MODULE 3

WIND ENERGY

Wind is caused by the uneven heating of the atmosphere by the sun, variations in the earth's surface, and rotation of the earth. Thus the wind energy is a form of solar energy

- Wind is the moving air and is caused by the differences in air pressure in our atmosphere. Mountains, bodies of water, and vegetation all influence wind flow patterns
- Wind energy (or wind power) describes the process by which wind is used to generate electricity
- Wind turbines convert the kinetic energy in the wind into mechanical power by rotating propeller like blades.
- A generator can convert mechanical power into electricity i.e. by rotating the propeller blades around a rotor. Mechanical power can also be utilized directly for specific tasks such as pumping water.

PROPERTIES OF WIND

- Wind is non-conventional energy source
- Wind is due to differences in air pressure in the atmosphere
- Wind at high pressure tends to move to areas at low air pressure, greater the pressure difference faster will be the flow of air
- In meteorology, winds are often referred to according to their strength, and the direction from which the wind is blowing.
- Wind strength can vary from light breeze to hurricane force
- The wind is also a critical means of transportation for seeds, insects, and birds, which can travel on wind currents for thousands of miles.
- Wind is characterized by two parameters. They are wind speed and wind direction. Wind speed indicates the speed of air movement from one point to another measured through a device called “anemometer” and the wind direction indicated the direction at which air is moving measured through a device “wind vane” attached to a direction indicator.

AVAILABILITY OF WIND ENERGY IN INDIA

The total installed capacity of wind power in India as on March 2017 is around 32 GW. Wind power generation capacity in India has significantly increased in recent years. As of 28 February 2021, the total installed wind power capacity is 38.789 GW, the fourth largest installed wind power capacity in the world.

Wind power capacity is mainly spread across the Southern, Western and Northern regions
(Note: GW = Gigawatt, 1 GW = 1000 megawatt = 109 watts)

Wind power costs in India are decreasing rapidly. The levelised tariff of wind power reached a record low of ₹2.43 per kWh (without any direct or indirect subsidies) during auctions for wind projects in December 2017. However, the levelised tariff is increased to ₹2.77 per kWh in March 2021.

The potential is far from exhausted. Indian Wind Energy Association has estimated that with the current level of technology, the ‘on-shore’ potential for utilization of wind energy for electricity generation is of the order of 65,000 MW. The unexploited resource availability has the potential to sustain the growth of wind energy sector in India in the years to come.

Wind in India are influenced by the strong south-west summer monsoon, which starts in May-June, when cool, humid air moves towards the land; further, the weak north-east winter monsoon, which starts in October, when cool, dry air moves towards the ocean. During March- August, the winds are uniformly strong over the whole Indian Peninsula, except the eastern peninsular coast. Wind speeds during November-March are relatively weak, although high winds are available during a part of the period on the Tamil Nadu coastline.

WIND VELOCITY

Wind velocity is the measure of speed of wind in horizontal direction. Wind velocity means pedestrian level wind speed measured at 2 m above ground. It is a measure of air ventilation which has a direct effect on outdoor thermal comfort

WIND POWER

Kinetic energy exists whenever an object of a given mass is in motion with a translational or rotational speed. When air is in motion, the kinetic energy in moving air can be determined as

$E_k = 0.5\, m\bar{u}^2 \ldots (1)$

Where m is the air mass and $\bar{u}$ is the mean wind speed over a suitable time period.

The wind power can be obtained by differentiating the kinetic energy in wind with respect to time, i.e.

$P_w = dE_k / dt = 0.5\, \dot{m}\bar{u}^2 \ldots (2)$

However, only a small portion of wind power can be converted into electrical power.

When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flow rate is

$\dot{m} = \rho A\bar{u} \ldots (3)$

Where is ρ the air density and A is the swept area of blades

Substituting (3) into (2), the available power in wind Pw can be expressed as

$P_w = 0.5\, \rho A\bar{u}^3$

MAJOR PROBLEMS ASSOCIATED WITH WIND POWER

Wind energy can have adverse environmental impacts, including the potential to reduce, fragment, or degrade

habitat for wildlife, fish, and plants.

- Wind power must still compete with conventional generation sources on a cost basis i.e. wind projects must be able to compete economically with the lowest-cost source of electricity, and some locations may not be windy enough to be cost competitive.

