greater vibratory stresses are encountered which will affect rotor system life. High tension cable it down of tower-shaft may require large extensive bearing for support.

(5) Finally since a Darrieus rotor cannot be yawed out of the wind or its blades feathered, special high torque braking system must be incorporated.

Other types of vertical-axis rotors include Magnus effect rotors, which consists of spinning cylinders. This concept was first demonstrated by experimentally by Magnus in 1912. When cylinders spun in a wind stream, translational forces are produced perpendicular to the wind stream by the Magnus effect (Fig. 6.8.11). Such a device can be used as a sail to propel ships or land vehicles (Fig. 6.8.12).

When a stationary horizontal cylinder is rotated about its axis in a cross wind, it will experience a *lift*-force. The effect is equally applicable to a vertical cylinder being rotated about its axis in a cross wind. It will experience a force perpendicular to its axis, which will cause it to move in a direction essentially perpendicular to that of the wind. The concept consists of several tall vertical cylinders that are rotated about their axes in the presence of wind. The resultant of the lift and drag forces, more in the direction of lift because of its larger value propels the cylinders horizontally along a track.

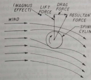


Fig. 6.8.11. The Magnus effect.

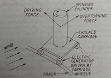


Fig. 6.8.12. The Magnus concept for generating electricity.

6.9. Analysis of Aerodynamic Forces acting on the Blade

Aerodynamic forces acting on a blade element tending to make it rotate are important parameters for a system engineer. This illustrates the basic principle of aeroturbine rotation.

First, we recognize that the whole general problem of forces on a wind generator blade are quite involved and beyond our scope here.

There are several basic types of blades an aeroturbine may have, e.g. sails, planes and aerodynamic surfaces based on the air craft wing cross-section for which there are many kinds. The early history of wind-mills is based on the first two ; modern higher efficiency wind-electric generators are based on use of blades with aerodynamic surfaces.

Consider the aerodynamic blade shown in Fig. 6.9.1. The blade can be thought of as a typical cross-sectional element of a two-bladed aeroturbine. The element shown is at some radius r from the axis of rotation. It is moving to the left. Because the blade is moving in the plane of rotation it sees a tangential wind velocity, V_T, in the plane of

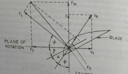


Fig. 6.9.1. Vector diagram of forces on a elemental blade section of an aeroturbine. (The blade is rotating to the left).

V = Impinging wind velocity.
V_T = Wind velocity in plane of rotation due to blade turning.
V_R = Resultant wind velocity seen by Aeroturbine blade.
F_L = Lift force (Normal to V_R).
F_D = Drag force (Parallel to V_R).
F_R = Resultant force on blade.
F_T = Torque producing component of F_R making aeroturbine rotate.
F_{th} = Thrust force component of F_R.
α = Angle of attack of blade.
β = Blade pitch angle.

rotation. This velocity component added vectorially to the impinging wind velocity gives the resulting wind velocity, V_R, seen by the rotating blade element. At right angles to V_R, is the lift force F_L caused by the aerodynamic shape of the blade. The drag force, F_D is parallel to V_R. The vector sum of F_L and F_D is F_R which has a torque producing component, F_T and a thrust producing component. The former is what drives the aero-turbine rotationally and the latter tends to flex the blade and also overturn the aerogenerator. The vector diagram is centred on the centre of lift of the aerodynamic blade. As is well-known from aircraft wing theory, one of the critical parameters is α, the angle of attack of the aerodynamic element. It determines lift and drag forces and hence speed and torque output of the aeroturbine. These quantities can be varied by changing the blade pitch angle β, and this is the basic torque control method used on large variable pitch wind-electric generators. The torque would determine the AC output power if a synchronous generator was used.

Since V_T increases linearly as we go out radically, r, on an inclined aeroturbine blade, it is necessary to adjust β with r so as to always have a positive angle of attack and to maintain reasonable stress levels within the blade. This mean that at larger r, β is made small while at small r, β is large. Thus the blade 'bites' the air more in close than near the tips. These considerations result in an aeroturbine blade with an apparent twist in it. The need for twisting windmills sails was recognised hundreds of years ago and widely used on Dutch windmills.

Having now achieved an elementary understanding of the basics of what turns the aeroturbine, we see that the airfoil orientation for an aeroturbine driven by the wind is exactly *opposite* to the orientation of a classical airplane propeller which is mechanically driven and whose function is to give a lift force in the axial direction. Thus, though aircraft wing theory is applicable to the operation of an aeroturbine, direct use of a classical aircraft propeller on an aeroturbine would not produce the most efficient aeroturbine because the aerodynamic surface is oriented backwards to what it should be.

6.10. Performance of Wind-machines

WECS efficiency is of interest to both aerogenerator designers and system engineers. As WECS is a capital intensive technology, it is desirable for the overall wind electric plant to have the highest efficiency possible, thus optimally utilizing capital resources and minimizing the busbar electric energy cost.

