5M ✓

.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-niform heating of the earth's surface by the sun. The air immediately bove a warm area expands, it is forced upwards by cool, denser air hich flows in from surrounding areas causing a wind. The nature of he terrain, the degree of cloud cover and the angle of the sun in the sky re all factors which influence this process. In general, during the day he air above the land mass tends to heat up more rapidly than the air ver 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 loss.

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

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

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*

amounts of power should have large rotors and be located i
high wind speeds. Where low or moderate powers are adeq
requirements can be relaxed.

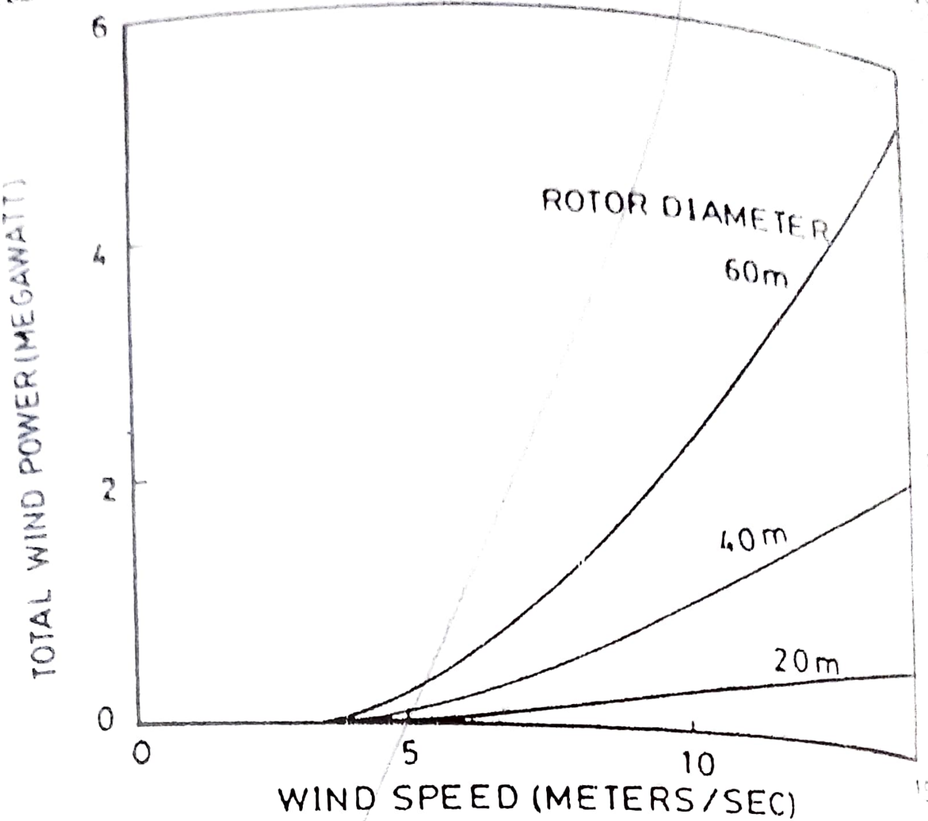


Fig. 6.2.1. Dependence of wind-rotor power on wind spe
and rotor diameter.

The physical conditions in a wind turbine are suc
fraction of the available wind power can be converted into
As the free wind stream encounters and passes throug
wind transfer some of its energy to the rotor and its speed
a minimum in the rotor wake. Subsequently, the wind st
energy from the surrounding air and at a sufficient dist
rotor the free wind speed is restored (Fig. 6.2.2 upper cur

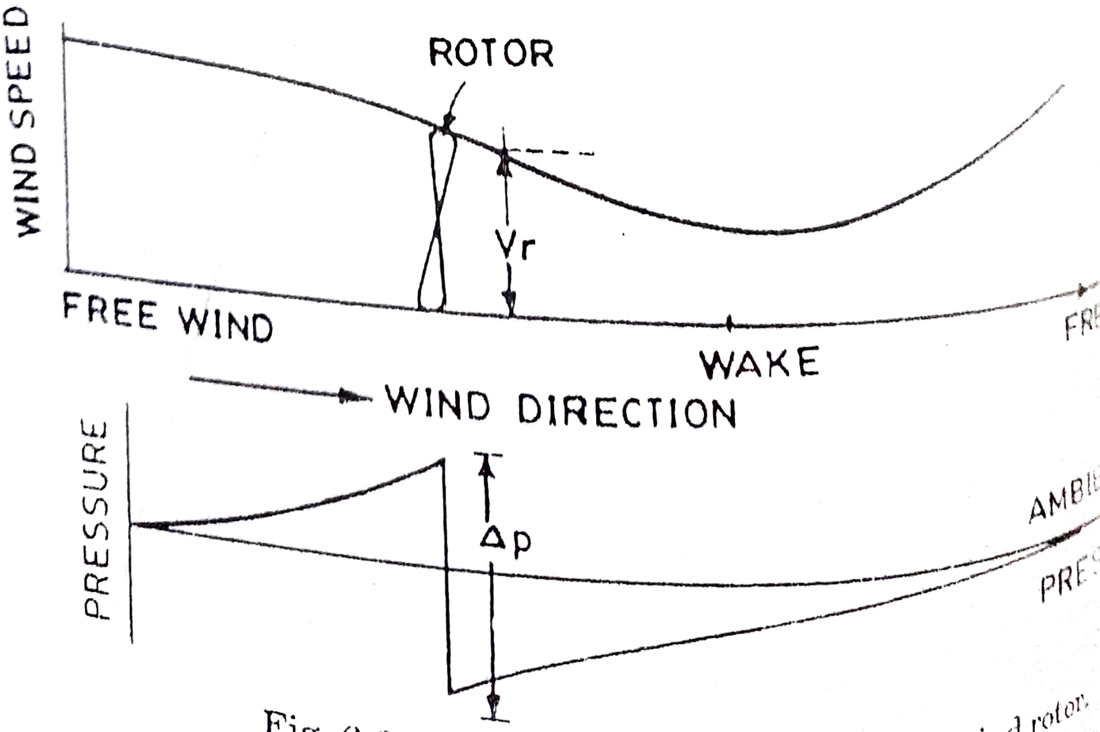


Fig. 6.2.2
ind rotor.