- Good land-based wind sites are often located in remote locations, far from cities where the electricity is needed. Transmission lines must be built to bring the electricity from the wind farm to the city.
- Wind resource development might not be the most profitable use of the land. Land suitable for wind-turbine installation must compete with alternative uses for the land, which might be more highly valued than electricity generation.
- Turbines might cause noise and aesthetic pollution.
- Wind plants can impact local wildlife. Birds have been killed by flying into spinning turbine blades.

WIND MACHINES

Wind machines or wind turbines or wind energy converter, are the devices that converts the wind's kinetic energy into electrical energy. Wind turbines are manufactured in a wide range of sizes, with either horizontal or vertical axes.

Two important wind rotor configurations are as follows:

1.Vertical-axis wind turbines (VAWT), here the axis of rotation is vertical with respect to the ground (and roughly perpendicular to the wind stream). The following are the two main types of VAWT:

- Darrieus (which uses lift forces generated by aerofoil)
- Savonius (which uses drag forces)

1.Horizontal-axis wind turbines (HAWT), in which the axis of rotation is horizontal with respect to the ground (and roughly parallel to the wind stream). HAWT can be further divided into three types:

- Dutch windmills
- Multi-blade water-pumping windmills
- High-speed propeller-type wind machines

VERTICAL AXIS WIND MILLS/TURBINES

1. Vertical axis Darrieus wind turbine

- **Constructional details**
  - Tower: The tower is a hollow vertical rotor shaft, which rotates freely about vertical axis
  - between top and bottom bearings. It is installed above a support structure. The upper part of

    the tower is supported by guy ropes. The height of the tower of a large turbine is around 100 m
  - Blades: It has two or three thin, curved blades shaped like an eggbeater in profile, with blades curved in a form that minimizes the bending stress caused by centrifugal forces- the so-called 'Troposkien' profile. The blades have airfoil cross section with constant chord length. The pitch of the blades cannot be changed.

