CHAPTER

5 WIND ENERGY

5.1. INTRODUCTION

Wind *is air set in motion by small amount of insolation reaching the upper atmosphere of earth*.

It contains *kinetic energy* (*K.E.*) which can easily be *converted to electrical energy*. Nature generates about 1.67×10^5 kWh of wind energy annually over land area of earth and 10 times this figure over the entire globe.

- This *wind energy*, which is an *indirect source of energy*, can be used to run a wind mill which in turn *drives a generator to produce electricity*.
- Although wind mills have been used for more than a dozen centuries for grinding grain and pumping water, interest in large scale power generation has developed

over the past 50 years. A largest wind generator built in the past was 800 kW unit operated in France from 1958-60. 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 r.p.m.

- In India the interest in the wind mills was shown in the last fifties and early sixties. Apart from importing a few from outside, new designs were also developed, but these were not sustained. It is only in last 20-25 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 *is relatively low and vary appreciably with seasons. These low and seasonal winds imply a high cost of exploitation of wind energy. In our country high wind speeds are however available in coastal areas of Sourashtra, Western Rajasthan and some parts of central India. In these areas there could be a possibility of using medium and large sized wind mills for generation of electricity.*

5.2. UTILISATION ASPECTS OF WIND ENERGY

Utilisation aspects of wind energy fall into the following *three* broad categories:

1. Isolated continuous duty systems which need suitable energy storage and reconversion systems.
2. Fuel-supplement systems in conjunction with power grid or isolated conventional generating units.
   - This utilisation aspect of wind energy is the *most predominant in use as it saves fuel and is fast growing particularly in energy deficient grids*.
3. Small rural systems which can use energy when wind is available.
   - This category has application in *developing countries with large isolated rural areas*.

5.3. CHARACTERISTICS OF WIND

The main characteristics of wind are:

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

5.4. ADVANTAGES AND DISADVANTAGES OF WIND ENERGY

Following are the *advantages* and *disadvantages* of wind energy:

Advantages:

1. It is a renewable energy source.
2. Wind power systems being non-polluting have no adverse effect on the environment.
3. Fuel provision and transport are not required in wind energy conversion systems.
4. Economically competitive.
5. Ideal choice for rural and remote areas and areas which lack other energy sources.

Disadvantages:

1. Owing to its irregularity, the wind energy needs storage.

2. Availability of energy is fluctuating in nature.
3. The overall weight of a wind power system is relatively high.
4. Wind energy conversion systems are noisy in operation.
5. Large areas are required for installation/operation of wind energy systems.
6. Present systems are neither maintenance free, nor practically reliable.
7. Low energy density.
8. Favourable winds are available only in a few geographical locations, away from cities, forests.
9. Wind turbine design, manufacture and installation have proved to be most complex due to several variables and extreme stresses.
10. Requires energy storage batteries and/or stand by diesel generators for supply of continuous power to load.
11. Wind farms require flat, vacant land free from forests.
12. Only in kW and a few MW range; it does not meet the energy needs of large cities and industry.

☞ 5.5. ENVIRONMENT IMPACTS OF WIND ENERGY

The *possible environment impacts of wind energy* are:

1. Wind energy creates *noise pollution* because of mechanical (gear box) aerodynamic noise.
2. The wind turbine produces *electromagnetic interference* when placed between radio, television etc. stations, as it reflects some electromagnetic radiations.
3. It produces *visual shining* because of reflection and refraction which depends upon turbine size, number of turbines in wind farm, design etc.
4. *Safety consideration* for life because of *accidental braking of blade*.
5. *Fatal collisions of birds* caused by rotating turbine blides.

5.6. SOURCES/ORIGINS OF WIND

Following are the two sources/origins of wind (a natural phenomenon):

1. Local winds.
2. Planetary winds.

1. **Local winds.** These winds are caused by *unequal heating and cooling of ground surfaces and ocean/lake surfaces during day and night*. During the day warmer air over land rises upwards and colder air from lakes, ocean, forest areas, and shadow areas flows towards warmer zones.

2. **Planetary winds.** These winds are caused by *daily rotation of earth around its polar axis and unequal temperature between polar regions and equatorial regions*. 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 available in land. 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 increases with height*. They have traditionally been measured at a standard height of 10 meters where they are found to be 20-25 percent greater than close to the surface. At a height of 60 m they may be 30-60 percent higher because of the reduction in the drag effect of the surface of the earth.

5.7. WIND AVAILABILITY AND MEASUREMENT

Wind energy can only be economical in areas of good wind availability. Wind energy differs with region and season and also, possibly to an even greater degree with local terrain and vegetation. Although wind speeds generally increases with height, varying speeds are found over different kinds of terrain. Observations of wind speed are carried out at meteorological stations, airports and lighthouses and are recorded regularly with ten minute mean values being taken every three hours at a height of 10 m. But airports, sometimes are in valleys and many wind speed meters are situated low and combinations of various other factors mean that reading can be misleading. It is difficult, therefore, to determine the real wind speed of a certain place without actual in-situ measurements.

The World Meteorological Organisation (WMO) has accepted the following *four methods of wind recording*:

(*i*) Human observation and log book.

(*ii*) Mechanical cup-counter anemometers.

(*iii*) Data logger.

(*iv*) Continuous record of velocity and direction.

1. **Human observation and log book.** This involves using the Beaufort Scale of wind strengths which defines visible "symptoms" attributable to different wind speeds. The method is *cheap* and *easily implemented* but is *often unreliable*. The best that can be said of such records is that they are better than nothing.

2. **Mechanical cup-counter anemometers.** The majority of meteorological stations use mechanical cup-counter anemometers. By taking the readings twice or three times a day, it is possible to estimate the mean wind speed. This is a *low cost method*, but is *only relatively reliable*. The instrument has to be in good working order; it has to be correctly sited and should be reliably read atleast daily.

3. **Data logger.** The equipment summarizes velocity frequency and direction. It is *more expensive and prone to technical failures but gives accurate data*. The method is tailored to the production of readily interpretable data of relevance to wind energy assessment. It does not keep a time series record but *presents the data in processed form*.