= [illegible] Newton. This

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

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

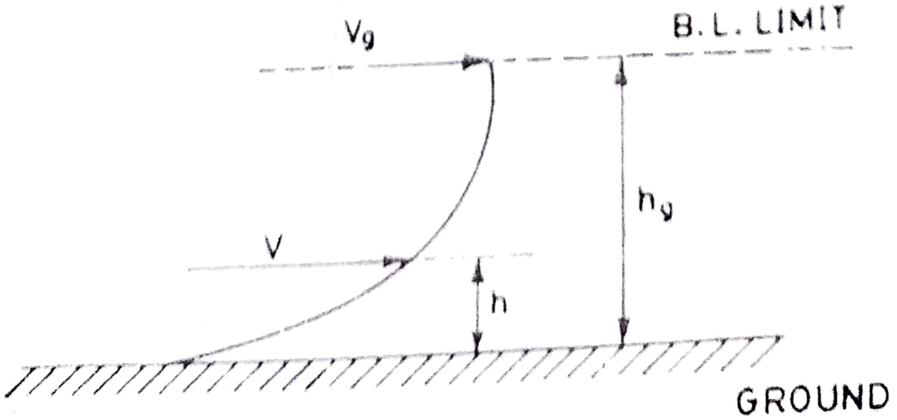


Fig. 6.3.1 Representation of gradient height and velocity.

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

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*

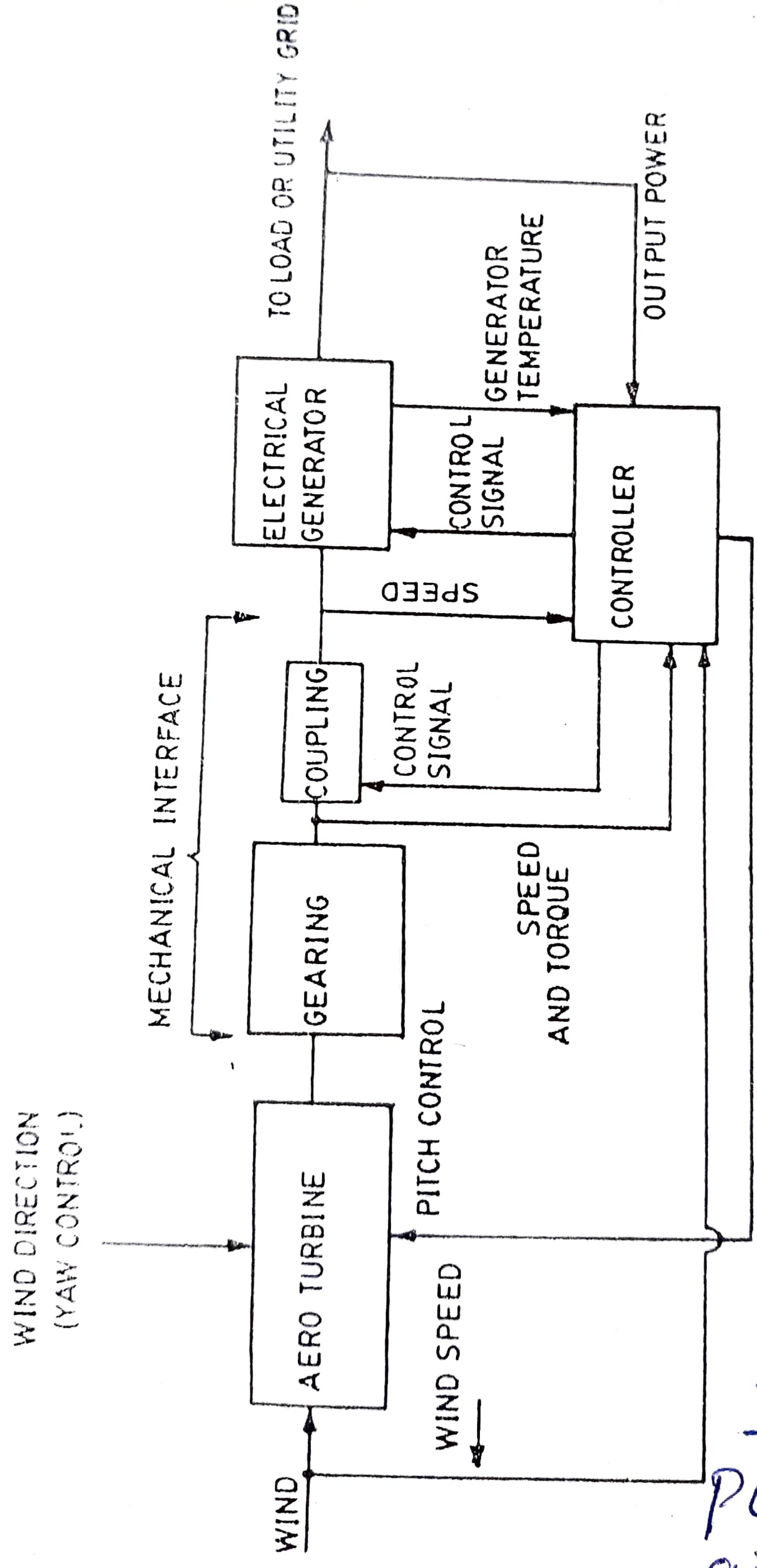


Fig. 6.5.1. Basic components of a Wind Electric System.

Power from wind mill

Instantane

Power may be given by,

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

otor

Rotors are mainly of two types :