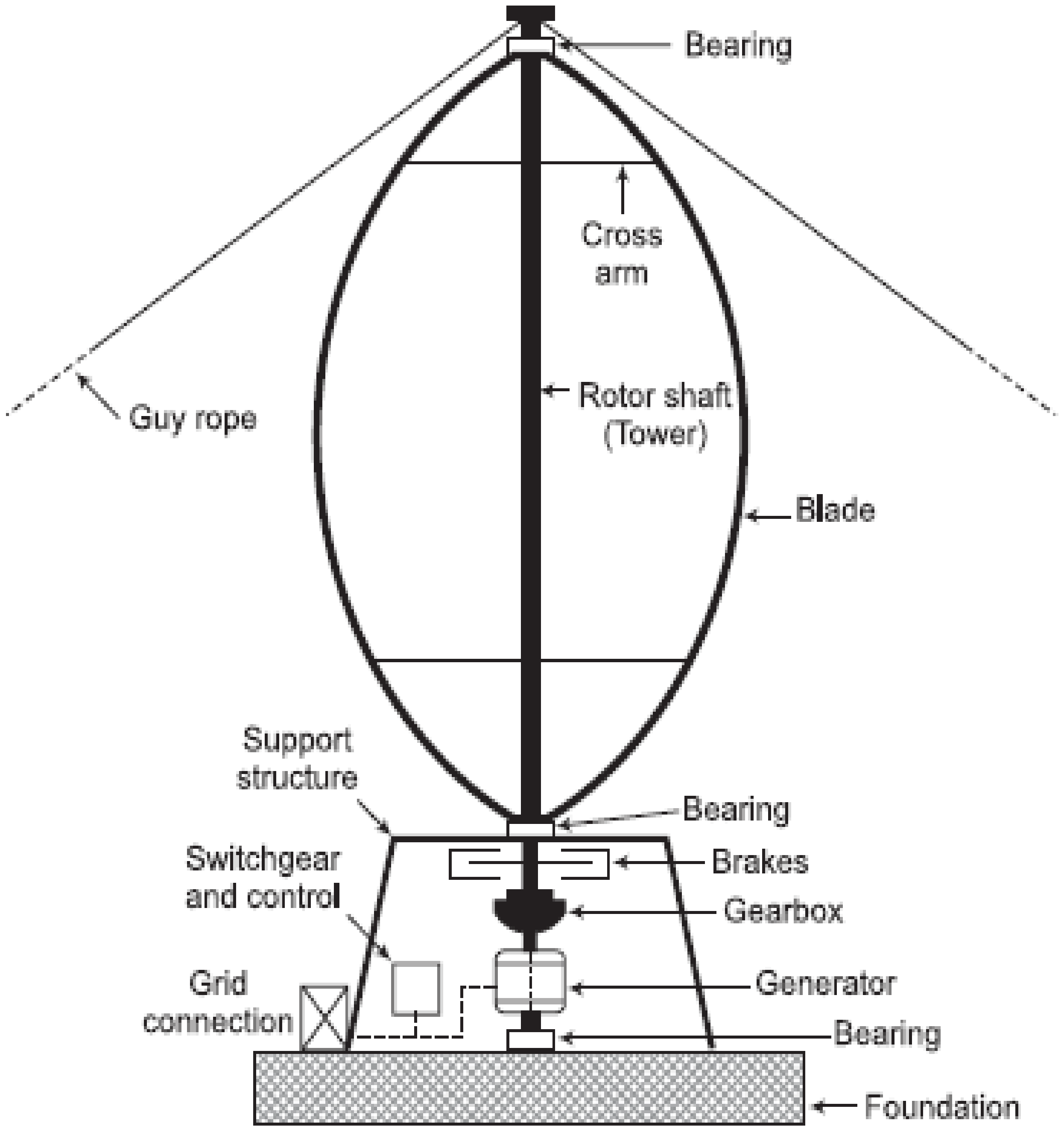

Fig 4.1: Vertical axis Darrieus wind turbine

- Support Structure: Support structure is provided at the ground to support the weight of the rotor. Gearbox, generator, brakes, electrical switchgear and controls are housed within this structure.
- The turbine consists of a number of aero foil usually but not always vertically mounted on a rotating shaft or framework
- Darrieus design, the aero foils are arranged so that they are symmetrical and have zero rigging angles, that is, the angle that the aero foils are set relative to the structure on which they are mounted.

- **Working principle**
  - In terms of operation, Darrieus utilizes the "lift" aerodynamic force to rotate.
  - By flowing around the structure, the wind creates suction on the front side of the turbine, driving the wings to rotate.
  - Because of the shape of the wings, they do not experience as much drag as Savonius turbines do. Once the rotation starts, Darrieus wind turbines are able to accelerate to rotate faster than the wind speed.
  - As the turbine tends to rotate, the electrical generator generates the electrical energy from the mechanical energy supplied by the rotation of rotor shaft.

- This arrangement is equally effective no matter which direction the wind is blowing—in contrast to the conventional type, which must be rotated to face into the wind.

- **Advantages**
  - The equipment (gear box and generator) can be placed close to the ground.
  - There is no need of a mechanism to turn the rotor against the wind
- **Disadvantages**
  - The efficiency is not very remarkable
  - The Darrieus is not a self-starting turbine, the starting torque is very low but it can be reduced by using three or more blades that result in a high solidity for the rotor.
  - Because wind speeds are close to the ground level, there is very low wind speed on the lower part of the rotor.
  - They are very difficult to mount high on a tower to capture the high level winds. Because of this, they are usually forced to accept the low, more turbulent winds, and they produce less in possibly more damaging winds.