The overall conversion efficiency, η_0 of an aerogenerator of the general type is

$$\eta_0 = \frac{\text{useful output power}}{\text{wind power input}} = \eta_A \cdot \eta_G \cdot \eta_C \cdot \eta_{G_{en}} \qquad \text{...(6.10.1)}$$

where

η_A = Efficiency of the aeroturbine

η_G = Efficiency of the gearing

η_C = Efficiency of the mechanical coupling

$\eta_{G_{en}}$ = Efficiency of the generator

We immediately recognise equation (6.10.1) as an application of cascaded energy conversion, from which overall efficiency will be strongly determined by the lowest efficiency converter in the cascade. For the aerogenerator this is the aeroturbine ; the efficiency of the remaining three elements can be made quite high but less than 100 per cent. It is now evident why so much emphasis is placed on the efficiency of the aeroturbine in wind literature.

Consider an arbitrary aeroturbine (Note that aeroturbine ≠ aerogenerator) of cross-sectional area A driven by the wind. Its efficiency would be :

$$\eta_A = \frac{\text{useful shaft power output}}{\text{wind power input}}$$

$$= C_P$$

$$= \text{coefficienct of performance.}$$

Thus the coefficient of performance of an aeroturbine is the fraction of power in the wind through the swept area which is converted into useful mechanical shaft power. The coefficient of performance is widely utilised throughout the recent wind literature. We have seen that C_p for horizontal axis wind machine has theoretical maximum value = 0.593 (Art. 6.2).

This theoretical efficiency limitation on a wind energy conversion system is loosely analogical similar to the thermodynamic Carnot efficiency limitation on a conventional thermal power plant.

We have also seen that the convertible power of energy is proportional to the cube of the wind speed. Thus if the wind speed decreases by 20%, the power output is reduced by almost 50%. The wind speed may very considerable from day to day and from season to season. The efficiency of a wind generator depends first and foremost on the design of an wind rotor and rotation speed, expressed as the ratio of blade tip speed to wind speed V_T/V if n is the rotation frequency, i.e. rotations per second, if a rotor of diameter D meters, the tip speed is πnD m/sec.

The dependence of the power coefficient on the tip speed ratio for some common rotor types is indicated in Fig. 6.10.1. It is seen that the two-bladed propeller type of rotor can attain a much higher power coefficient (*i.e.* it is more efficient) than the American multi-blade windmill and the classical Dutch four-bladed windmill. In practice two-bladed propeller (horizontal axis) rotors are found to attain a maximum power coefficient of 0.40 to 0.45 at a tip speed ratio in the range a roughly 6 to 10.

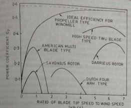


Fig. 6.10.1. Typical performance of wind machines.

Golding has derived the expression for aeroturbine efficiency as (refer Fig. 6.9.1).

$$\eta_A = \frac{1 - k\dfrac{V_T}{V}}{1 + k\dfrac{V}{V_T}} = C_p \qquad ...(6.10.2)$$

where $k = \dfrac{F_D}{F_L} = \dfrac{\text{drag}}{\text{lift}}$ ratio

V_T = wind velocity of blade element in plane of rotation due to blade turning.

V = impinging wind velocity.

Clearly if there were no drag, *i.e.* $k = 0$, then the efficiency would be unity. In actuality k can be made very small, depending on the airfoil chosen and the angle of attack. Also equation (6.10.2) tells us the efficiency would be low if $\dfrac{V_T}{V}$ were very large or again if it were small. One suspicians that there exists an optimum ratio of $\dfrac{V_T}{V}$ (tip speed ratio).

If one assembles models of various types of aeroturbine blades and puts them in a wind tunnel and runs carefully controlled experiments of their efficiencies as functions of their tip speed ratios, then one obtains a family of curves similar to that shown in Fig. 6.10.1. We first note that there are rather large differences between the various kinds of aeroturbine blades. The Savonious rotor and the American multi-blade (farm windmill) are obviously intended for low speed operation whereas the modern two blade type and Darrieus rotor type are intended for high speed operation more compatible with generating electric energy. The classical Dutch blade is intermediate. We also observe that all the blade performances fall below the ideal efficiency curve which has a maximum of 59.3 per cent. It is interesting to observe that the modern two blade aeroturbine has a peak power coefficient which is a large fraction of the theoretical maximum, *i.e.* they are well designed.

The power delivered and speed at which it is delivered has a bearing on the windmill a application. When these two are matched at the delivery end, the windmill as an energy conversion system can have the maximum utility. Therefore these two performance variables have come into picture, *i.e.* one is C_p *vs* V_{tip}/V characteristics and other is torque *vs* V_{tip}/V characteristics. Figs. 6.10.1 and 6.10.2 shows trends in the variation of performance for some of the windmills as discussed above.

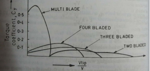


Fig. 6.10.2. Performance of wind machines.

It may be concluded that a two blade propeller has potentially the best performance of the system considered. This explains why virtually all large-scale systems built in the past employed two or three bladed machines. As the number of blades (and consequently the blade surface) increases, the C_p max decreases and occurs at lower V_{tip}/V ratio. This implies that for high performance, the blades rotate at high r.p.m. (and generally have air-foils for the surface). Consequently the torque is low. These types are preferred for electric power generation. The multi blade types with high starting torque on the other hand are more suitable for pumping water. In practice, it is impossible to build wind driven generators capable of operating at the same efficiency at all wind speeds. First, there is a minimum wind speed below which no power can be generated because of friction losses. Also, above a selected maximum speed, *i.e.* the rated wind speed, the extracted power is held constant by stabilizing the rotor speed, for instance when the wind speed exceeds the maximum selected by the designer, the rotor blades are progressively turned on their axes to reduce the effective area facing the wind. As a result, the fraction of power extracted decreases as the wind speed increases, beyond the rated speed (refer Fig. 6.8.7). Finally at about 30 m/sec, the rotor is furled to avoid damage.

