UNIT – 3

Wind Energy

- Important Repeated Questions

3.1 Introduction

3.2 Power in Wind

3.3 Power extraction from wind

3.4 Example

3.5 Basic Components of a wind energy conversion system (WECS)

3.6 Design Consideration

3.7 Site Selection Consideration

3.8 Wind Energy Development in India

Important Repeated Questions:

1. **Explain basics of lift and drag in wind turbines.**
    - Appeared in: W23 (Q3b, 04 marks), S23 (Q2a, 03 marks), S22 (Q3b, 04 marks)
2. **Explain solidity, tip speed ratio, power coefficient for wind mill.**
    - Appeared in: W23 (Q3a OR, 03 marks), S22 (Q3a, 03 marks), W24 (Q3a, 03 marks)
3. **Explain horizontal axis vs vertical axis wind turbines.**
    - Appeared in: W24 (Q4a, 03 marks), S23 (Q3b, 04 marks)
4. **Explain site selection criteria for wind energy conversion system.**
    - Appeared in: W25 (Q3b OR, 04 marks), S24 (Q3b, 04 marks)

Wind Basics & Components

1. **What is wind? Classify wind mills.**
    - Appeared in: W24 (Q4a, 03 marks), S24 (Q4a, 03 marks)
2. **Explain yaw control and pitch control mechanisms.**
    - Appeared in: S25 (Q3b, 04 marks), W22 (Q3b, 07 marks part)

Wind Performance & Theory

1. **Derive expression for maximum power, torque, axial thrust from wind turbine.**
    - Appeared in: W22 (Q1c, 07 marks), S25 (Q3c, 07 marks)
2. **Prove maximum turbine output when $V_e = V_i/3$.**
    - Appeared in: W23 (Q3c, 07 marks), S22 (Q3c, 07 marks)

Wind Applications & Environment

1. **Explain safety and environmental aspects of wind energy.**
    - Appeared in: W25 (Q3c OR, 07 marks)
2. **How does wind energy reduce greenhouse gas emissions?**
    - Appeared in: W24 (Q2a, 03 marks)

Legends: W- Winter, S- Summer, Q- Question and 03/04/07- Marks of Question

3.1 INTRODUCTION

- Wind is essentially air in motion, which carries with it kinetic energy.
- The amount of energy contained in the wind at any given instant is proportional to the wind speed at that instant.
- Wind results primarily by unequal heating of the earth's surface by the sun.
- About 2% of the total solar flux that reaches the earth's surface is transformed into wind energy.
- Solar energy meets clouds, uneven surfaces, and mountains while reaching the earth.
- This unequal heating causes temperature, density, and pressure differences on the earth's surface that are responsible for local wind formation.
- During daytime, the air over the land mass heats up faster than the air over the oceans. Hot air expands and rises while cool air from oceans rushes to fill the space, creating local winds.
- At night the process is reversed as the air cool more rapidly over land than water over off-shore land, causing breeze.
- On a global scale, the primary force for global winds is developed due to differential heating of the earth at equatorial and Polar Regions.

3.2 POWER IN 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 of the energy and convert it into useful work.
- Three factor determine the output from a wind energy converter:
  - The wind speed
  - The cross-section of wind swept by rotor
  - The overall conversion efficiency of the rotor, transmission system and generator or pump.
- Wind mill/turbine converts the kinetic energy of the wind into mechanical energy.
- The total power of the wind stream is equal to the time rate of kinetic energy.

$$K.E. = \frac{1}{2} mV^2$$

- The amount of air passing in unit time through an area A with velocity V

$$= A.V \ m^3/s$$

∴ Mass flow rate of air m =ρ A • V

Where, ρ is the density of air.

$$K.E. = \frac{1}{2} (\rho AV)V^2$$

$$= \frac{1}{2} \rho A.V^3 \text{ J/s}$$

$$\therefore \text{Total power}, P_t = \frac{1}{2} \rho A.V^3 \text{ Watts}$$

- This equation 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.
- Wind velocities below 5 m/s and above 25 m/s are not suitable for wind turbine.
- Wind power is proportional to the intercept area. Thus, wind turbine with a large swept area has higher available power.
- Normally, area is circular with diameter D, Thus

$$A = \frac{\pi}{4} D^2$$

$$P_t = \frac{1}{2} \rho . \frac{\pi}{4} D^2.V^3$$

$$P_t = \frac{\pi}{8} \rho .D^2.V^3$$

- It is clear that power is proportional to the square of the diameter of swept area.
- The total wind power density is defined as the total wind power per unit area of wind stream.

$$\rho = \frac{P_t}{A}$$

Effects of wind speed and rotor diameter on wind power

- Wind machines intended for generating substantial amount of power should have large rotor and be located in areas of high wind speeds.

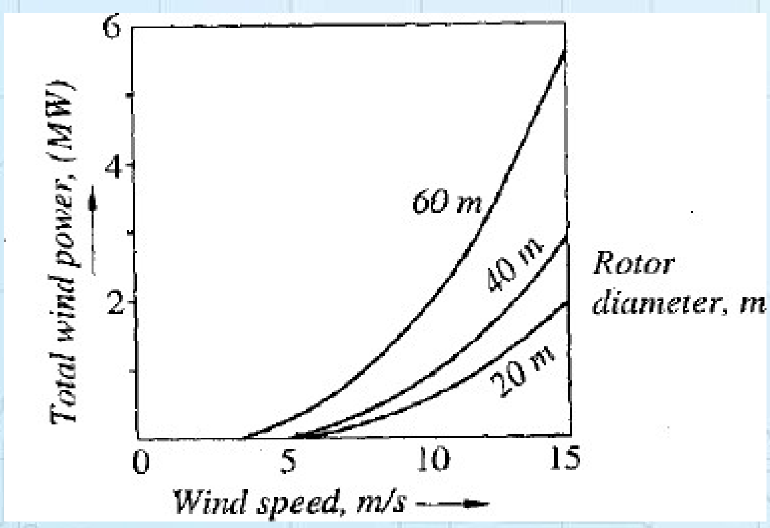

Fig 4.1 Effects of wind speed and rotor diameter on wind power

Power coefficient

- The fraction of the free-flow wind power that can be extracted by a wind turbine rotor is called the power coefficient.
  Mathematically,

$$\text{Power co-efficient} = \frac{\text{Power of wind turbine}}{\text{Power available in the wind}}$$

- The maximum theoretical power coefficient is equal to 0.593.

3.3 POWER EXTRACTION FROM WIND

- Wind turbines extract energy from wind stream by converting the kinetic energy of the wind to rotational motion required to operate an electric generator.
- The velocity of the flowing wind decreases due to conversion of kinetic energy into shaft power.
- It is assumed that the mass of air which passes through rotor is only affected and remains separate from the air which does not pass through the rotor.
- As the free wind interacts with the turbine rotor, the wind transfer part of its energy into the rotor and the speed of the wind decreases to a minimum leaving a trail of disturbed wind called wake. The variation in velocity is considered to be smooth from far upstream to far downstream.
- Wind flow is considered incompressible and hence the air stream flow diverges as it passes through the turbine. Also the mass flow rate of wind is assumed constant at far upstream, at the rotor and at far downstream.