2. Vertical axis Savonius wind turbine

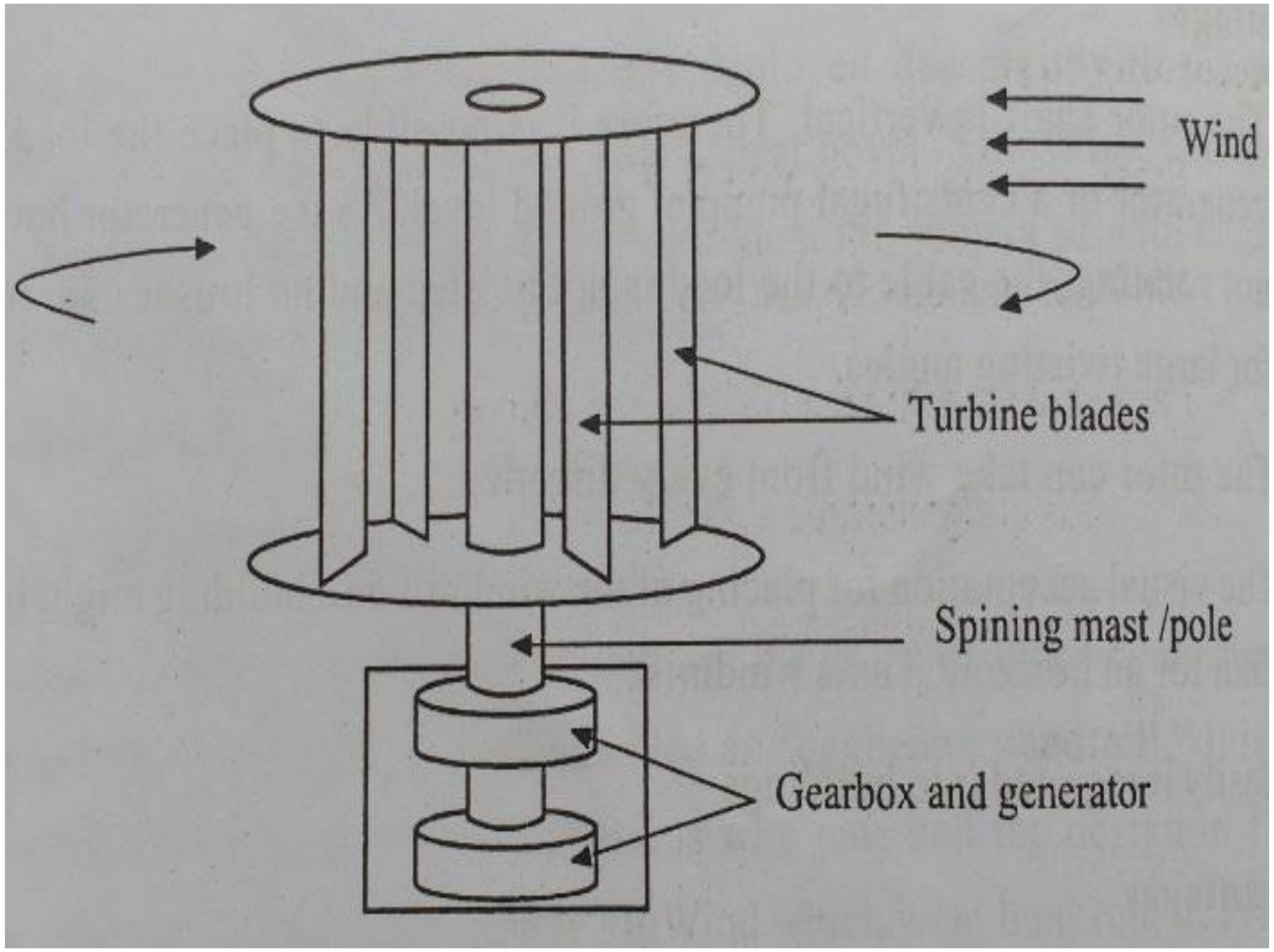

Fig 4.2: Vertical axis Savonius wind turbine

- **Constructional details**
  - The Savonius wind turbine is a simple vertical axis device having a shape of half-cylindrical parts attached to the opposite sides of a vertical shaft (for two-bladed arrangement) and operate on the drag force, so it can't rotate faster than the wind speed.
  - Aerodynamically, it is a drag-type device consisting of two or three scoops.
  - Because of the curvature, the scoops experience less drag when moving against the wind than with the wind.
- **Working principle**
  - The differential drag causes the Savonius turbine to spin.
  - Because they are drag-type devices, Savonius turbines extract much less of the wind's power than other similarly sized lift-type turbines.
  - As the wind blows into the structure and comes into contact with the opposite faced surfaces (one convex and other concave), two different forces (drag and lift) are exerted on those two surfaces.
  - The basic principle is based on the difference of the drag force between the convex and the concave parts of the rotor blades when they rotate around a vertical shaft. Thus, drag force is the main driving force of the Savonius rotor
- **Advantages**
  - Always self-starting, if there are at least three scoops
  - Relatively easy to make
- **Disadvantages**
  - Low efficiency: around 15%.