(*i*) Horizontal axis rotor and

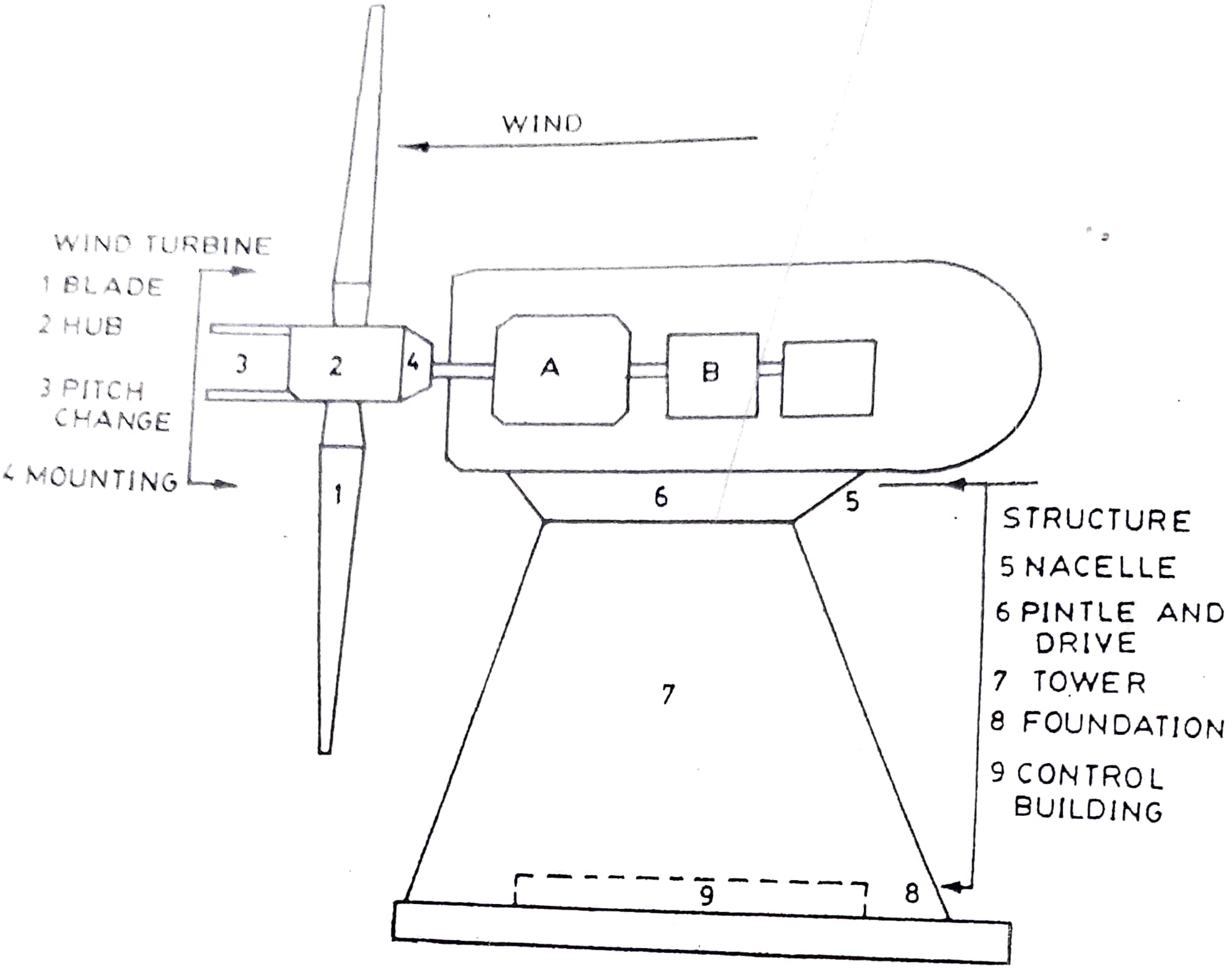
(*ii*) Vertical axis rotor.

us

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.

$P = (\frac{1}{2} \rho V^3)$ Continue (263)



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

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 upwind 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 upwind 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

Types of
wi

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 made 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.

energy

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. O a larger scale costs can be competitive with conventional electricity an 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 capacit because of its irregularity.

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

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

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

(vi) Present systems are neither maintenance ~~free~~ not-practical reliable. However, the fact that highly reliable propeller engines a built for aircraft suggest that the present troubles could be ove come by industrial development work.

6.8. Wind Energy Collectors

6.8.1. Introduction.

A windmill is a machine for wind ener conversion. A wind turbine converts the kinetic energy of the wind motion to mechanical energy transmitted-by the shaft. A generat further converts it to electrical energy, thereby generating electricit The term 'windmill' which originally implied a mill for grinding gra becomes an obvious misnomer when applied to electric power gener tion. The term is still widely used however, *Aerogenerators* avoids th difficulty. Only in the last century have windmills been used to genera electric power.

Wind *aerogenerators* or wind turbine generators of WECS a 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 cr wind axis rotors respectively. In the former types, the rotors oriented normal to the direction of wind, while in the latter types, effective surface of the rotor moves in the same direction as the wi

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

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

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

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

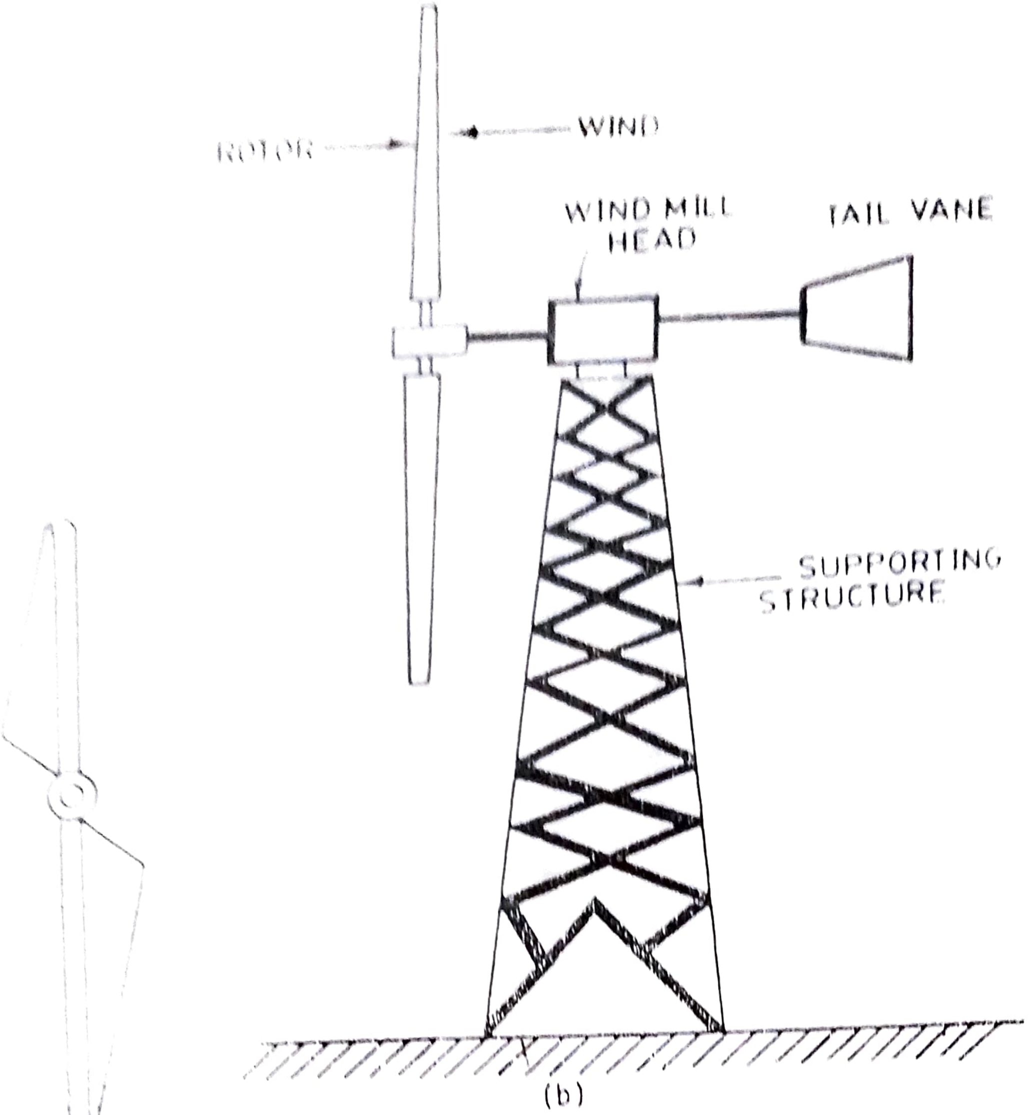
Vertical axis machines are of simple design as compared t horizontal axis type.