Only at intermediate wind speeds does the system efficiency reach its optimum and the power extracted then follows a V^3 law. The range of optimum operation depends on the engine which was selected so as to give optimum output over the year. In our example, this could be in the range of 10-14 m/sec, 14 m/s being the rated velocity maintained also at higher wind speeds ; only there depending on the degree of sophistication, could between 70 and 85% of the convertible wind energy by transforming into kinetic energy by the rotor. Up to 20% of this energy would be lost in the gear type transmission, which connects the rotor shaft to the electric generator. The energy which is available for conversion over all wind speed is a function of the wind speed duration spectrum. There is a similarity with solar cells, the efficiency of which is strongly affected by the wavelength spectrum of the sun's radiation. For exploitable spectra, this spectral efficiency is comprised between 8% and 20%. Hence altogether, the total system efficiency of a wind generator amount to 3—7%.

Table 6.10.1

	Percentage of total available	*Percentage of maximum available*
Total wind energy	100%	
Maximum theoretical convertible (59.3% ≃ 60%)	60%	100%
System efficiency (0.60) at rated wind speed. (Rotor effi. 0.75 transmission gear efficiency 0.08)	36%	60%
Energy integrated over the total speed spectrum (efficiency 0.08—0.2)	3—7%	5—12%

As a general rule, ≃ the conversion efficiency at a given location depends on what might be termed as wind quality ; a steady wind is the ideal case, never encountered in practice, whereas a wind that varies greatly in speed is difficult to convert.

6.11. Generating Systems

6.11.1. Introduction

The basic components of a wind-electric conversion system are shown in Fig. (6.11.1). Aeroturbines convert wind energy into rotary mechanical energy. A mechanical interface, consisting of a step-up gear

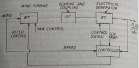


Fig. 6.11.1. Components of wind electric system.

and a suitable coupling transmits the energy to an electrical generator. The output of this generator is connected to the load or system grid. The controller senses the wind direction, wind speed, power output of the generator and other necessary performance quantities of the system and initiates appropriate control signals to take suitable corrective actions. The system should be protected from excessive temperature rise of the generator, electrical faults and extra wind conditions.

The choice of an electrical generator and control method to be employed (if any) can be decided by consideration of the following three factors :

(*i*) the basis of operation *i.e.* either constant tip speed or constant tip speed ratio

(*ii*) the wind-power rating of the turbine and

(*iii*) the type of load demand *e.g.* battery connection.

Wind power ratings can be divided into three convenient grouping, *small* to 1 kW, *medium* to 50 kW and *large* 200 kW to megawatt frame size.

Electrical generators types applicable to each of these ratings are :

Small—permanent, magnet, d.c. generators.

Medium—permanent magnet, d.c. generator, induction generator, synchronous generator.

Large—induction generator, synchronous generator.

The electrical control strategy employed for any particular scheme can be designed to effect control of the generator, the power transmission link or the load.

6.11.2. Schemes for electric generation

Several schemes for electric generation have been developed. These schemes can be broadly classified under three categories :

(*i*) Constant—speed constant frequency systems (CSCF)

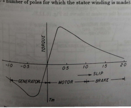
(*ii*) Variable speed constant frequency systems (VSCF)

and (*iii*) Variable speed variable frequency systems (VSVF).

(1) **Constant speed constant frequency system (CSCF).** Constant speed drive has been used for large generators connected directly to the grid where constant frequency operation is essential.

(*a*) **Synchronous Generator.** For such machines the requirement of constant speed is very rigid and only minor fluctuations about 1% for short durations (fraction of a second) could be allowed. Synchronisation of wind driven generator with power grid also will pose problems with gusty winds.

(*b*) **Induction Generator.** If the stator of an induction machine is connected to the power grid and if the rotor is driven above synchronous speed N_s ($N_s = 120\, f/p$), the machine becomes a generator and delivers constant line frequency power to the grid. (f = line frequency and p = number of poles for which the stator winding is made). The



per unit slip is 0 and 0.05. The output power of wind driven induction generator is uniquely determined by the operating speed. The pull out torque (T_M) condition should not be exceeded. When this happens the speed continues to increase and the system may 'run away'. The torque-speed characteristics of an induction machine in the motor and generating modes are shown in Fig. (6.11.2). Induction generators are basically simpler than synchronous generators. They are easier to operate, control and maintain, have no synchronisation problems and rae economical. However, they draw their excitation from the grid and hence impose reactive volt ampere burden. But static capacitors can be used to overcome this problem.

(*ii*) **Variable speed constant frequency scheme.** (VSCF Scheme). Variable-speed drive is typical for most small wind generators used in autonomous applications, generally producing variable frequency and variable voltage output. The variable speed operation of wind electric system yield higher outputs for both low and high wind speeds. This results in higher annual energy yields per rated installed kW capacity. Both horizontal axis and vertical axis turbines will exhibit this gain under variable speed operation. The popular schemes to obtain constant frequency output are as follows :

(*a*) **AC—DC—AC link.** With the advent of high powered thyristors and high voltage d.c. transmission systems, a.c. output of the 3-phase alternator is rectified using a bridge rectifier and then converted back to a.c. using line commutated inverters. They utilise an a.c. source (power lines) which periodically reverses polarity and causes the commutation to occur naturally. Since frequency is automatically fixed by the power line, they are also known as synchronous inverters. The block diagram of the system is shown in Fig. (6.11.3).