HORIZONTAL AXIS WIND TURBINE

- **Constructional details**
  - The rotor consists of the hub and blades of the wind turbine. Most turbines today have upwind rotors with three blades
  - The drive train consists of the other rotating parts of the wind turbine downstream of the rotor.
    These typically include a low-speed shaft (on the rotor side), a gearbox, and a high-speed shaft (on the generator side). Other drive train components include the support bearings, one or more couplings, a brake
  - The purpose of the gearbox is to speed up the rate of rotation of the rotor from a low value
    (tens of rpm) to a rate suitable for driving a standard generator (hundreds or thousands of rpm).
  - This category includes the wind turbine housing, the machine bedplate or main frame, and the yaw orientation system. The main frame provides for the mounting and proper alignment of the drive train components. The nacelle cover protects the contents from the weather
  - This category includes the tower itself and the supporting foundation. The principal types of
    tower design currently in use are the free-standing type using steel tubes, lattice (or truss) towers, and concrete towers.
  - A wind turbine control system includes the following components: Sensors – speed, position, flow, temperature, current, voltage, etc.;

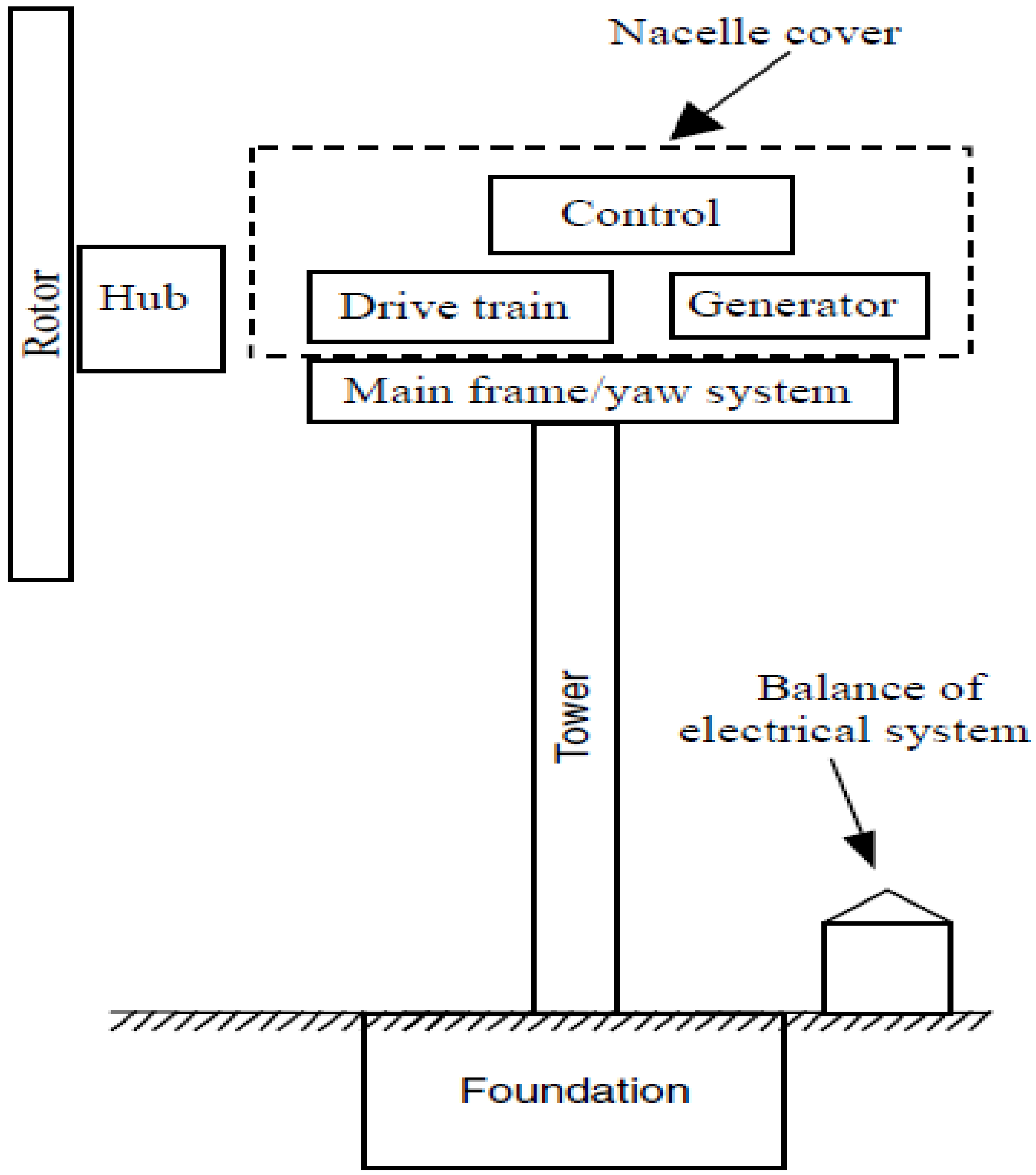

Fig 4.3: Horizontal axis wind turbine

Controllers – mechanical mechanisms, electrical circuits;

Power amplifiers – switches, electrical amplifiers, hydraulic pumps, and valves; Actuators – motors, pistons, magnets, and solenoids;

Intelligence – computers, microprocessors.