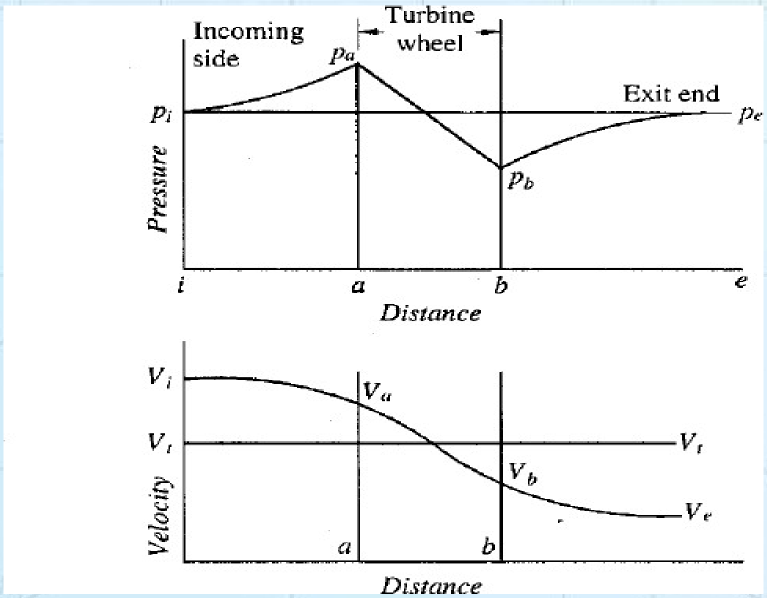

Fig 4.2 Pressure and velocity curve of wind

– Most commonly used wind turbine is horizontal axis, propeller type. Consider this wind turbine,

Let,

a = Inlet plane,
b- Exit plane,
P_i - Incoming wind pressure,
V_i =Incoming wind velocity, P_e - Wind pressure at exit e, V_e = Wind velocity at exit e, v = Specific volume = 1/ρ.

$V_i > V_e$

Applying total energy equation, considering flow energy and kinetic energy of wind

$$u_1 + p_i.v + \frac{V_i^2}{2g} + Z_1 + \Delta q = u_2 + p_a.v + \frac{V_a^2}{2} + Z_2 + \Delta w$$

Where,

Z=potential energy =0
$\frac{V_i^2}{2g}$ = kinetic energy
u= internal energy =0
$p.v$=flow energy
Δq=net heat added=0
Δw=net work done=0
g=1 m²/s

Therefore,

$$p_i.v + \frac{V_i^2}{2} = p_a.v + \frac{V_a^2}{2}$$

$$p_i + \frac{V_i^2}{2v} = p_a + \frac{V_a^2}{2v}$$

$$p_i + \frac{\rho V_i^2}{2} = p_a + \frac{\rho V_a^2}{2}$$

Similarly, for exit area

$$p_e + \frac{\rho V_e^2}{2} = p_b + \frac{\rho V_b^2}{2}$$

The wind velocity decreases from a to b, because kinetic energy is converted to mechanical work.

Therefore,

$$V_i > V_a, V_b > V_e \quad \text{and} \quad p_a > p_i, p_b < p_e$$

$$p_a - p_b = \left(p_i + \rho\frac{V_i^2 - V_a^2}{2}\right) - \left(p_e + \rho\frac{V_e^2 - V_b^2}{2}\right)$$

Assume that at exit end away from the turbine at e, can be assumed to ambient i.e. $P_e = P_i$ and $V_t = V_a = V_b$

$$p_a - p_b = \rho.\left(\frac{V_i^2}{2} - \frac{V_e^2}{2}\right)$$

$$p_a - p_b = \rho.\left(\frac{V_i^2 - V_e^2}{2}\right)$$

If 'A' is the projected area of wind turbine perpendicular to the wind stream, the axial force F is given by

$$F_X = (p_a - p_b)A = \rho A\left(\frac{V_i^2 - V_e^2}{2}\right)$$

But, Axial force also equal to the change of momentum

$$F_X = \dot{m}.\Delta V$$

$$F_X = \rho A V_t (V_i - V_e)$$

By equating the equations,

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

$$\left(\frac{V_i^2 - V_e^2}{2}\right) = V_t (V_i - V_e)$$

$$\frac{(V_i + V_e)(V_i - V_e)}{2} = V_t (V_i - V_e)$$

Now consider the total thermodynamic system bounded by i and e.

$$w = KE_i - KE_e = \frac{V_i^2 - V_e^2}{2}$$

Power 'P' is defined as rate of work done.

$$P = \dot{m}\frac{V_i^2 - V_e^2}{2} = \rho A V_t \frac{V_i^2 - V_e^2}{2}$$

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

$$P = \frac{1}{4}\rho A\left(V_i + V_e\right)\left(V_i^2 - V_e^2\right)$$

For maximum power, $\frac{dp}{dV_e} = 0$

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

$$(3V_e - V_i)(V_e + V_i) = 0$$

By Solving,

$$V_e = -V_i \text{ and } V_e = \frac{1}{3}V_i$$

$V_e = \frac{1}{3}V_i$ is the only physically acceptable $(\because V_e \neq -V_i)$

Thus,

$$\left(V_e\right)_{opt} = \frac{1}{3}V_i \rightarrow \text{Optimum exit velocity}$$

– This is the condition for maximum power.

Maximum power

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

Ideal or maximum theoretical efficiency / power coefficient (CP)

$$\eta_{max} = \frac{P_{max}}{P_{total}} = \frac{\frac{8}{27}\rho A V_i^3}{\frac{1}{2}\rho A V_i^3}$$

$$\eta_{max} = \frac{16}{27} = 0.593$$

The factor 0.593 is known as Bets limit.

Forces on blades and thrust on turbine

– The circumferential force or torque causing the rotation of the wind turbine shafts depends on the turbine rated power output and rotor angular velocity.

$$T = \frac{P}{\omega} = \frac{P}{\pi DN}$$

Where,

T=torque, Nm

ω=angular velocity of turbine wheel, rad/s

N=rotational speed of shaft, rpm

D=diameter of turbine wheel in m

Efficiency is given by

$$\eta = \frac{P}{P_t}$$

$$\therefore P = \eta P_t = \eta \frac{1}{8} \rho \pi D^2 V_i^3$$

Substituting the values in equation…..