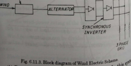


Fig. 6.11.3. Block diagram of Wind Electric Scheme.

(*b*) **Double Output Induction Generator.** In this system a slip-ring induction motor is used as shown in Fig. (6.11.4). Rotor power

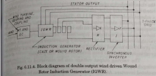


Fig. 6.11.4. Block diagram of double output wind driven Wound Rotor Induction Generator (IGWR).

output at slip frequency is converted to line frequency power by rectification and inversion output power is obtained both from stator and rotor and hence this device is called *double output induction generator*. Rotor output power has the electrical equivalence of an additional impedance in the rotor circuit. Therefore, increasing rotor outputs lead to increasing slips and higher speeds. Such an operation increases the operating speed range from N_s to $2\ N_s$, *i.e.* slip varying from 0 to 1.0.

(c) **A.C. commutation generator.** This system is also known as *Scherbius* system employs two polyphase windings in the stator and a commutator winding on the rotor. Basic problems in employing this device for wind energy conversion are the cost and the additional maintenance and the care required by the commutator and the brush gear.

(iii) **Variable Speed Variable Frequency (VSVF) Schemes.** Since resistive heating loads are essentially frequency insensitive, the

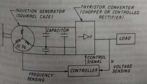


Fig. 6.11.5. Schematic diagram of capacitor self-excited (squirrel cage) induction generator.

a.c. generator can be effected at a variable frequency corresponding to the changing derive speed. For this purpose capacitor excited (self-excited) squirrel caze induction machines can be conveniently used. Such a scheme is shown in Fig. (6.11.5). These systems are gaining importance for stand alone wind power applications. The magnitude and frequency of the emf depends on the value of the load impedance, prime-mover speed and excitation capacitance. Methods of analysing these variable—voltage variable frequency generators have been developed to predict the no-load and load performance characteristics. Computer programmes have also been formulated for this purpose.

The varying output voltage can be converted to constant d.c. using choppers or controlled rectifiers on constant a.c. using force—commutated inverters. AC converters and transducers can be introduced to monitor and control the desired performance quantities.

6.11.3. Generator Control

Control schemes which act on the generator alone are largely decided upon by the type of the generator employed.

Permanent magnet—there is no readily available means of controlling this type of machine directly. In order to vary the torque established by a permanent magnet alternator, it is necessary to change the armature current. Thus in normal operation the output voltage and frequency must be allowed to vary with wind speed.

D.C. generator—usually of the shunt or parallel field winding type in which a small variation of the field current achieved by means of a variable resistor connected in the field circuit will vary the terminal voltage and hence the power output. It should be noted that with the judicious choice of generator and load resistance a fairly good natural match can be obtained between the power and speed characteristics of the generator and the wind turbine thus obviating the need for any complicated control schemes and allowing variable speed operation of the turbine.

Induction generator. When used to supply power to an isolated load the machine may be made to self excite by means of a bank of capacitors connected to the terminals. Variation of this capacitance value varies with the terminal voltage and output frequency of this system.

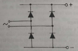
When a *wound rotor induction generator* is used for a grid connection application, power control is achieved by varying the slip energy of the rotor circuit. This may be achieved through a variety of methods such as : rotor resistance control, cascading or variable speed slip-power recovery schemes.

Caze rotor induction generators can be made to operate over a wider speed range by pole changing or pole amplitude modulating the main winding to achieve one, two or three separate speed ratings.

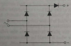
Synchronous machine power control is readily achieved through variation of the d.c. field excitation current. The frequency of the output voltage will be variable with wind speed for an isolated machine and fixed for a grid connected machine.

Transmission Control

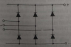
The most effective method of varying the power flow in the transmission link between the generator and its connected load is by means of a silicon controlled rectifier device. This unit employs power electronic devices (thyristors) whose conduction periods (*i.e.* on off time) can be controlled by applying delayed trigger pulses to the gate of each individual thyristor. Some common arrangements are shown in Fig. 6.11.6 (*a*, *b*, *c*).



(*a*) Single phase controlled bridge.



(*b*) Single phase uncontrolled bridge with d.c. chopper.



(*c*) 3 phase fully controlled bridge

Fig. 6.11.6. Transmission control.

Such schemes enables smooth control of the power in the system to be carried out but suffer from the disadvantages of being expensive since they must be rated to carry the normal full load power flow plus short time overload capability.

6.11.4. Load Control

Scheme employing switched load resistors enable stepwise load approximation to be made to the power (rotational speed) characteristic of the wind turbine. Operation within the maximum current loading of the generator can be set and the discrete resistance values selected so that for a particular wind speed, operation of the turbine is held fairly close to the C_p maximum value. This method of controls ideally suited to small stand alone wind turbines and has the merits of being cheap, simple and effective where the load demand is for the resistance heating.

6.12. Energy Storage

Operation of a wind turbine is not practical at very high or very low wind speeds. Consequently, if other sources, such as electric utility power, are not available, some form of energy storage is required. When the power generated exceeds the demand, the excess energy would be stored for use at other times. For WEC machines of low and intermediate electric power, battery storage is convenient.