6.8.2. Horizontal-Axial Machines

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

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

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



(a)
TWO BLADE PROFILE

(b)
SCHEMATIC OF A HORIZANTAL AXIS TYPE WIND MILLS

Fig. 6.8.1

2. *Horizontal axis propeller type using single blade.* In this rangement, a long blade is mounted on a rigid hub (Fig. 6.8.2). duction generator and gear box are also shown. If extremely long ades (above say 60 m) are mounted on rigid hub, large blade root ending moments may occur due to tower shadow, gravity and sudden ifts in wind directions. To reduce rotor cost, use of low cost counter eight 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.

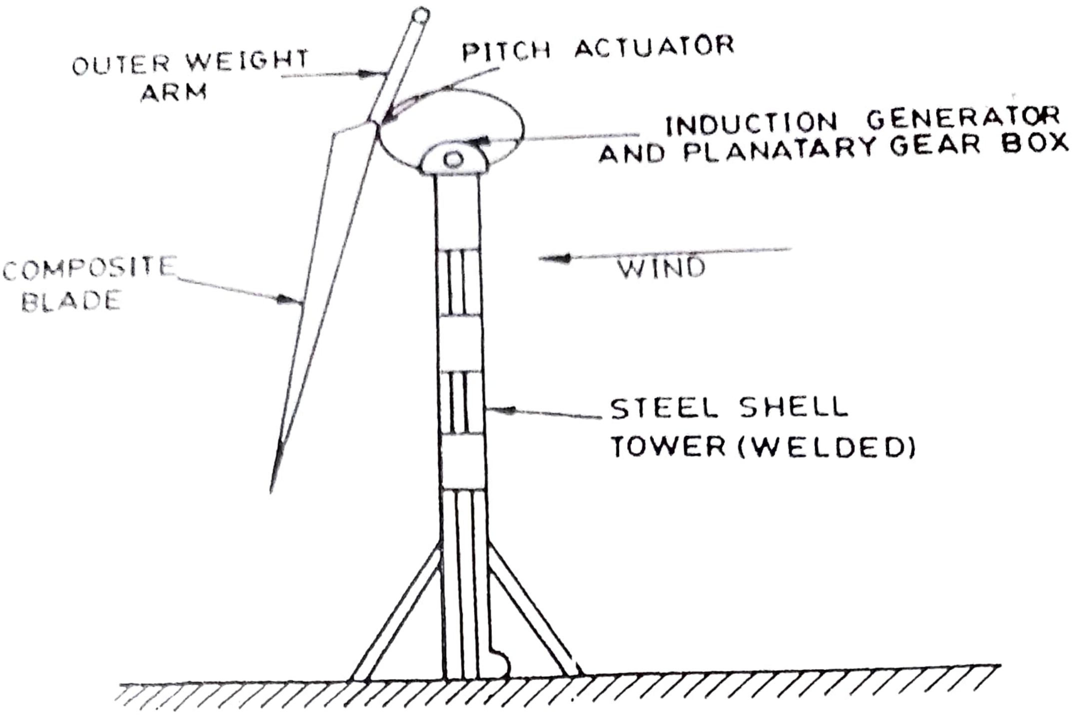
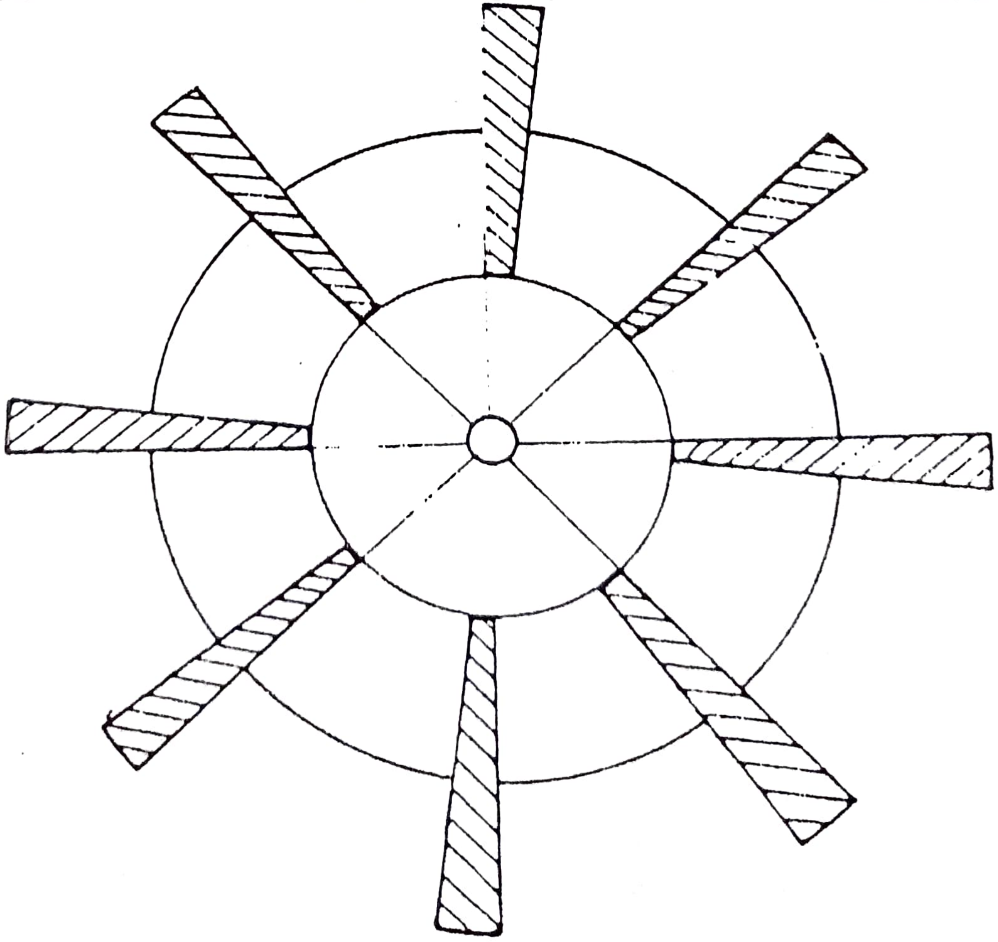


Fig. 6.8.2. Horizontal axis single blade wind mill.

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



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.