4. **Continuous record of velocity and direction.** This is how data is recorded at major airports of permanently manned meteorological stations. The *equipment is expensive and technically complex*, but it retains a detailed times-series record (second-by-second) of wind direction and wind speed. Results are given in copious quantities of data which require lengthy and expensive analysis.

Variation of wind speed with elevation:

The speed of wind *increases* with height above ground. *Increase in wind speed with height above ground level is called* **wind shear**. The wind speed at the ground is *zero* due to the *friction* between the ground surface and the air. *Increase* in wind speed with height is due to *temperature gradient* and it depends on the type of terrain over which the wind has travelled and atmospheric stability.

The change in wind speed with height, based on the data from several locations, for sites of low ground roughness, can be expressed as:

$$\frac{U_{w_2}}{U_{w_1}} = \left(\frac{H_2}{H_1}\right)^{\alpha} \qquad ...(5.1)$$

where U_{w1} and U_{w2} are wind speeds at levels H_1 and H_2 respectively. This is known as *power law index* "α" which depends on the roughness of terrain. Its value is taken as $\mathbf{\frac{1}{7}}$ for *open land* and **0.10** for calm *sea area.*

The value of power index for a particular site is obtained from the measured wind at two heights by the following relation:

$$\alpha = \frac{\log U_{w2} - \log U_{w1}}{\log H_2 - \log H_1} \qquad ...(5.2)$$

- The ideal wind energy have a *low value* of α.
- Normally, wind measurements are carried out an elevation of 10 m. However, modern wind turbines are installed at a winds height of 25 to 50 m.
- Wind speed at the required height is calculated from Eqn. (5.1) with $\alpha = \frac{1}{7}$.

5.8. PRINCIPLE OF WIND ENERGY CONVERSION AND WIND POWER

The wind power can be computed by using concept of *kinetics*. *A wind mill works on the principle of 'converting kinetic energy of the wind to mechanical energy'.*

Let, U_w = Velocity of wind, km/h, and

ρ = Density of air (1.225 kg/m^3 at sea level); and

(*Air density* is a function of *altitude, temperature and barometric pressure*)

Air density A = Area, through which the air flows.

Then, the amount of air passing in unit time (m) through area A, with velocity U_w is given by:

Mass, $m = \rho A U_w$

$$\therefore \quad \text{Kinetic energy (K.E.)} = \frac{1}{2} m U_w^2$$

$$= \frac{1}{2} \times \rho A U_w \times U_w^2 = \frac{1}{2}\rho A U_w^3 \text{ watts}$$

i.e. $$\text{Total power } (P_{\text{total}}) = \frac{1}{2}\rho A U_w^3 \qquad ...(5.3)$$

From Eqn. (5.3) it is obvious that power output of a wind mill *varies as cube of the wind velocity* (*i.e.* Power output $\propto U_w^3$)

Further, P_{total} can be expressed as:

$$P_{\text{total}} = \frac{1}{2}\rho \times \frac{\pi}{4} D^2 \times U_w^3 = \frac{1}{8}\rho\pi D^2 U_w^3 \qquad ...(5.4)$$

where, D = diameter (in meters) in *horizontal axis* aeroturbines.

All this power *cannot be extracted* because, for this, wind velocity *would have to be reduced to zero* which means that the wind mill would accumulate static air around it which would *prevent the wind mill operation*.

Theoretically, a fraction $\frac{16}{27} \simeq$ *0.593 (59.3%) of the power in the wind is 'recoverable'*. This is called "**Gilbert's limit**" or "**Betz coefficient**". Aerodynamically, efficiency for converting wind energy to mechanical energy *can be reasonably assumed to be 70%*. So the mechanical energy *available at the rotating shaft is limited to 40% or at the most 45% of wind energy*.

Eqn. (5.4) indicates that maximum power available from the wind *varies according to square of the diameter* of the intercept area (or square of the root diameter) normally taken to be swept area of the aeroturbine. The combined effects of wind speed and rotor diameter variations are shown in Fig. 5.1. Thus, *wind machines intended for generating substantial amounts of power should have large rotors and be located in areas of high wind speeds.*

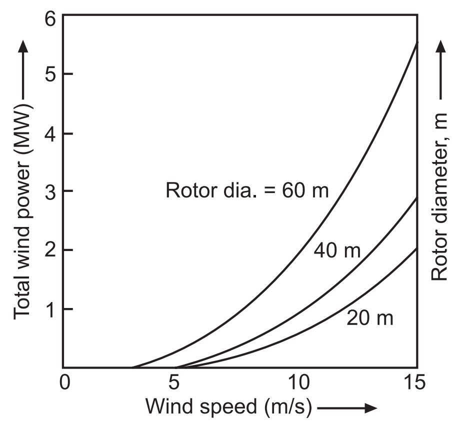

Fig. 5.1. The combined effects of variations of wind speed and diameter.

State-wise wind power potential and wind power addition capacity (as on 31-12-2004) are given in table 5.1 and table 5.2 respectively.

- The best medium–sized and large modern wind turbines (20 kW and above) normally achieve efficiencies of slightly better than 40% (*i.e.*, almost two-thirds of the theoretical maximum) when they convert the kinetic power of the wind to shaft power by passing it through the turbine disc. The more sophisticated smaller units in the 2-20 kW range can achieve 30-40 percent rotor efficiency, while even quite crude designs and small machines of 1 kW or less commonly reach 25 to 30%, which is about half the theoretical value.