Storage adds flexibility to use of WECS in that it permits peak shaving and capacity saving as well as fuel saving. However, it can be expensive, and each utility will have to evaluate whether or not to install it. Storage makes it possible to deliver electric load power demand during times when wind is below normal or non-existent. Storage also makes it possible to deliver short peaks of power for exceeding the rated power capacity of the plant. It improves the reliability of the wind electric system over what it would be without storage. The energy may be used in a variety of forms, *e.g.* as heat, mechanical, electrical, chemical and magnetic.

For wind turbines with power outputs upto about 20 kW, direct current generators can be used to charge batteries directly. For higher powers, alternating current generators are required and the current must be rectified for battery charging. The chemical reaction taking place in the cell or battery when it is charged is reversed when the cell is discharged. Thus in the charged cell, electrical energy is stored as *chemical energy*, which can be recovered as electrical energy when the cell is discharged. Direct current from the batteries can be utilized to heat water for space heating and for domestic hot water, and to operate lights and small tools and appliances. Conversion into alternating current by means of an inverter, may be necessary for large tools and appliances and for televi-

Other kinds of storage may be more desirable in agricultural operations. For example, if the wind energy is to be used for heating green houses or drying crops, it can be stored as hot water (*Heat storage*). Either direct or alternating current may then be used in resistance heaters without the need for batteries. Alternatively, the mechanical motion produced by the wind turbine can be converted directly into heat by frictional effects, such as by churning water.

In *water power storage* or mechanical storage, high-power aerogenerators are integrated with an electric utility, a favourable situation would be operation of several wind turbines in connection with a *hydroelectric power plant*. If the total power, wind and hydroelectric being generated should exceed the demand, the hydroelectric plant can be partly shutdown ; alternatively, the excess power could be used to pump water from an auxiliary reservoir at the bottom of the dam back into the main reservoir. In this way, the overall capacity of the hydroelectric system would be increased.

Another alternative ; for possibly storing energy, is to store the energy in a volume of *compressed air*. A wind turbine for example, could be created which would directly pump air into a suitable pressurized storage tank. Then later when the wind is not blowing the energy stored in the air could be utilized to drive an air turbine whose shaft would then drive a generator, thus supplying the needed electric power when the wind is not blowing. Wind energy, with a d.c. output the power can be fed directly into an electrolyzer tank which produces hydrogen and oxygen from ordinary water. The hydrogen and oxygen gases produced can be stored either in gas or liquid forms, and when needed, be quickly and easily converted again directly into electric energy via the well known fuel cell. Hydrogen can also be used *as a fuel* to drive automobiles and other useful engines.

6.13. Applications of Wind Energy

Energy extracted from the wind is initially energy in the form of rotary, translational, or oscillatory mechanical motion. This mechanical motion can be used to pump fluids or can be converted to electricity, heat, or fuel. Some of the most effective application are those that use energy derived directly from the wind, without further energy processing, conversion, or storage. However, if required, wind—derived energy can be converted to other forms of energy or can be stored through the use of compressed fluids, pumped hydrosystems, water-saver systems, batteries, hydrogen, flywheel, hot water, etc. Some energy is normally lost in each of these conversion or storage steps.

In any case, wind energy is one of the most flexible and tractable of all energy sources, since the mechanical energy derived directly from

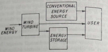


Fig. 6.13.1. Basic wind energy conversion system with energy storage.

the wind can be readily and efficiently converted to other forms of energy. The efficiency of converting wind—derived mechanical energy to heat or electrical energy is usually much higher for instance, then the efficiency of converting solar or fuel-derived heat energy to mechanical or electrical energy, since the efficiencies that can be attained when converting heat to mechanical or electrical energy are limited by the relatively low carnot cycle efficiencies, which, even under optimum conditions, usually do not exceed 30 to 35%.

Wind-turbine generators have been built in a wide range of power outputs from a kilowatt or so to a few thousand kilowatts. Machines of low power can generate sufficient electricity for space heating and cooling of homes and for operating domestic appliances. Low power WEC generators have been used for many years for the corosion protection of buried metal pipelines.

Applications of somewhat more powerful turbines, upto about *50 kW*, are for operating irrigation pumps, navigational signals (*e.g.*, light houses and buoys), and remote communication, relay, and weather stations, and for offshore oil drilling platforms.

Aerogenerators in the *intermediate power range*, roughly 100 to 250 kW, can supply electricity to isolated populations (*e.g.* on islands), to farm co-operatives, and to small industries. Finally, the *largest WEC generators*, with rated powers of a few thousand kilowatts are usually planned for interconnection with an electric utility system. Present indications are that the optimum economic diameter of a wind turbine with a two-bladed-propeller type rotor is about 110 M ; the electric power output would range from 2000 to 5000 kW or 2 to 5 megawatts (MW), where 1 MW is 1000 kW or 1 million watts.

Pumping Applications. A typical wind-powered pumping application is one that might use a horizontal—axis wind machine. An example is the ancient jib—sail design that is mostly wind used to pump irrigation water. Large number of water-pumping wind mills have been used on Indian farms. Other applications that are being developed include the pumping of water for aqueducts or for pumped-hydro storage of energy. In aqueduct systems, large-scale wind driven units can provide power for the pumping of water from the main reservoir to auxiliary reservoirs in other parts of the aqueduct system. This can be done either by the direct mechanical pumping of the water or through the generation of electricity by the wind units, and the subsequent use of this energy to operate electrical water pumps incorporated in the aqueduct system.