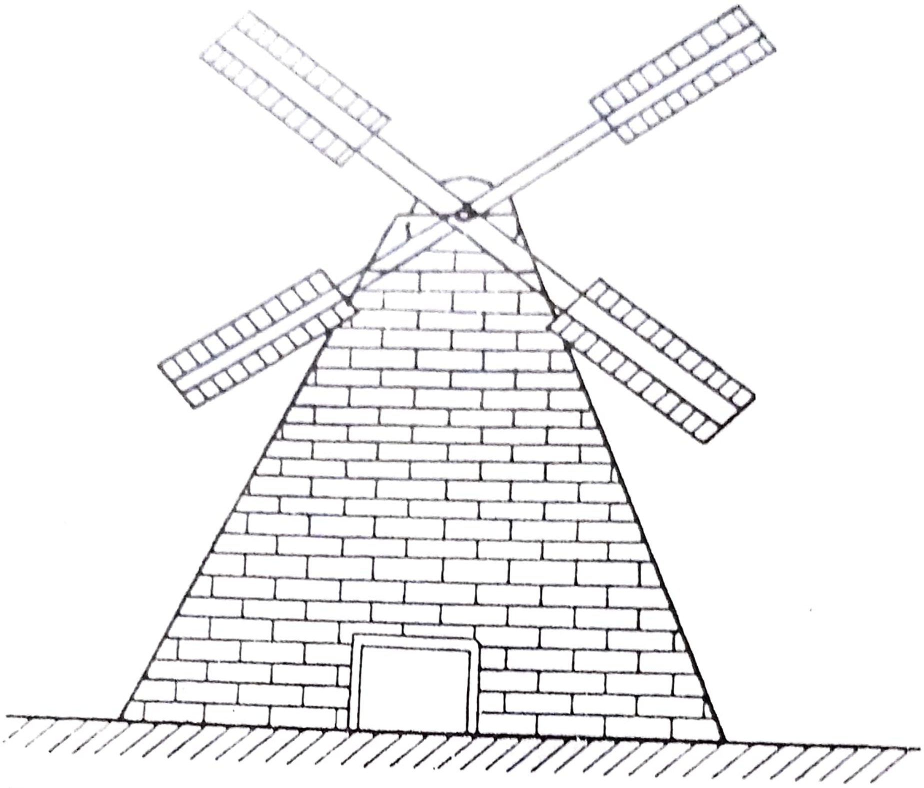
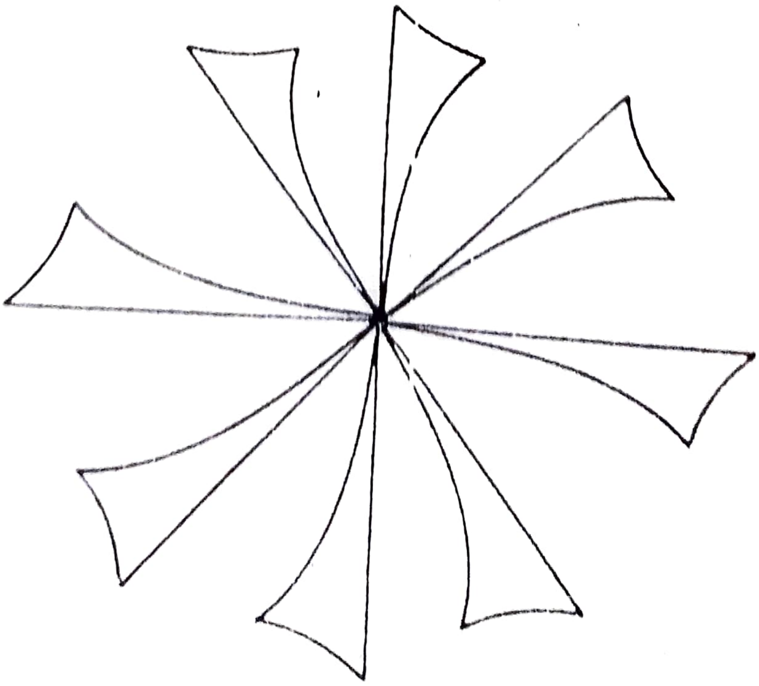


Fig. 6.8.4. Horizontal axis, Dutch type wind mill.

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.



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 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.

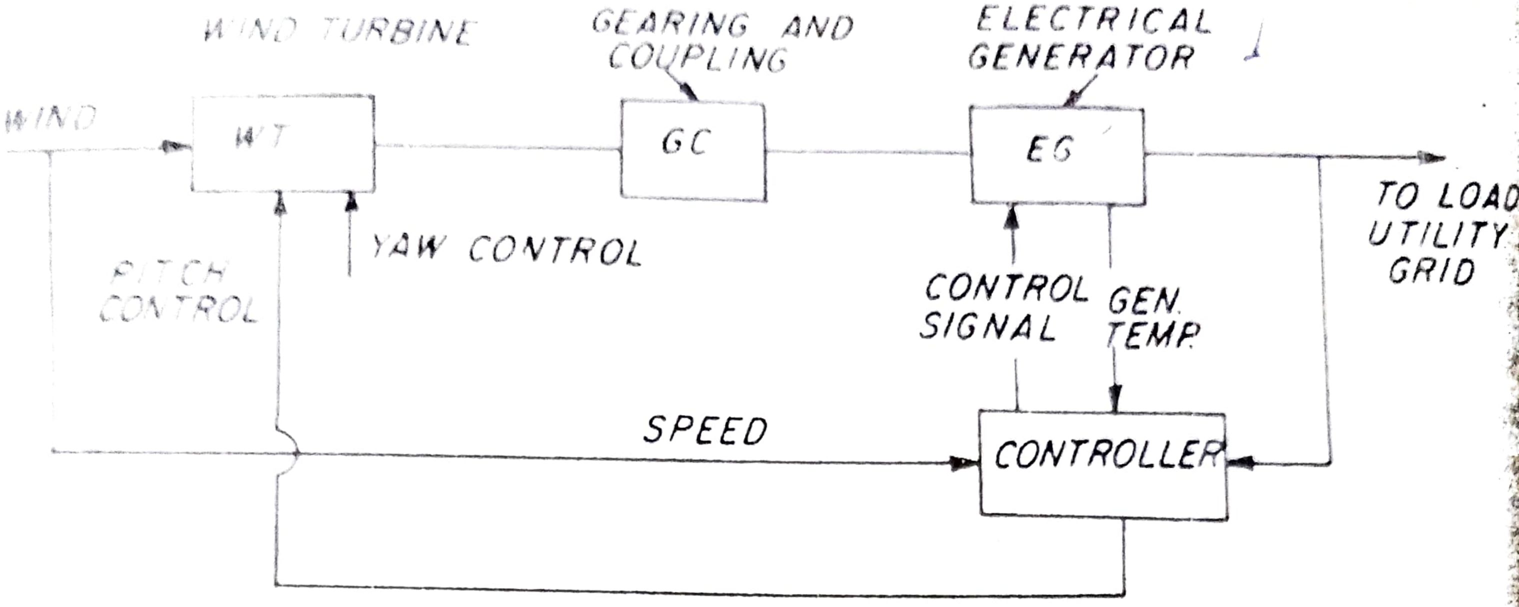


Fig. 6.11.1. Components of wind electric system.