Table 5.1 Wind power potential

State	*Gross potential (MW)* (a)	*Technical potential (MW)* (b)
Andhra Pradesh	8275	1750
Gujarat	9675	1780
Karnataka	6620	1120
Kerala	875	605
Madhya Pradesh	5500	825
Maharashtra	3650	3020
Orissa	1700	680
Rajasthan	5400	895
Tamil Nadu	3050	1750
West Bengal	450	450
Total	**45195**	**12875**

Table 5.2. State-Wise Wind Power Capacity Addition (As on 31.12.2004)

State	*Demonstration projects (MW) (a)*	*Private sector projects (MW) (b)*	*MW (Total) capacity (MW) (a) + (b)*
Andhra Pradesh	5.4	95.9	101.3
Gujarat	17.3	202.6	219.9
Karnataka	7.1	268.9	276.0
Kerala	2.0	0.0	2.0
Madhya Pradesh	0.6	27.0	27.6
Maharashtra	8.4	402.8	411.2
Rajasthan	6.4	256.8	263.2
Tamil Nadu	19.4	1658.0	1677.4
West Bengal	1.1	0.0	1.1
Others	0.5	0.0	0.5
Total	**68.2**	**2912.0**	**2980.2**

Characteristics of a good wind power site:

A good wind power site should have the following *characteristics*:

1. High annual wind speed.
2. An open plain or an open shore line.
3. A mountain gap.
4. The top of a smooth, well rounded hill with gentle slopes lying on a flat plain or located on an island in a lake or sea.
5. There should be no full obstructions within a radius of 3 km.

5.9. WIND ENERGY PATTERN FACTOR (EPF)

The **energy pattern factor (EPF)** *is the ratio of power from speed distribution to the power from coverage speed of the turbine blades.*

i.e.
$$EPF = \frac{\text{Power from speed distribution}}{\text{Power from average speed}}$$

Generally, *EPF* lies between 2 to 5.

5.10. BASIC COMPONENTS OF WIND ENERGY CONVERSION SYSTEM (WECS)

Fig. 5.2 shows the block diagram of basic components of a wind energy conversion systems.

— **Wind turbines** (Aeroturbines) *convert* the energy of moving air into *rotary mechanical energy*. These turbines requires pitch and yaw controls for proper operation.

— A **mechanical interface** consisting of a *step up gear* and a suitable *coupling* transmits the rotary mechanical to an **electrical generator**. The output of this generator is connected to the road or power grid as the application demands.

— A **controller** serves purposes of sensing: (*i*) Wind speed, (*ii*) Wind direction, shafts speed and torques at one or more points, (*iii*) Output power and generator temperature as necessary, (*iv*) Appropriate control signals for matching the electrical output to the wind energy input, and (*v*) Protect the system from extreme conditions brought about by strong winds, electrical faults etc.

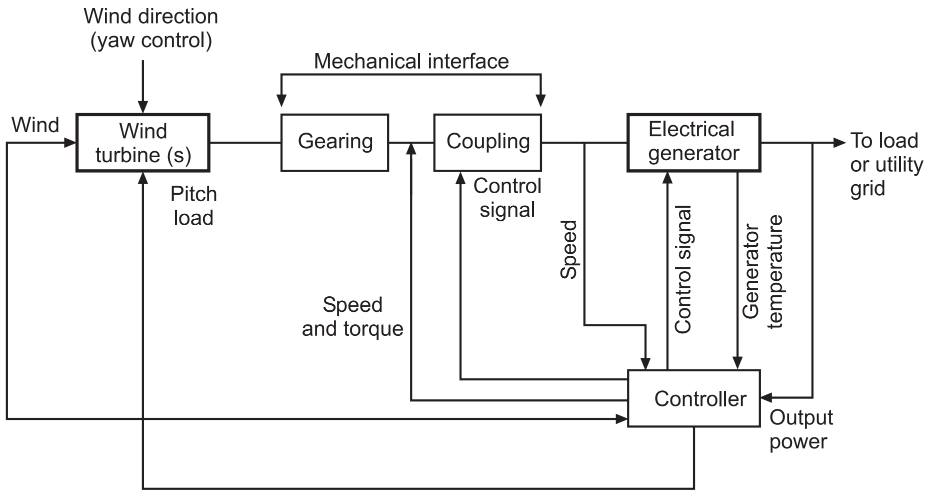

Fig. 5.2. Basic components of a wind energy conversion system (WECS).

5.11. ADVANTAGES AND DISADVANTAGES OF WIND ENERGY CONVERSION SYSTEMS (WECS)

The *advantages and disadvantages* of wind energy conversion systems as follows:

Advantages:

1. Wind energy, a renewable energy source, can be *tapped free of fuel cost*.
2. The wind turbine generation (WTG) produces electricity which is *environmentally friendly*.
3. Wind power generation is *cost effective.*
4. It is *economically competitive* with other modes of power generation.
5. Quite *reliable*.
6. Electric power can be supplied to *remote inaccessible areas*.

Disadvantages:

1. As the wind speed is variable, wind energy is *irregular, unsteady* and *erratic*.
2. Wind turbine design is *complex*.
3. Wind energy systems require storage batteries which contribute to *environmental pollution*.
4. Wind energy systems are *capital intensive* and *need government support*.
5. Wind energy has *low energy density* and normally available at only selected geographical locations away from cities and load centers.
6. For wind farms (which are located in open areas away from load centres), the *connection to state grid is necessary.*
7. 'Large units' have *less cost* per kWh, but *require capital intensive technology*. In contrast 'small units' are *more reliable* but have *higher capital cost per kWh.*

5.12. CONSIDERATIONS FOR SELECTION OF SITE FOR WIND ENERGY CONVERSION SYSTEMS (WECS)

Following *factors* should be given due considerations while selecting the site for WECS:

1. Availability of anemometry data.
2. High annual average wind speed.
3. Availability of wind curve at the proposed site.
4. Wind structure at the proposed site.
5. Altitude of the proposed site.
6. Terrain and its aerodynamic.
7. Local ecology.
8. Distance to roads or railways.
9. Nearness of site to local centre/users.
10. Favourable land cost.
11. Nature of ground.

5.13. TERMS AND DEFINITIONS

1. **Aerodynamics.** It is the branch of science which *deals with air and gases in motion and their mechanical effects*.
2. **Airfoil or aerofoil.** A *streamlined air surface designed for air* to flow around it in order to produce *low drag* and *high lift forces*.
3. **Angle of attack.** It is the angle between the relative air flow and the closed of the air foil (Fig 5.3).