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

But, maximum efficiency (η= 16/27)

$$T_{max} = \frac{16}{27} \cdot \frac{1}{8} \cdot \frac{\rho D V_i^3}{N}$$

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

Axial force or thrust

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

$$= \rho \left(\frac{\pi}{4} D^2 \right) \left(\frac{V_i^2 - V_e^2}{2} \right)$$

$$F_x = \frac{\pi}{8} \rho D^2 \left(V_i^2 - V_e^2 \right)$$

The condition for maximum efficiency is

$$\text{But}, V_e = \frac{1}{3} V_i$$

$$\therefore F_{x\,max} = \frac{\pi}{8} \rho D^2 \left[V_i^2 - \left(\frac{V_i}{3} \right)^2 \right]$$

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

– From above equation, it is clear that axial forces are proportional to the square of the diameter of the turbine wheel, this limits turbine wheel diameter of large size.

3.4 EXAMPLE

1. **A propeller type, horizontal shaft wind turbine has diameter of 80 m and its operating speed is 40 rpm at maximum efficiency. Wind at 1 bar and 25°C has a velocity of 10 m/s.**

- Calculate :

I. Total power density in the wind stream.
II. maximum obtainable power density,
III. a reasonable obtainable power density assuming η= 35%,
IV. total power produced, and
V. Torque and the axial thrust produced at maximum efficiency.

Solution:

Given: D = 80 m, N = 40 rpm, p = 1 bar, T =25°C = 298 K, V_i = I0m/s, η=35%

Density of air is given by

$$\rho = \frac{p}{RT} = \frac{1 \times 10^5}{287 \times 298} = 1.169 \text{ kg/m}^3$$

I. Total power density in the wind stream:

$$\text{Total power}, P_t = \frac{1}{2} \rho A . V_i^3$$

$$\text{Power density} = \frac{P_t}{A} = \frac{1}{2} \rho . V_i^3 = \frac{1}{2} \times 1.169 \times (10)^3$$

$$= 584.5 \text{W/m}^2$$

II. Maximum power density:

$$\text{MaximumPower density} = \frac{P_{max}}{A} = \frac{8}{27} \rho . V_i^3$$

$$= \frac{8}{27} \times 1.169 \times (10)^3$$

$$= 346.37 \text{W/m}^2$$

III. A reasonable obtainable power density:

$$\frac{P}{A} = \eta \frac{P_t}{A} = 0.35 \text{x} 584.5 = 204.575 \text{W/m}^2$$

IV. Total power produced:

P = Power density x Area

$$= 204.575 \times \frac{\pi}{4} (D)^2 = 204.575 \times \frac{\pi}{4} (80)^2$$

$$= 1028.3 \text{x} 10^3 \text{ W} = 1028.3 \text{kW}$$

V. Torque and axial thrust:

$$T_{max} = \frac{2}{27}\cdot\frac{\rho D V_i^3}{N} = \frac{2}{27}\cdot\frac{1.169 \times 80 \times 10^3}{40/60}$$

$$= 10391.11 \text{N.m}$$

$$F_{x\,max} = \frac{\pi}{9}\rho D^2 V_i^2 = \frac{\pi}{9} \times 1.169 \times (80)^2 (10)^2$$

$$= 261157.1 \text{ N}$$

2. **The following data refer to a wind mill of a wind farm in Gujarat. Average wind speed = 23.5 km/hr, Atmospheric pressure = 1.01 bar, Atmospheric temperature =30°C, Power coefficient = 0.41, Total power output capacity of wind farm = 1 MW.**

- Determine :

I. Available power density of wind,

II. Actual power density of wind mill,

III. Number of wind mills in the farm if the rotor diameter is 25 m.

Solution:

Given data:

V_i = 23.5 km/hr= 6.53 m/s, p= 1.01 bar, T= 30°C = 303 K, C_p = 0.41,

Total capacity = 1 MW, D = 25 m

Density of air is given by

$$\rho = \frac{p}{RT} = \frac{1.01 \times 10^5}{287 \times 303} = 1.161 \text{kg/m}^3$$

(i) Available power density of wind:

$$\text{Power density} = \frac{P_t}{A} = \frac{1}{2}\rho . V_i^3 = \frac{1}{2} \times 1.161 \times (6.53)^3$$

$$= 161.637 \text{W/m}^2$$

(ii) Actual power density of wind mill:

$$\text{Actual power density} = \frac{P}{A} = C_p \times \frac{P_t}{A}$$

$$= 0.41 \times 1.161.637 = 66.27 \text{ W/m}^2$$

(iii) Number of wind mills:

Power developed by wind mill, P= Actual power density x area

$$= 66.27 \times \frac{\pi}{4} D^2 = 66.27 \times \frac{\pi}{4} \times 25^2$$

$$= 32530.21 \text{ W}$$

$$\text{No. of windmills} = \frac{\text{Totalcapacity of wind farm}}{\text{Power developed by one windmill}}$$

$$= \frac{1\text{x}10^{6}}{32530.21} = 30.74$$

$$\approx 31$$

3.5 BASIC COMPONENTS OF A WIND ENERGY CONVERSION SYSTEM (WECS)

– The main components of a wind energy conversion system (WECS) in the form of block diagram.

– A wind energy conversion system converts wind energy into some form of electrical energy. In particular, medium and large scale WECS are designed to operate in parallel with a utility AC grid. This is known as a grid-connected system. A small system, isolated from the id, feeding only to a local load is known as autonomous or isolated power system.

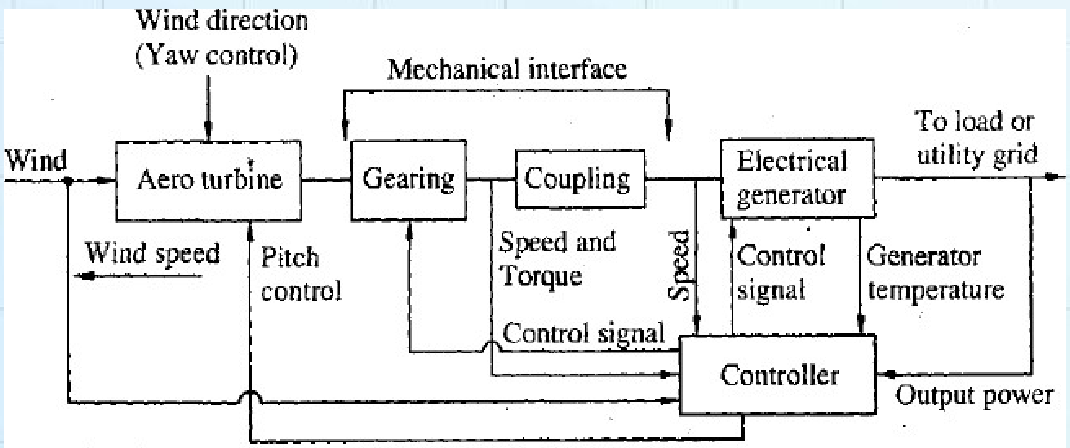

Fig 4.3 wind energy conversion system

Types of wind mills

1. According to orientation of the axis of rotor

- Horizontal axis: When the axis of rotation is parallel to the air stream (i.e. horizontal), the turbine is said to be a Horizontal Axis Wind Turbine (HAWT).
- Vertical axis: When the axis of rotation is perpendicular to the air stream (i.e. vertical), the turbine is said to be a Vertical Axis Wind Turbine (VAWT)

2. According to useful electrical power output

- Small output: up to 2 kW
- Medium output: 2 to 100 kW output
- Large output: More than 100 kW output

3. According to type of rotor

- Propeller type: It is horizontal axis high speed rotor.