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)

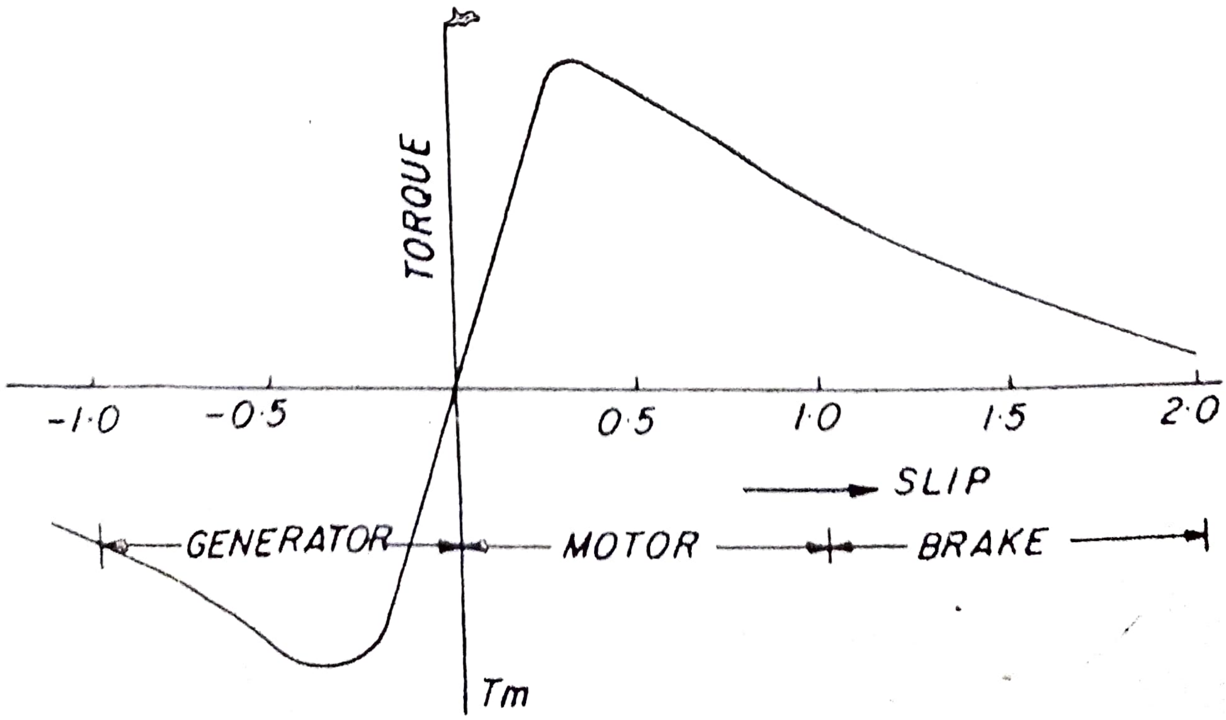
(*ii*) Variable speed constant frequency systems (VSCF)

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).

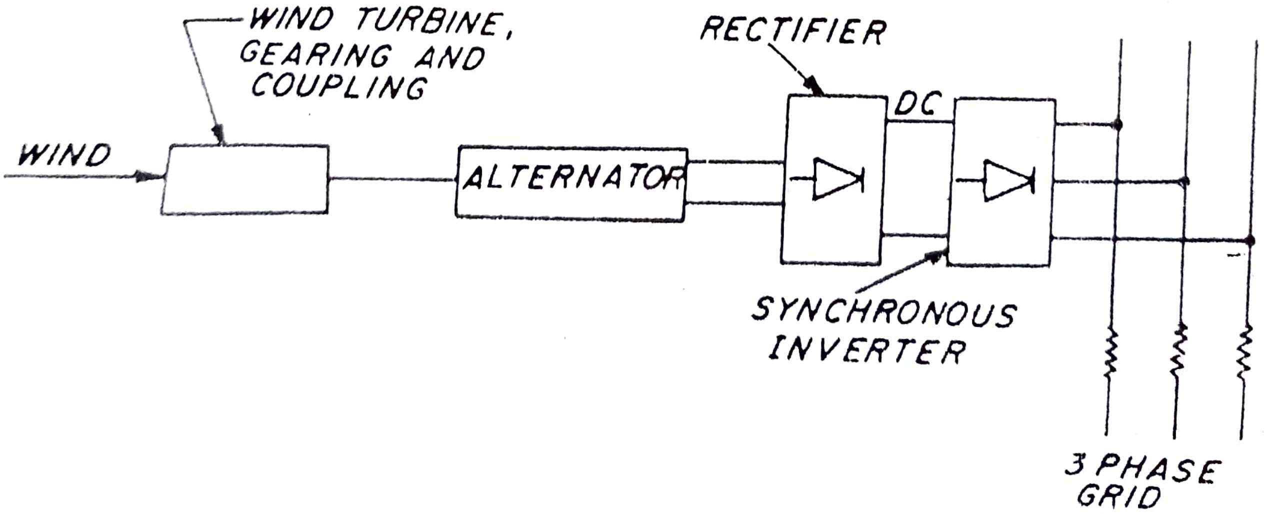


Fig. 6.11.3. Block diagram of Wind Electric Scheme.

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

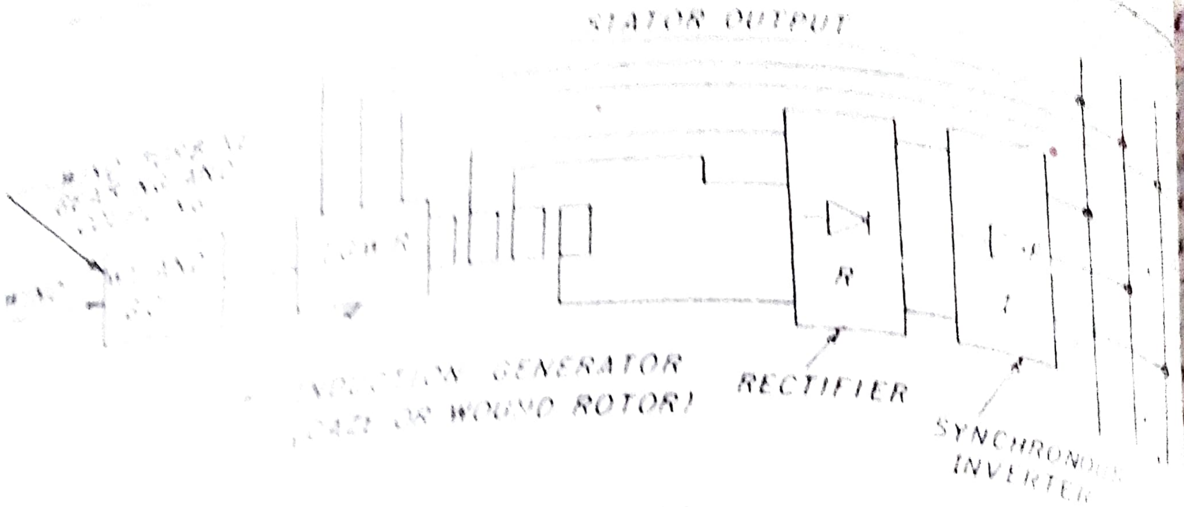


Fig. 6.11.4 Block diagram of double output wind driven Wound Rotor Induction Generator (IGWR).