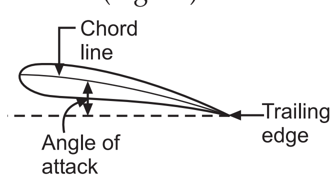

Fig 5.3. Angle of attack

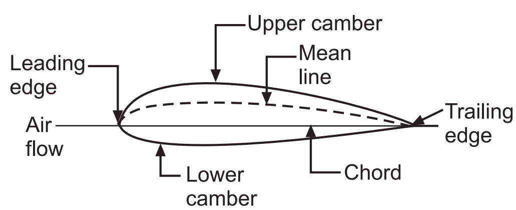

Fig 5.4. Air foil showing edges, camber and chord.

4. **Blade.** An important part of a wind turbine that *extracts wind energy*.
5. **Leading edge.** It is the front edge of the blade that *faces towards the direction of flow* (Fig. 5.4).
6. **Trailing edge.** It is the rear edge of the blade that *faces away from the direction of wind flow* (Fig. 5.4).
7. **Mean line.** A line that is *equidistant* from the upper and lower surfaces of the air foil (Fig. 5.4).
8. **Camber.** It is the *maximum distance between the mean line and the chord line, which measures the curvature of the airfoil*.
9. **Rotor.** It is the *primary part* of the wind turbine that *extracts energy* from the wind. It *constitutes the blade-and-hub assembly*.
10. **Hubs.** Blades are fixed to a hubs which is a *central solid part of the turbine*.
11. **Pitch angle.** It is the *angle between the direction of wind and the direction perpendicular to the planes of blades*.

12. **Pitch control.** It is the *control of pitch angle by turning the blades or blade tips* [Fig. 5.5 (*a*)].
13. **Yaw control.** It is the *control for orienting (steering) the axis of wind turbine in the direction of wind* [Fig. 5.5 (*b*)].
14. **Teethering.** It is see-saw like swinging motion with hesitation between two alternatives. The *plane of wind turbine wheel is swung in inclined position at higher wind speeds by teethering control* [Fig. 5.5 (*b*)].

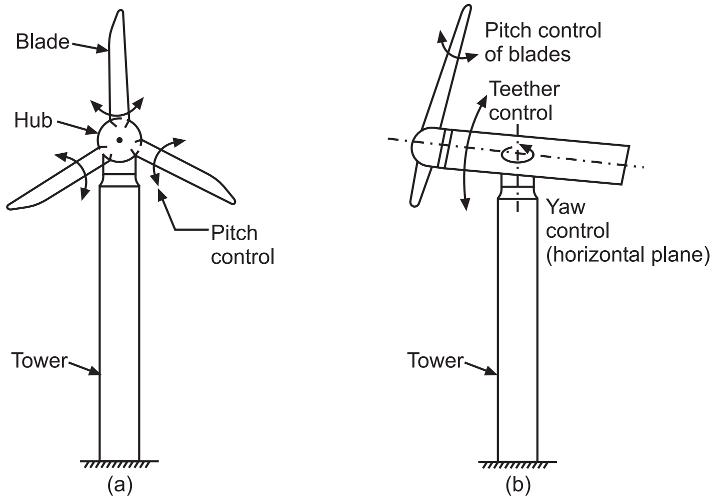

Fig. 5.5. Controls in wind–turbines: Pitch control; Yaw control; Teether control.

15. **Solidity.** *It is ratio of blade area to the swept area* (area covered by the rotating rotor).
16. **Drag force.** It is the force component which is *in line with the velocity of wind*.
17. **Lift force.** It is the force component *perpendicular to drag force*.
18. **Windmill.** It is the *machinery driven by the wind acting upon sails* used chiefly in flat districts for grinding of corn, pumping of water etc.

    Wind turbine (Aeroturbine, wind machine). It is a machine which *converts wind power into rotary mechanical power*. A wind turbine has aerofoil blades mounted on the rotor. The wind drives the rotor and produces rotary mechanical energy.

    Wind turbine generator unit. It is an *assemblage* of a wind turbine, gear chain, electrical generator, associated civil works and auxiliaries.

    Wind farm (wind energy park). It is a *zone comprising several turbine-generator units, electrical and mechanical auxiliaries, substation, control room* etc.

    Wind farms are located in areas having *continuous favourable wind*. Such locations are on-shore or off-shore away from cities and forests.

    Nacelle. It is an *assemblage* comprising of the wind turbine, gears, generator, bearings, control gear etc. *mounted in a housing*.
19. **Wind speeds for turbines:**

    (*i*) ***Cut-in-speed.*** It is the *wind speed at which wind–turbine starts delivering shaft power*. For a typical horizontal shaft propeller turbine it may be *around 7 m/s*.

(*ii*) ***Mean wind speed.*** $U_{wm} = \dfrac{U_{w_1} + U_{w_2} + \ldots U_{w_n}}{n}$

(*iii*) ***Rated wind speed.*** *It is the velocity at which the wind–turbine generator delivers rated power*.

(*iv*) ***Cut-out wind velocity (furling wind velocity).*** It is the *speed at which power conversion is cut out*.

5.14. 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.

Following are the *two primary mechanisms for producing* forces from the wind: Refer to Fig. 5.6

(*i*) Lift force (F_L), (*ii*) Drag force (F_D).

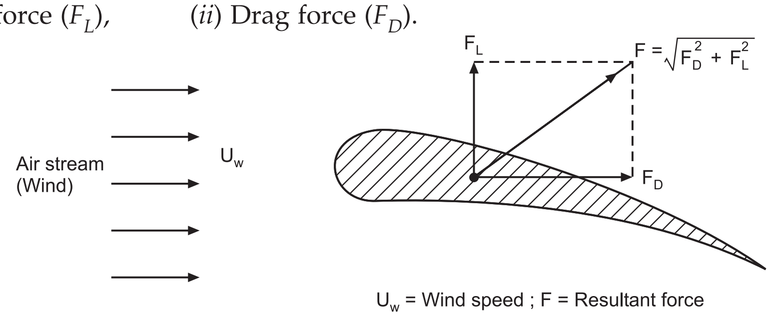

Fig. 5.6. Lift and drag on an airfoil.