There are two main families of wind turbines : wind pumps and wind generators. A pump generally involves a high-solidity rotor with a low TSR connected mechanically to a piston pump, which a generator is usually driven through a gear-box by a low-solidity rotor.

The two main end-uses of wind pumps (irrigation and water supply) have very different technical operational and economic requirements. Irrigation designs are generally unsuitable for water supply duties, which may require heads 10-100 m high. Despite these limitations, however, water supply pumps are sometimes used for irrigation. Since many water supply wind pumps must run unattended for most of the time, their design should incorporate protection devices to prevent over speeding in storms and sturdy parts that required little attention. Consequently they are usually built of components manufactured from industrial steel and drive piston pumps *via.* reciprocating pump rods. This type of construction is expensive in relation to the output but the reliability and low maintenance are worth the price to someone like an Australian farmer, who may have a dozen wind pumps spread over a large area of semi-desert to sustain several thousand head of cattle. In contrast, irrigation being seasonal, the mill may only be useful for a few months of the year. It also involves pumping much larger volumes of water through a low head. Because the intrinsic value of the water is low, it is essential to keep costs down. In addition, someone is usually present during irrigation to tend the machine. Therefore, windmills used for irrigation are generally indigeneous designs that are built by the farmer as a method of low-cost mechanization.

If water-supply wind pumps are used on farms for irrigation, it may be difficult to provide piston pumps large enough to absorb the power from the windmill at low heads. Also, most wind pumps of this kind must be located over the pump in substantial, reinforced-concrete foundations. This usually makes them better suited for pumping from wells or bore holes than from open water, for which a surface-water suction pump can be used on the other hand, most indigeneous irrigation wind pumps, such as the Chinese models, use rotary pumps of one kind or another that are more suitable for low heads. These do not achieve mechanical forces as high as those of industrial wind pumps, which often pull their rods with a force equivalent to 1 *t* or more enough to uproot any carelessly installed pump. Furthermore, most indigeneous designs are much cheaper and easier to install because they are lower in height and do not require concrete foundations.

In pumped-hydro applications, the wind units can be used to supply power to pump from an auxiliary reservoir below hydro-electric dam back into the main reservoir above the dam. This enables the water stored in the main reservoir to be replenished when the wind is blowing, thereby adding to the capacity of the hydro-electric system to generate base-load electric power.

Wind power can also be used compress air for use in various applications, including the operation of gas turbines for generating electricity during the peak-demand periods of a public utility system. For this type of application, conventional gas turbines can be modified to separate the compressor, generator, and power stages by clutches. In one mode of operation, the motor generator operating as a motor and powered by a wind machine drives the air compressor. The compressed air is fed into a storage tank or into a large cavern, aquifer, or depleted natural gas well. Under this mode, the power turbine is inoperative, and no fuel is consumed.

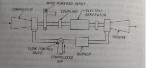


Fig. 6.13.2. Wind-assisted gas-turbine generating unit.

In a second mode of operation, when the demand for power exceeds the supply of the base-load utility system, the compressor is disengaged, and the power turbine is connected to the generator. The burner that drives the power turbine is fed fuel and compressed air from storage to generate power for the utility system.

The temperature of air is raised when it is compressed without loss of heat (*i.e.* adiabatic compression). In this case, less heat will need to be added to the air, when it is eventually used to drive a turbine at a given efficiency, than if its heat has been allowed to escape from the storage container and the temperature of the air had been allowed to drop to the ambient temperature (*i.e.* isothermal storage). Adiabatic storage is obviously better, from the standpoint of energy conservation, than isothermal storage.

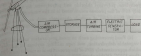


Fig. 6.13.3. System with compressed-air storage.

Wind-powered pumps can be used to desalinate water, using reverse osmosis units.

Wind-powered pumps can also be used to save fuel and electricity by compressing the working fluids used in heat pumps for space-heating applications, as discussed below.

Direct Heat Applications. Mechanical motion derived from wind power can be used to drive heat pumps or to produce heat from the friction of solid materials, or by the churning of water or other fluids, or in other cases, by the use of centrifugal or other types of pumps in combination with restrictive orifices that produce heat from friction and turbulence when the working fluid flows through them. This heat may then be stored in materials having a high heat capacity, such as water, stones, eutectic salts, etc., or the heat may be used directly for such applications as heating and cooling of water, and air-space for residential, commercial, industrial and agricultural buildings or for various types of industrial or agricultural process-heat applications. Heating system designed for heating of the building is done by using the electricity generated by the wind machine to provide resistive heating of water that is circulated through the buildings.

A home heating system that uses a wind-powered pump and a restrictive orifice to derive direct heat for a building, without first generating electricity also has been developed.

Examples of possible wind-powered agricultural process heat applications include green house applications, crop drying, milk processing, food processing, refrigeration, frost protection, ventilation, and waste processing.

Examples of typical industrial processes that might be able to use low temperature heat (*i.e.* upto approximately 175°C) produced by wind energy include the following.

(1) Production of inorganic chemicals, including borax, bromine, chlorine, caustic soda, potassium chloride, and sodium metal.