output at slip frequency is converted to line frequency power b tification and inversion output power is obtained both from stat rotor and hence this device is called *double output induction gen* Rotor output power has the electrical equivalence of an add impedance in the rotor circuit. Therefore, increasing rotor outpu to increasing slips and higher speeds. Such an operation increas operating speed range from N_s to 2 N_s, *i.e.* slip varying from 0 t

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

(*iii*) **Variable Speed Variable Frequency (VSVF) Sch** Since resistive heating loads are essentially frequency insensit

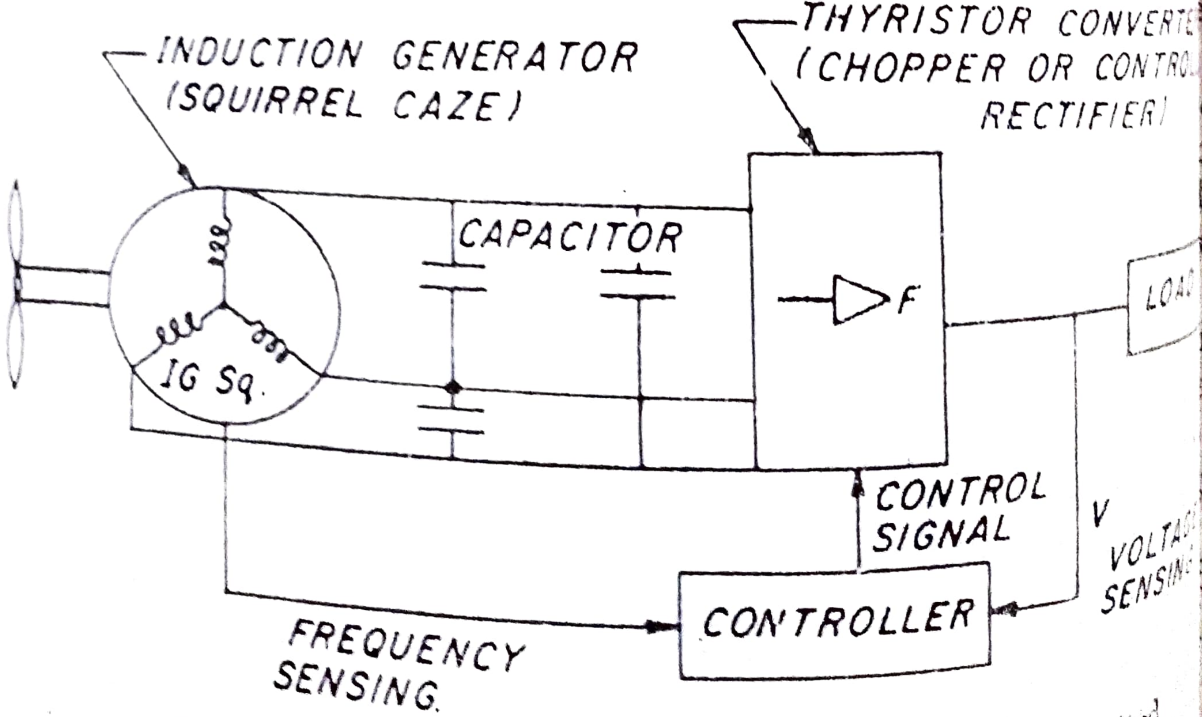


Fig. 6.11.5 … lf excited

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

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

6.11.3. Generator Control

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

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

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

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

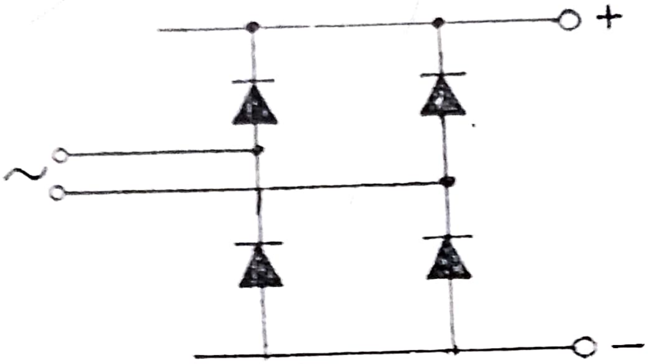
When a *wound rotor induction generator* is used for a grid onnection application, power control is achieved by varying the slip ergy of the rotor circuit. This may be achieved through a variety of ethods such as : rotor resistance control, cascading or variable speed lip-power recovery schemes.

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

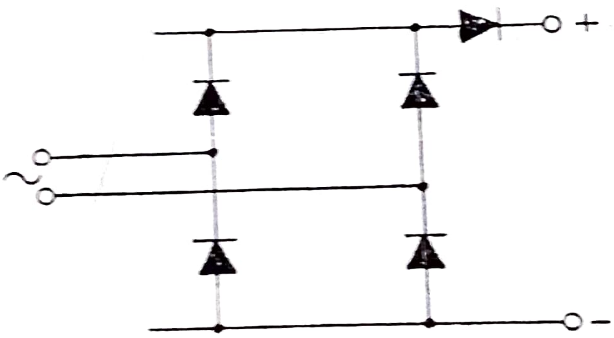
Synchronous machine power control is readily achieved through variation of the d.c. field excitation current. The frequency of the output voltage will be variable with wind speed for an isolated machine and fixed for a grid connected machine.

Transmission Control

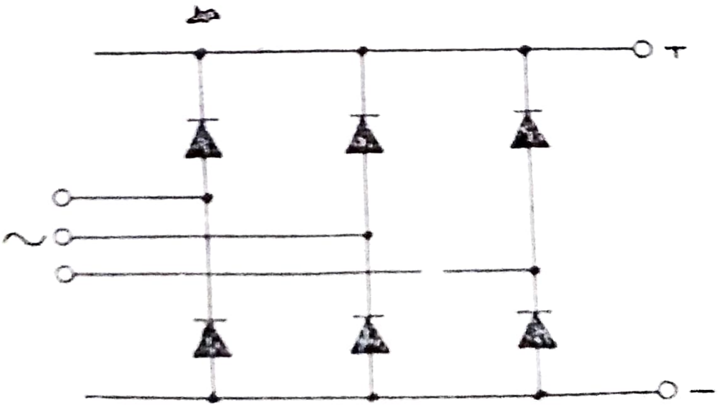
The most effective method of varying the power flow in the transmission link between the generator and its connected load is by means of a silicon controlled rectifier device. This unit employs power electronic devices (thyristors) whose conduction periods (*i.e.* on off time) can be controlled by applying 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 instal 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 television sets.