Lift force. The component of force at *right angles* to the direction of air stream on the airfoil is called the *lift force* (F_L) .

Drag force. The component of force *in the direction of stream* is called *drag force* (F_D).

— When air stream approaches the airfoil along the axis of symmetry, the force acting on the body is only the drag force, in the direction of flow and there is *no lift force*. *The production of lift force requires asymmetry of flow while drag force exists always. It is possible to create drag without lift but impossible to create lift without drag*.

'Lift forces' are produced by changing the velocity of 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*. The 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 high* **lift/drag ratio** (LDR); in some cases it can generate lift forces perpendicular to air stream direction, 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 acute, upto the point where the angle of the air flow on low pressure side becomes excessive*. When this happens, the air flow breaks away from the low pressure side, a *lot of the 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 the *drag dissipates energy*.

The design of each wind turbine specifies the *angle* at which the airfoils should be set to achieve the *maximum LDR*.

- Besides air foils, following are other two *mechanisms for creating lift*:

(*i*) ***Magnus effect.*** This effect is caused by spinning a cylinder in 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 *generally not applied*.

(*ii*) ***Blowing air through narrow slots in a cylinder.*** In this mechanism, air is blown through narrow slots in cylinder, so that it energies *tangentially*; this is known as "*Thwaites slot*". This also creates a rotation (or circulation) of the airflow, which in turn generates lift. *Because the LDR of airfoils is generally much better than those of rotating and slotted cylinders the latter techniques probably have little practical potential*.

5.15. EXTRACTION OF WIND ENERGY

Energy from wind stream is extracted by a wind turbine, by *converting the kinetic energy (K.E.) of the wind to rotational motion required to operate an electric generate*.

In order to compute the mathematical relationships, let us make the following assumptions:

1. The *flow of wind is 'incompressible'*, and hence the air stream *diverges* as it passes through the turbines
2. The *mass flow rate of wind is 'constant'* at *far upstream, at the rotor and at far down stream*.

Let,
p = Atmospheric wind pressure,
p_{us} = Pressure on *upstream* of wind turbine,
p_{ds} = Pressure on *downstream* of wind turbine,
U_w = Atmospheric wind velocity,
$(U_w)_{us}$ = Velocity of wind upstream of wind turbine,
$(U_w)_{bl}$ = Velocity of wind at blades,
$(U_w)_{ds}$ = Velocity of wind downstream of wind turbine before the wind front reforms and regains the atmospheric level,
A_{bl} = Area of blades,
$\dot{m}$ = Mass flow rate of wind, and
ρ = Density of air.

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

$$\text{K.E.} = \frac{1}{2}\dot{m}(U_w)^2{}_{bl}$$

And,
$$\dot{m} = \rho\, A_{bl}(U_w)_{bl} \qquad \text{...(5.5)}$$

$$\therefore \quad \text{K.E.} = \frac{1}{2}\rho A_{bl}(U_w)_{bl} \times (U_w)^2{}_{bl} = \frac{1}{2}\rho A_{bl}(U_w)^3_{bl}$$

The force on the rotor disc, F is given as:

$$F = (p_{us} - p_{ds})A_{bl} \qquad \text{...(5.6)}$$

Also, $$F = \dot{m}[(U_w)_{us} - (U_w)_{ds}] \qquad ...(5.7)$$

[momentum per unit time from upstream to downstream winds]

Applying Bernoulli's equation to upstream and downstream sides, we get:

$$p + \frac{1}{2}\rho(U_w)_{us}^2 = p_{us} + \frac{1}{2}\rho(U_w)_{bl}^2 \qquad ...(5.8)$$

and, $$p_{ds} + \frac{1}{2}\rho(U_w)_{bl}^2 = p + \frac{1}{2}\rho(U_w)_{ds}^2 \qquad ...(5.9)$$

Solving the above equations, we obtain:

$$p_{us} - p_{ds} = \frac{1}{2}\rho\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] \qquad ...(5.10)$$

Equating Eqns. (5.6 and 5.7), we get:

$$(p_{us} - p_{ds})\, A_{bl} = \dot{m}[(U_w)_{us} - (U_w)_{ds}] = \rho A_{bl}\,(U_w)_{bl}\,[(U_w)_{us} - (U_w)_{ds}] \qquad ...(5.11)$$

Solving Eqns. (5.10 and 5.11), we get:

$$\frac{1}{2}\rho\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] = \rho(U_w)_{bl}\,[(U_w)_{us} - (U_w)_{ds}]$$

or, $$(U_w)_{bl} = \frac{[(U_w)_{us} + (U_w)_{ds}]}{2} \qquad ...(5.12)$$

In a wind turbine system "*Speed flow work*", W, is equal to the difference in kinetic energy between upstream and downstream of turbine for unit mass flow, $\dot{m} = 1$. Therefore,

$$W = (K.E.)_{us} - (K.E.)_{ds}$$

or, $$W = \frac{1}{2}\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] \qquad ...(5.13)$$

The *power output 'P'* of wind turbine (rate of doing work) is given as:

$$P = \frac{1}{2}\dot{m}\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] = \dot{m}\left[\frac{(U_w)_{us}^2 - (U_w)_{ds}^2}{2}\right]$$

$$= \rho A_{bl}\left[\frac{(U_w)_{us} + (U_w)_{ds}}{2}\right]\left[\frac{(U_w)_{us}^2 - (U_w)_{ds}^2}{2}\right]$$

$$\left[\because \dot{m} = \rho A_{bl}\,(U_w)_{bl} = \rho A_{bl}\left\{\frac{(U_w)_{us} + (U_w)_{ds}}{2}\right\} \quad \text{...using Eqn. (5.12)}\right]$$

or, $$P = \frac{1}{4}\rho A_{bl}\,[(U_w)_{us} + (U_w)_{ds}]\left[(U_w)_{us}^2 - (U_w)_{ds}^2\right] \qquad ...(5.14)$$