(2) Production of plastic materials and synthetics such as polyethylene, polyvinyl chloride and polystyrene, for which approximately 45% of the process steam used is in the range of 100—175°C.

(3) Production of organic chemicals such as various types of alcohols and solvents, synthetic perfumes, flooring materials, rubber processing chemicals, etc.

(4) Food processing such as meat preparation and packing fruit and vegetable dehydration, wet corn milling, soybean oil milling etc. for which approximately 80% of the process heat is used at temperature less than 175°C. Of this about 25% is used for process heating, 15% for cooking, and dehydration.

(5) Textile processing, primarily steam or hot air, for drying, curing, and finishing of both yarns and textiles.

Electric Generation Applications. Wind power can be used in centralized utility applications to drive synchronous a.c. electrical generators. In such applications, the energy is fed directly into power networks through voltage step-up transformers.

WECS units can be integrated with existing hydro electrical networks and used in a "water-saver" mode of operation. When the wind is blowing, electrical generation at the hydroelectric plants in the network can be reduced by an amount equal to that being produced by the WECS units. Thus, part of the network load that is ordinarily produced by the hydroelectric generators is supplied by the wind turbines. Under these conditions some of the water that would have

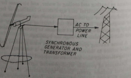


Fig. 6.13.4. System with direct feed to main powerline.

been used by the hydroelectric plant to supply the load is saved in the reservoir and made available for later use when the wind is not blowing. Additional hydroelectric generating facilities are provided at the hydroplant to allow the water that was saved in the reservoir to be used at a greater rate when the wind was not blowing, thereby providing a firm generating capacity equal to the *firm* generating capacity of the hydroplant plus the *average* generating capacity of the wind-powered plant.

In dispersed applications, wind power can be used to generate dc electrical power that, in turn, can be used for dc applications or space heaters, such as resistance heaters, or can be stored in batteries and then inverted for used by a.c. loads.

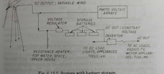


Fig. 6.13.5. System with battery storage.

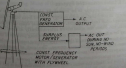


Fig. 6.13.6. Alternative for converting and storing wind energy : system with flywheeling storage.

There are a number of commercial units available for these types of dispersed operations and all can be used independently or tied into a utility network using an induction generator or a synchronous inverter.

In centralised or dispersed applications requiring constantly available sources of power, the energy can also be stored in the form of mechanical motion of a flywheel or as hydrogen and oxygen gases

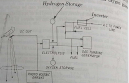


Fig. 6.13.7. Alternative for converting and storing wind energy system with hydrogen storage.

derived from the electrolytic dissociation of water. The hydrogen and oxygen can be stored in liquid form in tanks, or in gaseous form in tanks, caverns, aquifers, depleted natural gas wells, etc. The stored hydrogen can be used either as a fuel or direct space heating or industrial process heat, or it can be reconverted to electricity through the use of fuel cells, gas turbine generators that burn hydrogen, or by other means.

6.14. Interconnected System

There appear to be important advantages to use wind-derived energy in combination with energy derived from other sources, such as conventional fuels, sunlight, ocean thermal differences, bioconversion fuels, etc. Since the wind blows intermittently in most locations there may be a need to store wind energy over long periods of time, perhaps upto ten days or more, if the energy is being used for isolated applications requiring continuous power. The cost of providing sufficient storage capacity for such applications can be reduced if the wind-derived power is interconnected with other sources of power. For instance, since in most locations the wind often blows when the sun is not shining, and *vice versa*, a system using wind energy collectors and sun energy collectors (solar thermal collectors or solar photovoltaic arrays) in combination can be expected to require less energy storage capacity than systems that use these type of collectors separately.

A combination of solar and wind energy systems are being experimented in a number of isolated locations not connected to the grid. Such a system is shown in Fig. 6.14.1. Depending on the frequency

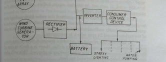


Fig. 6.14.1. Solar-wind system with storage battery supplying to various consumers.

of the wind generator, consumer circuits could be switched on and off through a consumer control device to ensure that the frequency does not fluctuate by more than few percent of its rating. Similarly solar generator may consist of many sections linked individually to the battery and a number of sections kept in operation depends on the charge on the battery and wind speed. Many remote power systems throughout the world rely on diesel generators for the production of electrical power. Such applications include village electrification, irrigation and water pumping. Many of these applications incur high electric generating costs due to the price of diesel fuel. Coupling renewable energy systems, such as wind and photovoltaic (PV) and batteries with a diesel set can lower the cost of generation of electricity by reducing the amount of fossil fuel required. Desi„ning such hybrid systems require two major considerations :

(i) determining an optimal mix of power generation sources to meet the required load while providing the lowest busbar cost of electricity,

(ii) arriving at a system operating strategy that maximises the use of renewable sources and allows the diesel set to run at full load when required.

6.15. Safety Systems

Safety systems of the wind turbines comprise the following features :

(i) *The computer.* The wind turbine is controlled by a computer which monitors the most important gauging instruments and compares the results. If errors are found the wind turbine is stopped.

(ii) *Emergency Stop.* If a situation arises which calls for the wind turbine to be stopped immediately, the emergency stop is used. The wind turbine will stop in few seconds by feathering the blades directly into the wind. It can not be started again before what caused the emergency stop has been rectified.

(iii) *Revolution Counters.* To prevent the rotor from racing, two revolution counters have been mounted on the shaft. These operate quiet independently and activate the emergency stop if the revolutions of the turbine exceed 24 rpm which is maximum.