- Multiple blade type: It is horizontal axis low speed rotor.
- Savonius type: It is vertical axis rotor.
- Darrieus type: It is vertical axis rotor.

3.4.1. Horizontal Axis Wind Turbine (HAWT)

– Horizontal axis machines have emerged as the most successful type of turbines. These are being used for commercial energy generation in many parts of the world.

– They have low cut-in wind speed, easy furling and, in general, show high power coefficient.

– However, their design is more complex and expensive as the generator and gear box are to be placed at the top of the tower. Also, a tail or yaw drive is to be installed to orient them in the wind direction.

– Main components:
  1. Turbine blades
  2. Hub
  3. Nacelle
  4. Power transmission system
  5. Generator
  6. Yaw control
  7. Brakes
  8. Tower

1. Turbine blades

– Wind turbine blades need to be light weight and possess adequate strength and hence require to be fabricated with aircraft industry techniques.

– The blades are made of glass fibre reinforced plastic (F.R.P.). They have an aerofoil type of cross section to create lift as the air flows over them.

– The blades are slightly twisted from the outer tip to the root to reduce the tendency to stall.

– In addition to centrifugal force and fatigue due to continuous vibration, there are many extraneous forces arising from wind turbulence, gust, gravitational forces and directional changes in the wind. All these factors have to be considered at the designing stage.

– The diameter of a typical, MW range, modern rotor may be of the order of 100m.

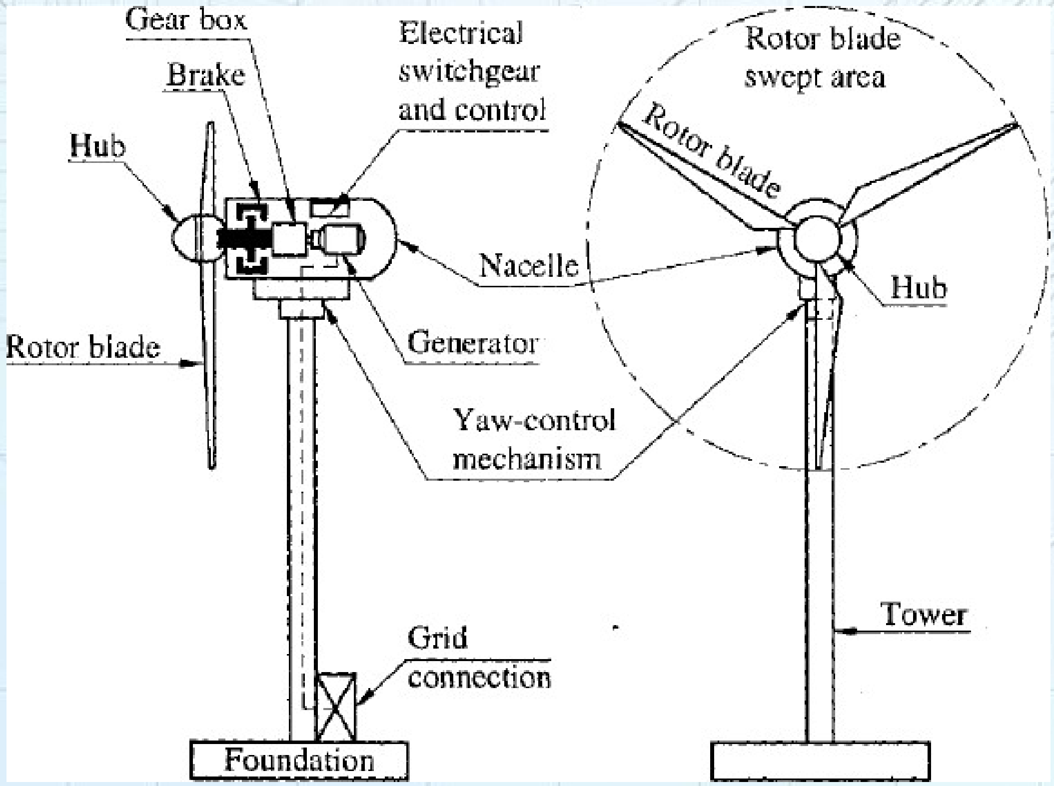

Fig 4.4 Horizontal Axis Wind Turbine

- Modern wind turbines have two or three blades.
- Two or three blade rotor HAWT are also known as propeller type wind turbine. Three blades are more common in Europe and other developing countries including India. The American practice, however, is in favour of two blades.

2. Hub

- A hub is the central solid portion of the rotor wheel. All blades are attached to the hub. The pitch angle control mechanism is also provided inside the hub.

3. Nacelle

- It houses the generator, the gear box, brakes, hydraulic system, and the yawing mechanism. Nacelle is placed at the top of the tower and is linked with the rotor.

4. Power transmission system

- Mechanical power generated by rotor blades is transmitted to the generator through a gear box. From the gear box, the transmission shaft rotates the generator with a built-in friction clutch. The gear box is provided to increase the speed to suit the generator.
- The generated electrical power is conducted to ground terminals through a cable.

5. Generator
- Generally, the grid connected large wind turbines have induction generators. They use reactive power from grids and feed the generated power to boost the grid supply.
- Medium capacity wind turbines use synchronous generators installed to electrify villages and remote places.
- Small capacity wind turbines use permanent magnet DC generators which supply power to microwave stations and illuminating light houses.

6. Yaw control
- Yaw control continuously tracks and keeps the rotor axis in the wind direction. Yawing is done by two yawing motors, which mesh with a big-toothed wheel mounted on top of the tower. Wind direction sensor is used to maintain the orientation.
- During high speed wind, i .e. more than the cut-out speed, the machine is stopped by turning the rotor axis at right angles to the wind direction. In small wind turbines, a tail vane is used for passive yaw control.

7. Brakes
- Brakes are used to stop the rotor when power generation is not desired. An emergency stop activates the hydraulic disc brakes fitted to the high speed shaft of the gear box.

8. Tower
- The tower supports the nacelle and rotor. Modern wind turbine generators are instal led on tubular towers.
- Both steel and concrete towers are being used.

Types of rotors
- The rotors for HAWT have been developed in various types of shapes and sizes depending on wind speed and nature of application.
- Propeller type, high speed wind turbine rotors is shown in Fig. They are suitable for applications such as electrical power generation. The rotational speeds of propeller type are in the range of 300-400 rpm. Large HAWTs have been manufactured with two and three blades as discussed earlier.
- A single blade rotor, with a balancing counterweight is economical, has simple controls but it is noisier and produces unbalanced forces. It is used for low-power applications.