To get P_{max} (maximum turbine output), differentiating Eqn. (5.14) w.r.t. $(U_w)_{ds}$ and equating to zero, we get:

$$\frac{dP}{d(U_w)_{ds}} = 3(U_w)_{ds}^2 + 2(U_w)_{us}\,(U_w)_{ds} - (U_w)_{us}^2 = 0$$

The above quadratic equation has the following *two solutions*.

$$(U_w)_{ds} = \frac{1}{3}(U_w)_{us} \quad \text{and} \quad (U_w)_{ds} = (U_w)_{us}$$

For power generation $(U_w)_{ds} < (U_w)_{us}$, so we can have only

$$(U_w)_{ds} = \frac{1}{3}(U_w)_{us} \qquad ...(5.14\ (a))$$

Substituting Eqn. (5.14 (*a*)) in Eqn. (5.14), we get:

$$P_{\max} = \frac{1}{4}\rho A_{bl}\left[(U_w)_{us} + \frac{1}{3}(U_w)_{us}\right]\left[(U_w)^2_{us} - \left\{\frac{1}{3}(U_w)_{us}\right\}^2\right]$$

$$= \frac{1}{4}PA_{bl}\left[\frac{4}{3}(U_w)_{us}\right]\left[\frac{8}{9}(U_w)^2_{us}\right]$$

or,
$$P_{\max} = \frac{8}{27}\rho A_{bl}\,(U_w)^3_{us} \qquad ...(5.15)$$

$$= \frac{16}{27}\left[\frac{1}{2}\rho A_{bl}\,(U_w)^3_{us}\right]$$

$$= 0.593\left[\frac{1}{2}\rho A_{bl}\,(U_w)^3_{us}\right]$$

Total power in the wind, stream, $P_{total} = \frac{1}{2}\rho A_{bl}\,(U_w)^3_{us}$ ...(5.15 (*a*))

$\therefore$ $P_{\max} = 0.593\, P_{total}$

Now, "*coefficient of power*", $C_P = \frac{P_{\max}}{P} = 0.593$ ...(5.16)

The factor **0.593** is known as **Blitz limit.**

5.16. CLASSIFICATION AND DESCRIPTION OF WIND MILLS/MACHINES

5.16.1. Classification of Wind Mills/Machines

The wind mills machines are *classified* as follows:

1. **Based on the type of rotor:**
   (*i*) Propeller type (horizontal axis)
   (*ii*) Multiblade type (horizontal axis)
   (*iii*) Savonius type (vertical axis)
   (*iv*) Darrieus type (vertical axis).
2. **Based on orientation of the axis of rotor*:***
   (*i*) Horizontal axis
   (*ii*) Vertical axis.

5.16.2. Description of Wind Mills/Machines

1. **Propeller type wind mill:** Refer to Fig. 5.7

These are *most commonly used wind mills*. Such a wind mill has *two or three* blades for *economical reasons*. Though the two blade design is *most efficient,* yet it faces the difficulty of *vibrations* during orientation to wind direction called '*Yaw control*'. These machines are rated from 1 to 3 MW.

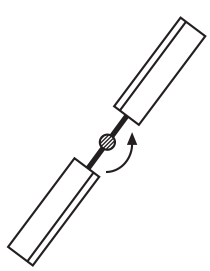

Fig. 5.7. Propeller type (two blade design).

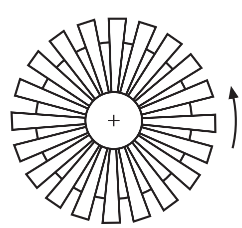

Fig. 5.8. Multiblade type.

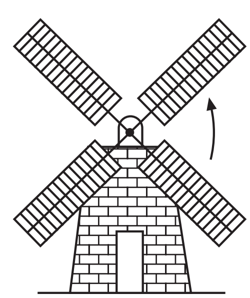

Fig. 5.9. Four-blade dutch wind mill.

2. **Multiblade type wind mill:** Refer to Figs. 5.8 and 5.9.

The multiblade wind turbines are *high solidity* turbines used for *pumping the water* because of *high starting torque characteristics.*

The multiblade rotors are *less efficient* because of interference of blades in each other but they are *less noisy*.

3. **Savonius type wind mill:** Refer to Fig. 5.10.

This type of wind mill has hallow circular cylinder sliced in half and the halves are mounted on vertical shaft with a gap in between. Torque is produced by pressure *difference* between the two sides of the half facing the wind.

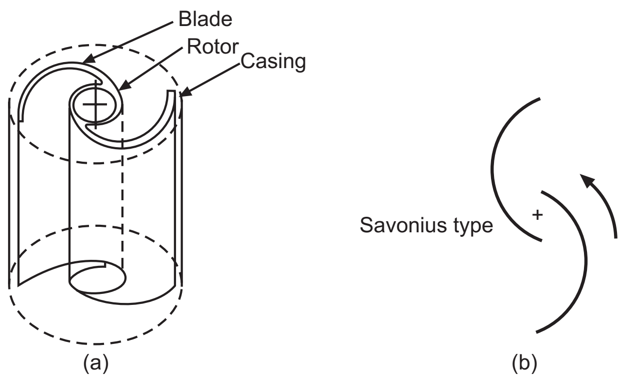

Fig. 5.10. Savonius type wind mill.

This is *quite efficience but needs a large surface area*.

Advantages:

1. Low cost.
2. Operation at low wind velocity.
3. No need of yaw and pitch control.
4. Generator can be mounted at the ground level.

Applications. It is useful for *grinding grains*, *pumping water* etc.

4. **Darrieus type wind mill :** Refer to Fig. 5.11.

- This wind mill *needs much less surface area.*
- It is shaped like an egg beater and has two or three blades shaped like airfoils.

***Characteristics of Darrieus rotor*:**

(*i*) Not self starting, needs auxiliary starter.
(*ii*) High speed.
(*iii*) High efficiency
(*iv*) Potentially low capital cost.