In addition, the revolution counters transmit data to the computer where they are compared. If they differ, there is a fault in one of the revolution counters and the wind turbine is stopped. This will also occur if the blades are accelerated too fast.

(iv) *Wind Velocity.* This is measured and controlled by the computer in two ways. First gusts of wind are registered and if they are too strong the turbine is stopped. Then average wind speeds are measured over periods of 10 minutes, and the wind turbine is also stopped if they are too high.

(v) *The Parachutes.* Each blade tip has a parachute, which is activated if the rpm exceeds 28. An iron plumb bob, otherwise held in place by a magnet, is released from the blade trip, the centrifugal force exceeding the force of the magnet pulling out the parachute. This decrease the speed of the wind turbine considerable enough to stop it from racing. The parachute is an extra safety device should other fail. Till now they never been used.

(vi) *Lightning Rods.* The three blades and the mill or wind turbine cap are protected from lighting by these rods going from the tip of each blade to the ground.

6.16. Environmental Aspects

Wind turbines are not without environmental impact and their operation is not entirely risk-free. Following are the main effects due to a wind turbine.

(i) *Electromagnetic interference.* Interference with TV and other electromagnetic communication systems is a possibility with wind turbines as it is with other tall structures. TV interference is most likely in areas where there is a weak signal because of the distance from the transmitter, where existing reception is none too good due to the surrounding hills and where the wind turbine is exposed in good position to receive and scatter the signals. Interference can be overcome by dispensing with aerials and sending TV signals by cable in areas that would otherwise be affected.

(ii) *Noise*. The noise produced by wind farms falls into two categories. The first type is a mechanical noise from the gear box, generating equipment and linkages and the second type of aerodynamic in nature produced by the movement of the turbine blades. One component of the latter is the broad band noise which ranges upto several kilo hertz and the other is a low frequency noise of 15—20 Hz. Revolving blades generate noise which can be heard in the immediate vicinity of the installation, but noise does not travel too far.

(iii) *Visual Effects*. Megawatts power generating wind turbines are massive structures which would be quite visible over a wide area in some locations. A variety characteristics such as colour pattern, shape, rotational speed and reflectance of blade materials can be adjusted to modify the visual effects of wind turbines including the land scape in which they are installed.

Visual intrusion is probably the single most serious environmental problem associated with the on shore development of wind energy. Many of the best sites for wind turbines are in areas of outstanding natural beauty. Wind enthusiasts have argued that, like suspension bridges and some modern buildings, well-designed wind turbines can be aesthetically pleasing to the eye. They are more attractive than microwave transmission towers and television aerials.

(iv) *Bird life*. Tall structures represents a potential collision hazard to bird life. However, studies indicate that majority of migrating birds either fly at much higher altitudes or take avoiding action. It is likely to affect night-flying birds more and to be more of a problem with smaller, faster turning machines rather than very large rotors.

(v) *Risk*. The possibility of mishap is perhaps of greater concern to the public. The most serious failure from the safety point of view is the detachment of blade, or blade fragment which could be thrown a considerable distance and could damage people or property. A reliable control system to identify the fault situation rapidly and braking system to bring the rotor safely to rest could be the measures adopted to prevent such failures. Regular inspection and greater safeguards against overspeeding should minimise the hazard. Most wind machines will be in rural areas which makes it less likely that anyone would be injured or killed by flying debris if there were an accident.

Questions

6.1. What is the basic principle of wind energy conversion ?

6.2. Derive the expression for power developed due to wind.

6.3. Prove that in case of horizontal axis wind turbine maximum power can be obtained when :

$$\text{Exit velocity} = \frac{1}{3} \text{ wind velocity and}$$

$$P_{max} = \frac{8}{27} \rho A V^3. \qquad \text{(V.U. 1990)}$$

6.4. Wind at 1 standard atmospheric pressure and 15°C temperature has a velocity of 10 m/s. The turbine has diameter of 120 m and its operating speed in 40 r.p.m. at maximum efficiency. *Calculate* :

(*a*) the total power density in the wind stream,

(*b*) the maximum obtainable power density assuming $\eta = 40\%$,

(*c*) the total power produced (in kW) and

(*d*) the torque and axial thrust.

[**Ans.** 613 W/m^2, 363 W/m^2, 245 W/m^2, 2770 kW, 16, 347 N, 616, 255 N]

6.5. Describe the main considerations in selecting a site for wind generators.

6.6. Describe with a neat sketch the working of a wind energy system (WECS) with main components.

6.7. How are WEC systems classified ? Discuss in brief.

6.8. Discuss the advantages and disadvantages of wind energy conversion system ?

6.9. Describe horizontal axis type aerogenerators.

6.10. Discuss the advantages and disadvantages of horizontal and vertical axis windmill. What methods are used to overcome the fluctuating power generation of windmill ?

6.11. What are the advantages of vertical axis machines over horizontal type ? Describe a rotor for relatively low velocity wind.

6.12. Write short notes on :

(*i*) Applications of wind energy

(*ii*) Savonius rotor

(*iii*) Darrius rotor

(*iv*) Wind energy storage.

6.13. Describe the different schemes for wind electric generation or describe the generating systems. Also describe the generator control schemes.

6.14. Describe the main applications of wind energy, giving neat sketches.