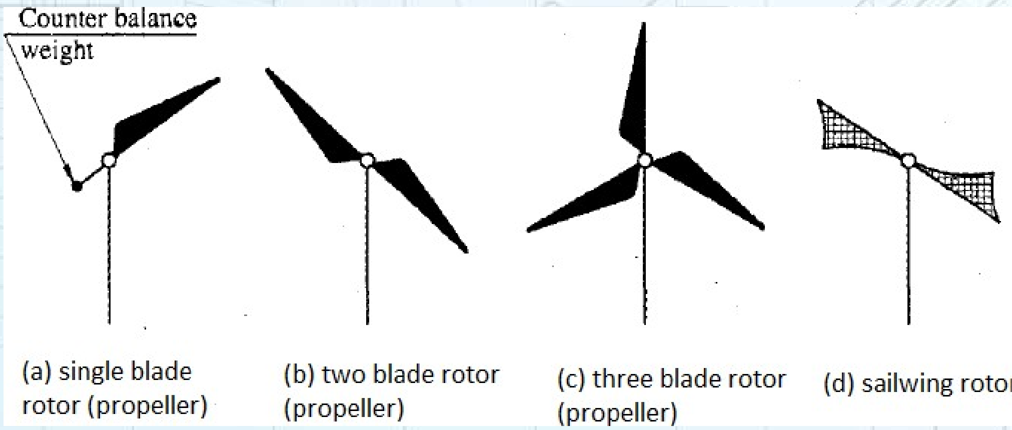

Fig 4.5 Rotor blade

- Sailwing rotor blade surfaces are made from cloth, nylon or plastics arranged as mast and pole. There is also variation in the number of sails used.
- Low speed wind turbine rotors are shown in Fig. They are most suited for water lifting applications which require a high starting torque. They can capture power even from very slow winds.

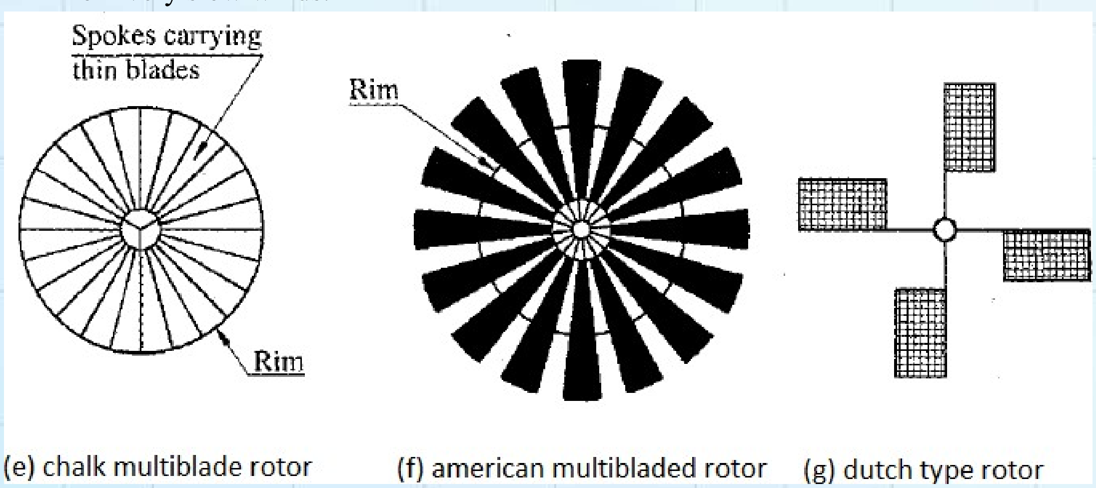

Fig 4.6 Multiblade rotor

- Multiblade rotor consists of number of curved sheet metal blades with increasing chord length away from the centre. Numbers of blades used are 12 to 20 which having their inner and outer ends fixed on to the respective rims. The speeds of multiblade type wind turbine rotors are 60 to 80 rpm.
- They have good power coefficient, high starting torque and added advantage of simplicity and low cost.
- Dutch type rotor is one of the oldest designs. The blade surfaces are made from an ray of wooden slats which feather at high wind speeds.

Pitch control system

- The pitch of a blade is controlled by rotating it from its root, where it is connected to the hub.
- The pitch control mechanism is provided through the hub of the rotor using hydraulic jack in the nacelle.
- The controller continuously adjusts the pitch to obtain the optimum performance.
- Thereby the power and speed of the wind turbine shaft is adjusted to match with the generator speed and its electrical output.

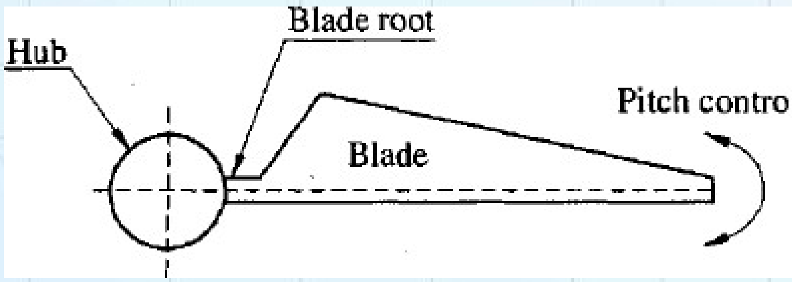

Fig 4.7 Pitch control

3.4.2. Vertical Axis Wind Turbine (VAWT)

- Vertical axis wind turbine (VAWT) is also known as cross-wind axis machines.
- In these machines, the axis of rotation is perpendicular to the direction of the wind.
- The main advantages of a VAWT compared to HAWT are:
  1. The vertical axis wind turbine receives wind from any direction, and hence the yawing system is not required.
  2. The generator, gearbox, etc. can be installed at the bottom of the tower, hence their tower design and installation is simple.
  3. The inspection and maintenance is easier.
  4. They are lighter in weight and cheaper in cost.
- VAWTs are generally not self starting and have low power coefficient, these are the major disadvantages. They require a mechanism to start from the stationary position. Additionally, there is a possibility of running the blades at very high speed and causing damage to the system.
- Main components:
    1. Rotor shaft or Tower
    2. Blades
    3. Support structure

1. Rotor shaft or Tower
– The tower is a hollow vertical rotor shaft, which rotates freely about the vertical axis between the top and bottom bearings. It is installed above a support structure. In the absence of any load at the top, a very strong tower is not required, which greatly simplifies its design.
– The upper part of the tower is supported by buy ropes. The height of the tower of a large turbine is around 100 m.
2. Blades
– It has two or three thin and curved blades. The blades are shaped like an eggbeater in a profile. The blades have an airofoil cross section with constant chord length. The pitch of the blades cannot be changed. The diameter of the rotor is slightly less than the tower height.
3. Support structure
– The support structure is provided at the ground to support the weight of the rotor.
– Generator, gear box, brakes, controls, and electrical switchgear are housed within this structure.
– Guy ropes are attached to the top for support.