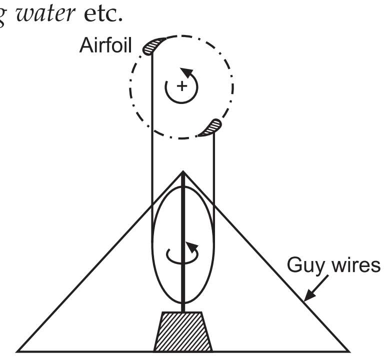

Fig. 5.11. Darrieus type wind mill.

Advantages:

(*i*) The generator, gear box etc. are placed on the ground.
(*ii*) No need of yaw mechanism to turn the motor against the wind.

It may be noted that:

- Both the Savonius and Darrieus types are mounted on a *vertical axis* and hence they *can run independently of the direction of wind*.

- The horizontal axis mills *have to face the direction of the wind* in order to generate power.

5. Horizontal axis wind machines :

Fig. 5.12 shows a schematic arrangement of a horizontal axis machine.

- Although the common wind turbine with a horizontal axis is *simple in principle*, yet the design of a complete system, especially a large one that would produce electric power economically, is *complex*.
- It is of paramount importance that the components like rotor, transmission, generator and tower should not only be as *efficient* as possible but they must also function *effectively in combination*.

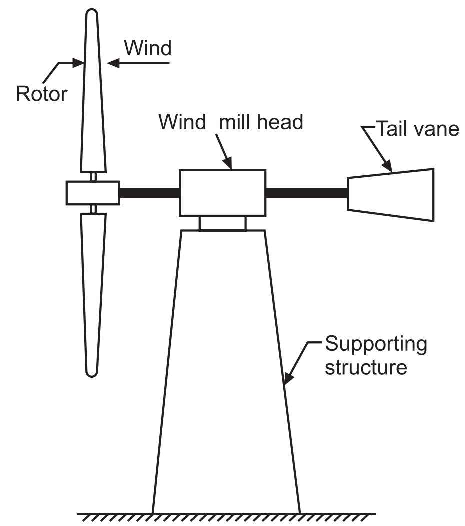

Fig. 5.12. Horizontal axis wind machine.

6. **Vertical axis wind machines :**

Fig. 5.13 shows vertical axis type wind machine.

- *One of the main advantages* of vertical axis rotors is that they do *not* have to be turned into the windstream as the wind direction changes, because their operation is independent of wind direction. These vertical axis machines are called *panemones*.

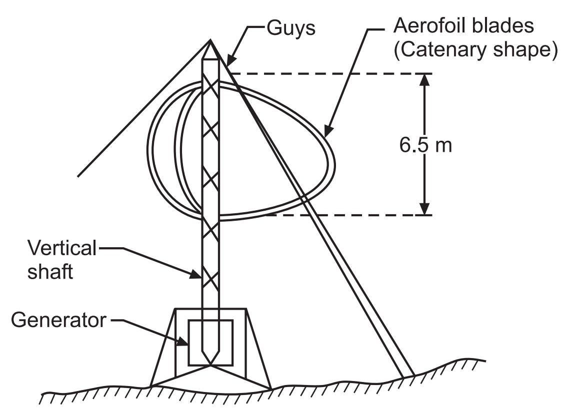

Fig. 5.13. Vertical axis wind machine.

Advantages of vertical axis wind machines:

1. The rotor is *not* subjected to continuous cyclic gravity loads since the blades do not turn end over end (Fatigue induced by such action is a major consideration in the design of large horizontal axis machines).
2. Since these machines would react to wind from any direction, therefore, they do *not* need yawing equipment to turn the rotor into the wind.
3. As heavy components (*e.g.* gear box, generator) can be located at ground level these machines may need *less* structural support.
4. The installation and maintenance are *easy* in this type of configuration.

Fig. 5.14 shows horizontal axis and vertical axis wind machines.

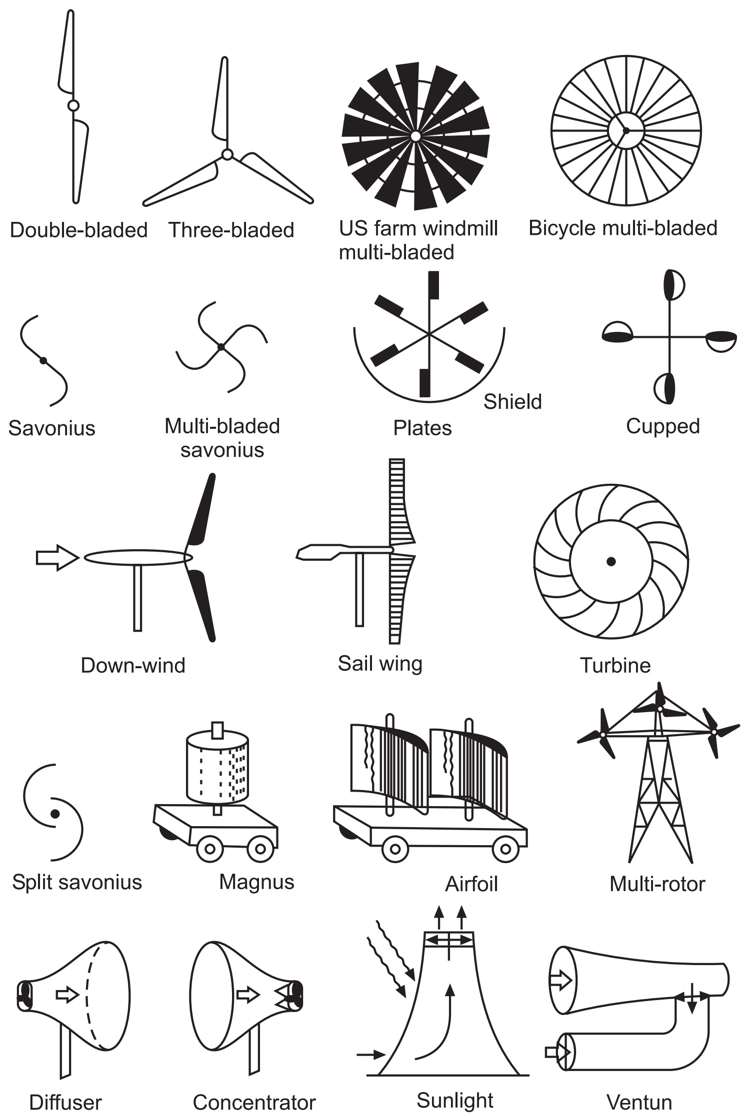

Fig. 5.14. Horizontal axis and Vertical axis wind machines. (Courtesy of DOE)

5.16.3. Blade Construction Methods

The major construction variations one finds while selecting a 'Wind energy conversion system (WECS)' generally will involve the blade. One popular blade material is *wood*, either laminated or solid, with or without fibreglass coatings, as shown in Fig. 5.15.