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

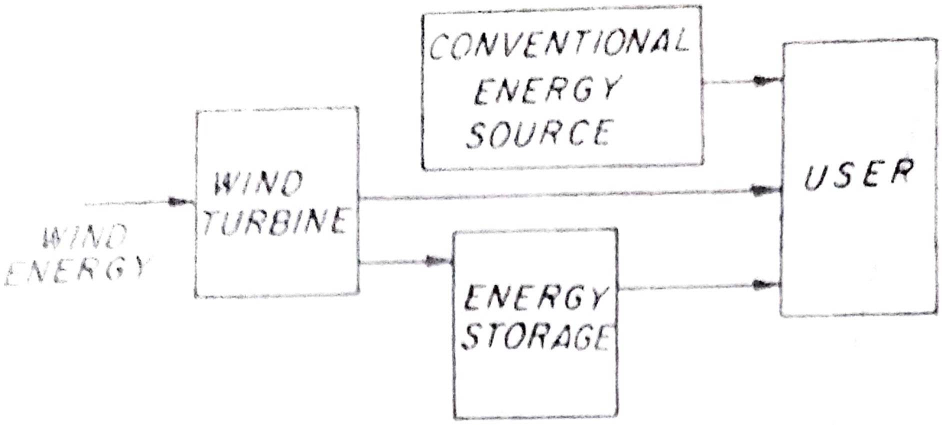
In water power storage or mechanical storage, high aerogenerators are integrated with an electric utility, a favou situation would be operation of several wind turbines in connectio a hydroelectric power plant. If the total power, wind and hydro being generated should exceed the demand, the hydroelectric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

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

6.13. Applications of Wind Energy

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

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



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

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

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

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

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

Pumping Applications. A typical wind-powered pumping ication is one that might use a horizontal—axis wind machine. An mple is the ancient jib—sail design that is mostly wind used to pump ation water. Large number of water-pumping wind mills have been l on Indian farms. Other applications that are being developed ude 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, some one 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.

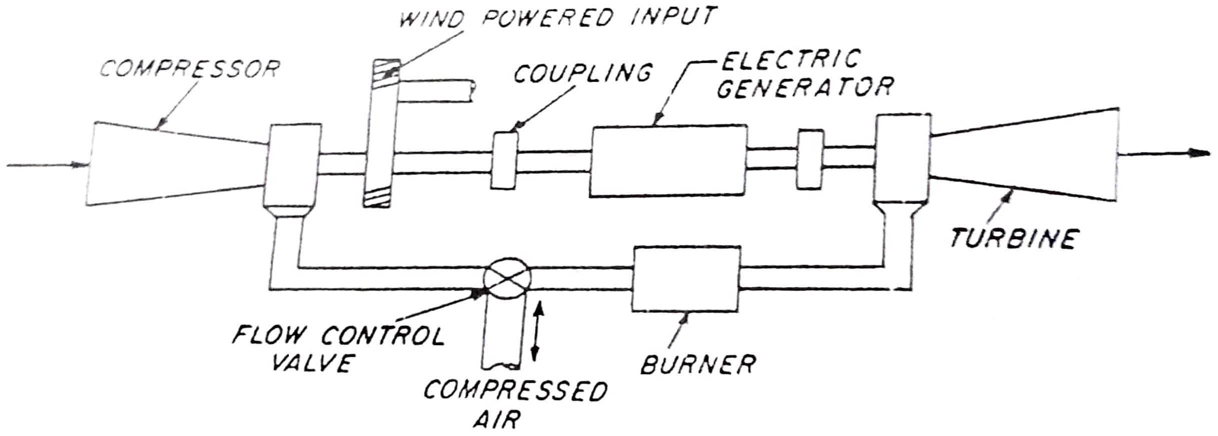


Fig. 6.13.2. Wind-assisted gas-turbine generating unit.

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 conserv than isothermal storage.

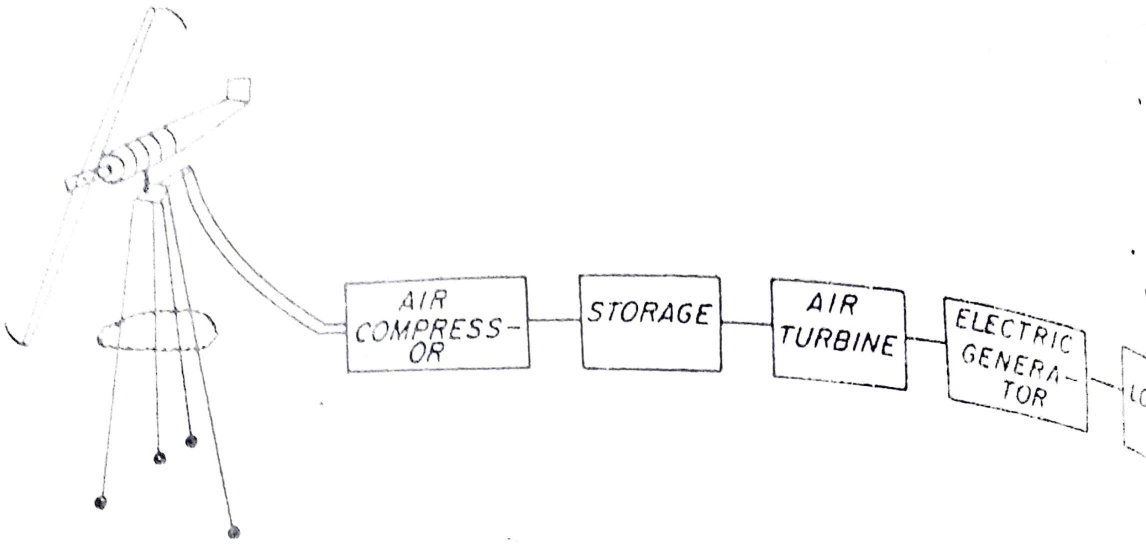


Fig. 6.13.3. System with compressed-air storage.

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

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

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

A home heating system that uses a wind-powered pum restrictive orifice to derive direct heat for a building, witho generating electricity also has been developed.

Examples of possible wind-powered agricultural proce applications include green house applications, crop dryin processing, food processing, refrigeration, frost protection, vent and waste processing.