Types of rotors

- The vertical axis rotors can be either drag or lift based.
- The drag based devices have relatively high starting torques compared to lift devices, but have relatively low tip to wind speed ratio and lower power outputs for a given rotor size. The important vertical axis rotors are described below.

1. Savonious rotor

- This type was invented by S.J. Savonius in the year 1920.
- This rotor consists of two half cylindrical or elliptical blades arranged in an 'S' shape .
- It is also known as S-rotor.
- The rotor works on drag force produced by the blades
- It has high starting torque, low speed and low efficiency
- It can extract power even from very slow wind, making it working most of the time.
- These are used for low power applications.
- Suitable for pumping application due to high starting torque.

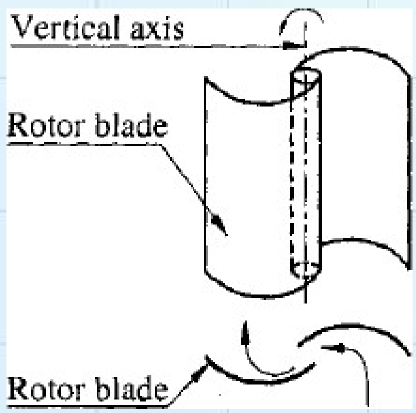

Fig 4.8 Savonius rotor

2. Darrieus rotor

- The Darrieus rotor was invented by Georges Jeans Darrieus.
- This rotor works due to the lift force produced by a set of airofoils.
- The blades are shaped like a troposkein profile (turning rope), which minimizes the bending stress caused by centrifugal forces.
- The Darrieus rotor is used for large scale power generation.
- Its power coefficient is considerably better than that of an S-rotor.
- This machine is not self starting, it can be started by using electrical generator as motor.
- At high wind speed it becomes difficult to control the output because the pitch of the blade cannot be changed.

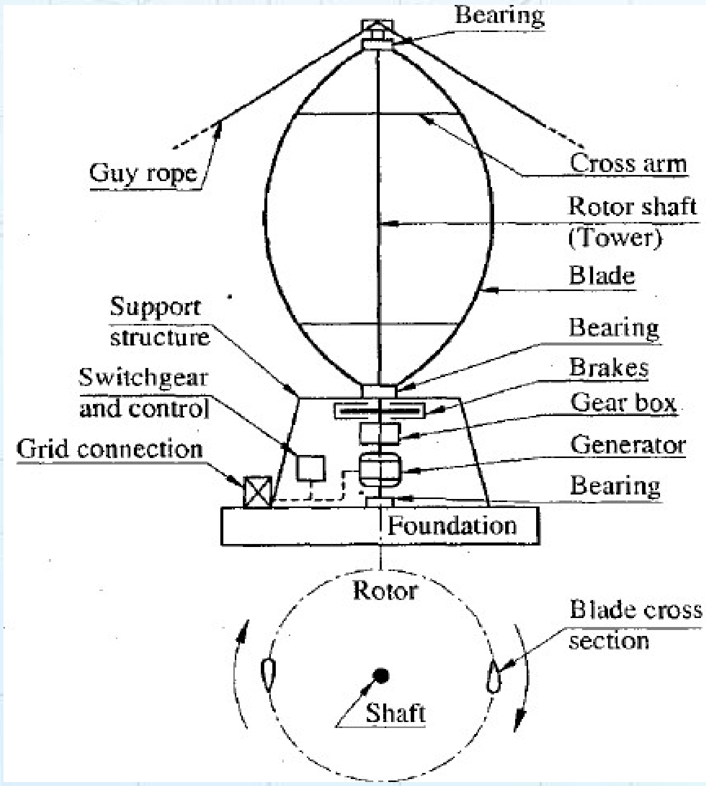

Fig 4.9 Darrieus type rotor

Comparison

Horizontal axis turbine	Vertical axis turbine
1. Axis of rotation is parallel to the air stream	1. Axis of rotation is perpendicular to the air stream.
2. Yaw control mechanism is required to adjust the rotor around vertical axis to keep it facing the wind.	2. No orientation of rotor is required; these turbines can generate power with the wind coming from any direction.
3. The heavy nacelle containing the gearbox, generator, etc. is mounted at the top of the tower, thus the design and installation is complex.	3. The nacelle is not required because the gearbox, generator, etc., are located at the ground, thus the design and installation is simple.
4. The power coefficient and tip speed ratio are high.	4. The power coefficient and tip speed ratio are considerably low.

5. The rotor is mounted at the top of high tower, it experience higher velocity wind. This yields more energy output	5. The rotor is generally mounted near ground proximity, it experience lower velocity wind. This yields less energy output.
6. Suitable for large scale power generation.	6. Suitable for small scale power generation and pumping applications.
7. Initial and maintenance cost are high.	7. Initial and maintenance cost are low.

3.6 DESIGN CONSIDERATION

- The fundamental design goal is to keep the cost of power lower than that from the turbine of the available design.
- Parameters: Power coefficient (C_p) , Tip speed ratio (λ), Solidity(σ)
- The wind turbine may be exposed to severe and unpredictable environmental conditions due to which its rotor design becomes complicated. The general procedure starts with identification of various rotor parameters and the choice of an airofoil. Then an initial blade shape is found using an optimum blade shape and assuming wake rotation. The final blade shape and performance are obtained iteratively based on drag, tip losses and ease of manufacture.
- The power P needed at a particular wind speed V_i is to be decided first. Also, the value of C_p and overall efficiency η for various components are to be predicted. The value of C_p for a well designed system is in the range of 0.4 to 0.45 and r^ may be taken as 0.9 for the combined drive train and generator.
- Power P obtained is given by,

$$P = C_P \cdot \eta \cdot P_t$$

$$\therefore P = C_P \cdot \eta \cdot \left(\frac{\pi}{8} \rho D^2 V_i^3 \right)$$

∴ Diameter of rotor

$$\therefore D = \sqrt{\frac{8P}{C_P \eta \rho \Pi V_i^3}}$$

Maximum torque T on a turbine rotor

$$T_{\max} = F_{\max} \times \frac{D}{2} = F_{\max} \cdot R$$

But,

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

$$\therefore T_{max} = \frac{1}{2}\rho A.V_i^2 R$$

For a wind turbine producing a shaft torque T, the torque coefficient C_T is defined by $C_T = T/T_{max}$

or

$$T = C_T \, .T_{max}$$

- The tip speed ratio (λ) is defined as the ratio of the blade's outer tip speed Vt to the upstream (free) wind speed Vi.