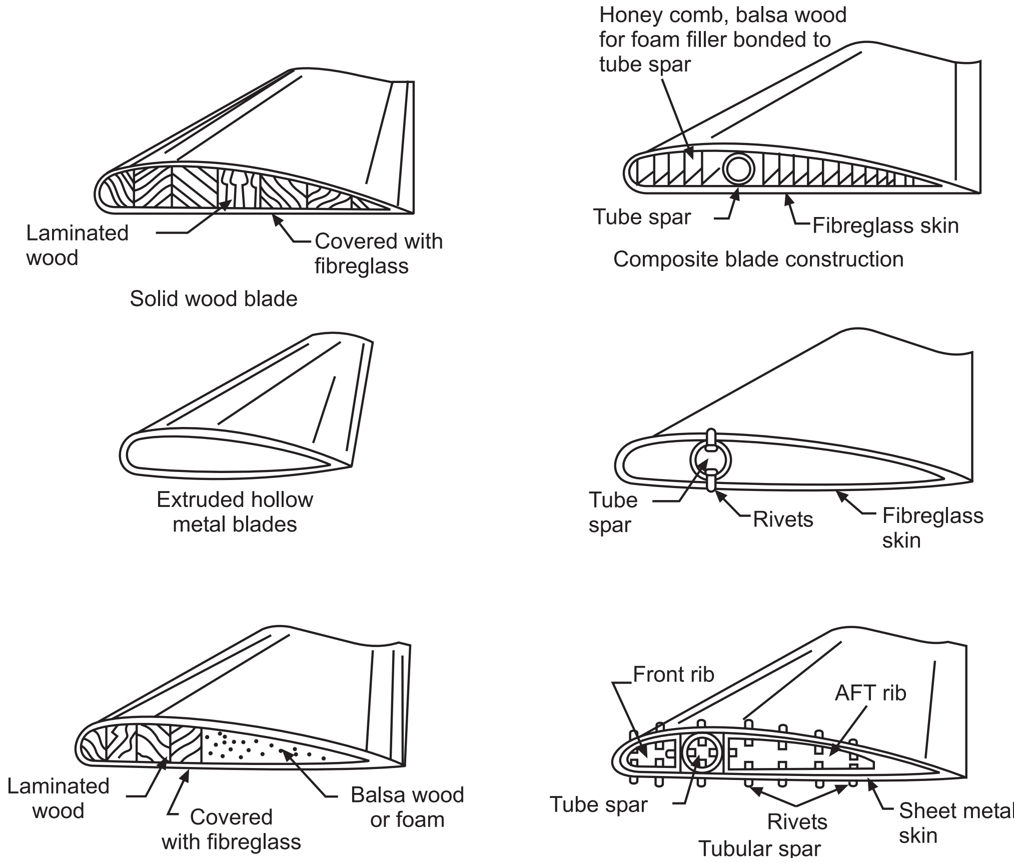

Fig. 5.15. Different blade construction methods (Courtesy of DOE).

5.16.4. Comparison between Horizontal axis and Vertical axis Wind Machines

S. No.	Aspects	Horizontal axis wind machines	Vertical axis wind machines
1.	*Power captured (for the same tower height)*	More	Less
2.	*Effect of fatigue (arising from numerous resonance in structure)*	No such problem arises	Suffer from fatigue effect
3.	*Appearance of the unwanted power periodicity*	Nil	Yes
4.	*Noise problem*	Less	More
5.	*Complexity of yaw mechanism*	Exists	No such problem arises
6.	*Complexity of design*	More	Less

5.16.5. Parameters to be Considered While Selecting a Wind Mill

The following *parameters* should be considered while selecting a wind mill/wind generator.

1. Low land cost.
2. The area should be open and away from cities.
3. Flat open area should be selected, as the wind velocities are high in flat open area.
4. The proposed altitude is to selected by taking average wind speed data.
5. Minimum wind speed should be available throughout the year.
6. Ground surface should be stable and have high soil strength.
7. It should be atleast 5 km away from the cities to reduce the effect of sound pollution.
8. The wind power should be near the customers, so that the transmission losses are minimised.
9. Approach road should be available upto site.

5.16.6. Design Considerations for Wind Turbine

The wind turbine must be able to meet the following *design considerations/criteria.*

1. It should be *small in size* and *suitable for roof mounting in urban area*.
2. *No riks* for its neighbourhood.
3. The efficiency should be good.
4. *Insensitive* to *turbulence*.
5. Suitable for *mass production for low price*.

5.16.7. Performance of Wind Mills

The performance of a wind mill is defined as '*Co-efficient of performance*'(C_p)

$$C_p = \frac{\text{Power delivered by the rotor}}{\text{Maximum power available in the wind}}$$

or
$$C_p = \frac{P}{P_{max}} = \frac{P}{\frac{1}{2}\rho A U_w{}^3} \quad ...(5.17)$$

where, p = Density of air,

A = Swept area, and

U_w = Velocity of wind.

Fig. 5.16 shows a plot between C_p and tip speed ratio ($TSR = U_{bt}/U_w$)
where, U_{bt} = Speed of blade tip.

It can be seen that C_p is the *lowest of Savonius* and *Dutch types* whereas the *propeller types have the highest value.*

In the designing of wind mills, it is upper most to keep the *power to weight ratio at the lowest possible level.*