Mathematically,

$$\lambda = \frac{V_t}{V_i} = \frac{\omega R}{V_i}$$

$$\therefore T_{max} = \frac{\rho A.V_i^2}{2}\left(\frac{\lambda V_i}{\omega}\right) = \frac{1}{2}\rho A.V_i^3\left(\frac{\lambda}{\omega}\right)$$

$$\therefore T_{max} = P_t\left(\frac{\lambda}{\omega}\right)$$

- The shaft power (P)

$$P = T.\omega = C_T T_{max}\omega$$

- But Power,

$$P = C_P P_t$$

$$C_P P_t = C_T T_{max}\omega = C_T P_t\left(\frac{\lambda}{\omega}\right)\omega$$

$$\therefore C_P = \lambda C_T$$

- From the Betz criterion the maximum value of Cp is 0.593

$$\therefore C_T)_{max} = \frac{C_P}{\lambda} = \frac{0.593}{\lambda}$$

- The tip speed ratio (λ) is chosen according to the type of application. E.g.
  - Water pumping wind turbine $1 < \lambda < 3$ is used.
  - Wind-electric generators have λ in the range $4 < \lambda < 10$.

- The number of blades can be chosen from the Fig., which represents number of blades for different values of λ. Curved blades can be used as airofoil if $\lambda < 3$ and more aerodynamic shape is required for $\lambda > 3$.
- The tip speed ratio at optimum power extraction is given by

$$\lambda = \frac{4\Pi}{\text{Number of blade}}$$

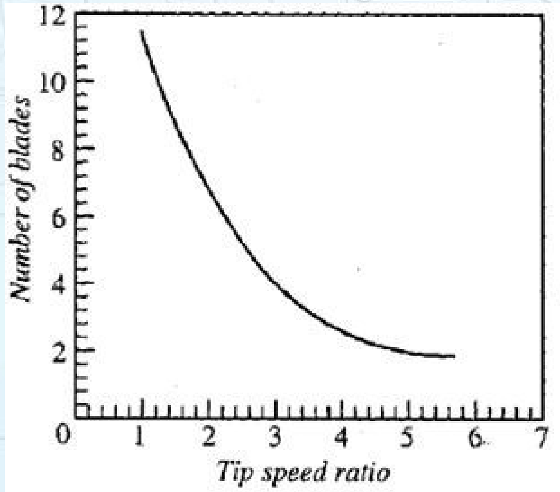

Fig 4.10 Number of blades versus tip speed ratio

Solidity
(σ)

- Solidity is defined as the ratio of the blade area to the swept frontal area of the wind turbine.
- Solidity determines the quantity of blade material required to intercept a certain wind area.

Mathematically,

$$\sigma = \frac{\text{Blade area}}{\text{Swept frontal area of turbine}} = \frac{BRb}{\Pi R^2}$$

$$\Rightarrow \sigma = \frac{Bb}{\Pi R}$$

Where,

B = Number of blades,
b = Blade width,
R = Blade radius.

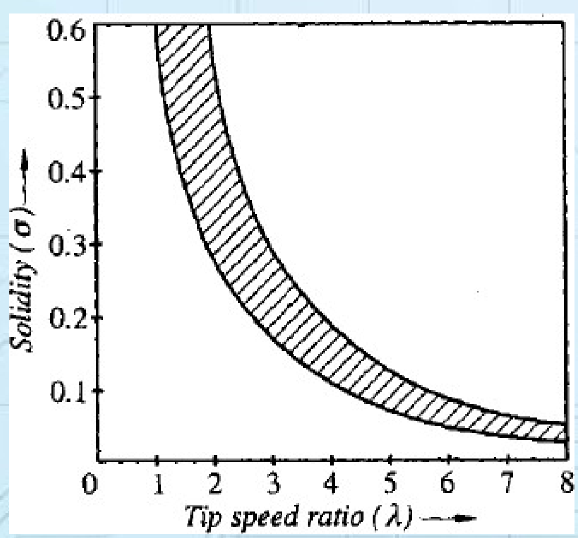

Fig 4.11 Variation of solidity with tip speed ratio

- A high solidity rotor rotates slowly and uses the drag force while a low solidity rotor uses lift forces.
- The solidity of the Savonious rotor is unity, and that of the American multiblade rotor is typically 0.7.

Blade design

- Wind turbine blades have an airofoil type cross section and a variable pitch. They are slightly twisted from the outer tip to the root.
- As shown in Fig., the force that propels the blades of a wind turbine comes from the chord of the airofoil, being tilted away from the direction of motion. The motion causing the 'wind due to motion' is the rotation of the blades.

Tower :

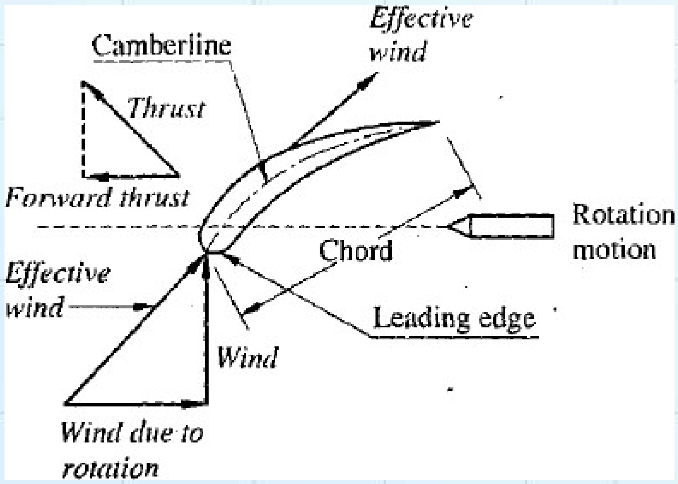

Fig 4.12 Wind turbine blade as an airofoil

- Winds are much stronger as the elevation above ground increases, and they are also less turbulent. Therefore, the tower should be as high as practical. Choice of tower height is based on an economic trade-off of increased energy capture versus increased cost.
- The minimum height of the tower for HAWT is that the blade tip should not touch the ground during rotation.
- The principle options in towers are tubular, pipe-type structures or trusses.

The overall conversion efficiency (η_0) of the system is given by

$$\eta_0 = \frac{\text{Useful power output}}{\text{Wind power input}} = \eta_A . \eta_G . \eta_C . \eta_{Gen}$$

Where,

η_A= Efficiency of the turbine=C_p,

η_G = Efficiency of the gearing,

η_C = Efficiency of the mechanical coupling,

η_{Gen} = Efficiency of the generator.

Variation of power coefficient with tip speed ratio

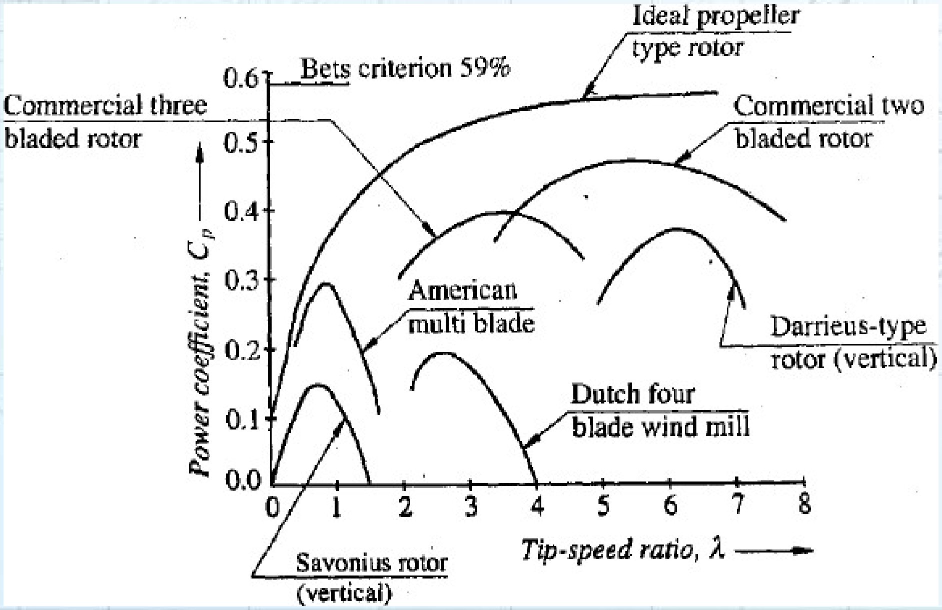

Fig 4.13 Variation of power coefficient with tip speed ratio

Variation of torque coefficient with tip speed ratio

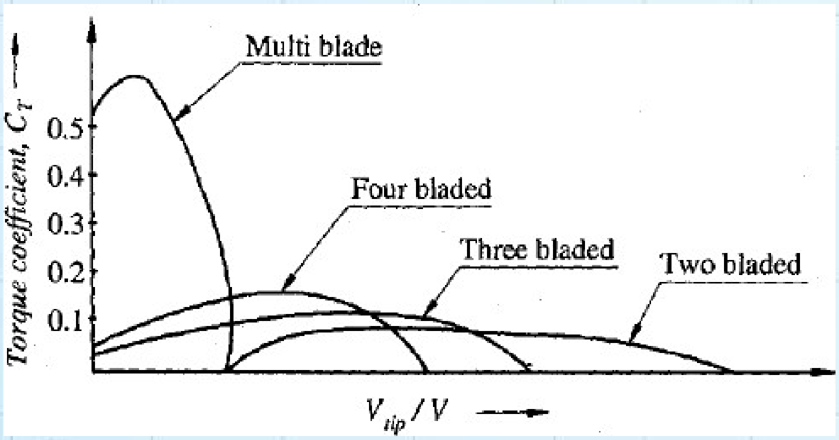

Fig 4.14 Variation of torque coefficient with tip speed ratio

3.7 SITE SELECTION CONSIDERATIONS

1. **Average annual wind speed**
   - The power available in wind increases rapidly with wind speed. Therefore, the main consideration for locating a wind-power generation plant is the availability of adequate and uniform average wind velocity throughout the year.
   - The total wind power from free wind stream increases as the cube of the wind speed. Therefore, wind velocities available should be in the range of 5 m/s to 25 m/s throughout the year.

2. **Area**
   - As the building, forests offers the resistance to the air movement, the wind farms are located away from cities and forests. Flat open area should be selected, as the wind velocities are high in flat open area.

3. **Altitude of the site**
   - Altitude of the proposed site should be considered. Higher altitude ground experience strong winds than lower altitude ground. Thus, altitude affects the electric power output of wind energy conversion system.
   - Wind velocities must be measured by anemometer at several heights from the ground The velocity of wind increases with height given by the relation:

$$V \propto H^{1/7}$$

   - This relation is applicable for the heights between 50 m to 250 m.

4. **Wind structure**
   - At the proposed site, wind should blow, smooth and steady all the time, i.e. the wind velocity curve should be flat. Wind specially near the ground is turbulent and gusty, and changes rapidly in direction and in velocity.

5. **Local ecology**
   - If small trees, grass or vegetations are present, all of which destructure the wind, then the height of the tower will increase, which increases the cost of the system.

6. **Nature of land and its cost**
   - The site selected should have high load bearing capacity. It would reduce the cost of foundation. The cost of the land should be low to reduce the initial cost.

7. **Transport facilities**
   - There should be transport facilities for transportation of heavy machinery, structures, materials, blades, etc to chosen site for installation.

8. **Nearness of site to load centre**
   - The site should be located near the load to which the power is supplied. The location of site near load centre reduces the cost of transmission lines and the losses occurring in it.

9. **Away from localities**
   - The selected site should be away from localities so that the sound pollution caused by wind turbine does not affect the habitants in near areas.

Four types of sites are considered as suitable:

Advantages

1. It is renewable and not depleted with the use like fossil fuels.
2. Wind energy generation is ecofriendly and does not pollute the atmosphere, unlike in the case of generation from coal, oil, etc.
3. The cost of installation of wind power plant is competitive compared to conventional power plant/Since, there is no fuel cost and low maintenance cost, the cost of energy produced in long run is almost free.
4. Wind energy system does not require fuel and its transportation.
5. In large portion of the world, wind blows for 320 days in a year and this gives them an advantage over sunlight in direct conversion programme.

Disadvantages

1. Wind energy is available in dilute and fluctuating in nature.
2. It is necessary to store wind energy in some other forms during periods of high winds for use later on during calm.
3. Favourable winds are available only in few geographical locations.
4. There is fluctuation in electric power depending on fluctuating wind speed.
5. The capital cost is high. At present it is about Rs. 3.5 crores/MW.
6. It causes negative impacts like noise, bird hits, land erosion, impact on wild life, etc.

3.8 WIND ENERGY DEVELOPMENT IN INDIA

- The wind power programme in India was initiated towards the end of the Sixth Plan, in 1983-84.
- In India, the wind energy programme is managed and implemented by the Ministry of New and Renewable Energy sources, Government of India. The wind power potential in India is 49,130 MW as per the official estimates in the Indian Wind Atlas (2010) by the Centre for Wind energy Technology.
- The potential is calculated with respect to 2% land availability at windy locations and pertains to a 50 meter hub height level of the wind turbines.
- A total capacity of 17365.03 MW has been established up to March 31,2012 in the country. India is now the fifth largest wind power producer in the world, after USA, Germany, Spain and China.
- The break-up of projects implemented in prominent wind potential states is as given in Table

Table 4.1

Sr No.	State	Potential (MW)	Installed capacity (MW)
1	Andhra Pradesh	5394	245.50
2	Gujarat	10609	2,966.30
3	Karnataka	8591	1,933.50
4	Kerala	790	35.1
5	Madhya Pradesh	920	376.40
6	Maharashtra	5439	2,733.30
7	Rajasthan	5005	2,070.70
8	Tamil Nadu	5374	6,987.60
9	Others	7008	3.2
	Total	**49130**	**17351.50**