- In addition to the generator, the wind turbine system utilizes a number of other electrical components. Some examples are cables, switchgear, transformers, power electronic converters, power factor correction capacitors, yaw and pitch motors that forms the balance of electrical system

- **Working principle**
  - The horizontal-axis wind turbine (HAWT) is a wind turbine in which the main rotor shaft is pointed in the direction of the wind to extract power
  - The rotor receives energy from the wind and produces a torque on a low-speed shaft.
  - The low-speed shaft transfers the energy to a gearbox, high-speed shaft, and generator, which are enclosed in the nacelle for protection.
  - The low-speed shaft connects to the gearbox, which has a set of gears that increase the output speed of the shaft to approximately 1,800 rpm for an output frequency of 60 Hz (or a speed of 1,500 rpm if the frequency is 50 Hz).
  - The high-speed shaft is then connected to the generator, which converts the rotational motion to AC voltage.
- **Advantages**
  - High power output
  - High efficiency
  - Highly reliable
  - High operational wind speed
- **Disadvantages**
  - Difficult to transport, install and maintenance
  - Stronger impact on environment
  - Strict regulations to be followed

ELEMENTARY DESIGN PRINCIPLES

- Wind turbine design is the process of defining the form and specifications of a wind turbine to extract energy from the wind.
- A wind turbine installation consists of the following,
  - Necessary systems needed to capture the wind's energy,
  - Point the turbine into the wind,
  - Convert mechanical rotation into electrical power, and
  - Other systems to start, stop, and control the turbine.

- **Aerodynamics**: The shape and dimensions of the blades of the wind turbine are determined by the aerodynamic performance required to efficiently extract energy from the wind.
- **Power control**: The centrifugal force on the spinning blades increases as the square of the rotation speed, which makes this structure sensitive to over speed.
  - The cut-in speed is around 3–4 m/s for most turbines, and cut-out at 25 m/s.
  - A control system involves three basic elements: sensors to measure process variables, actuators to manipulate energy capture along with component loading, and control algorithms to coordinate the actuators.
- **Stall:** A stall on an airfoil occurs when air passes over it in such a way that the generation of lift rapidly decreases. Usually this is due to a high angle of attack (AOA), but can also result from dynamic effects.

- **Furling**: Furling works by decreasing the angle of attack. A fully furled turbine blade, when stopped, has the edge of the blade facing into the wind.
- **Yawing**: Modern large wind turbines are typically actively controlled to face the wind direction measured by a wind vane situated on the back of the nacelle.
  - By minimizing the yaw angle (the misalignment between wind and turbine pointing direction), the power output is maximized and non-symmetrical loads minimized
- **Turbine size:** For a given survivable wind speed, the mass of a turbine is approximately proportional to the cube of its blade-length.
  - The maximum blade- length of turbine is limited by strength, stiffness, and transportation considerations.

COEFFICIENT OF PERFORMANCE OF A WIND MILL ROTOR

- It is the proportion of the power in the wind that the rotor can extract (it is also called power coefficient or efficiency; symbol Cp).
- It is physically impossible to extract all the energy from the wind, without bringing the air behind the rotor to a standstill.
- Maximum value is Cp of 59.3% (known as the Betz limit).
- In practice, real wind rotors have maximum Cp values in the range of 25%-45%.
- The performance coefficient of a rotor is the fraction of wind energy passing through the rotor disc, which is converted into shaft power.

AERODYNAMIC CONSIDERATIONS IN WIND MILL DESIGN

The VAWT and HAWT use either lift or drag forces to harness the wind.

- Out of these types, the horizontal- axis lift device is the most commonly used.
- Other than a few experimental machines, virtually all windmills come under this category.
- There are two primary physical principles by which energy can be extracted from the wind.
  - lift force.
  - drag force
  - or combination of the two

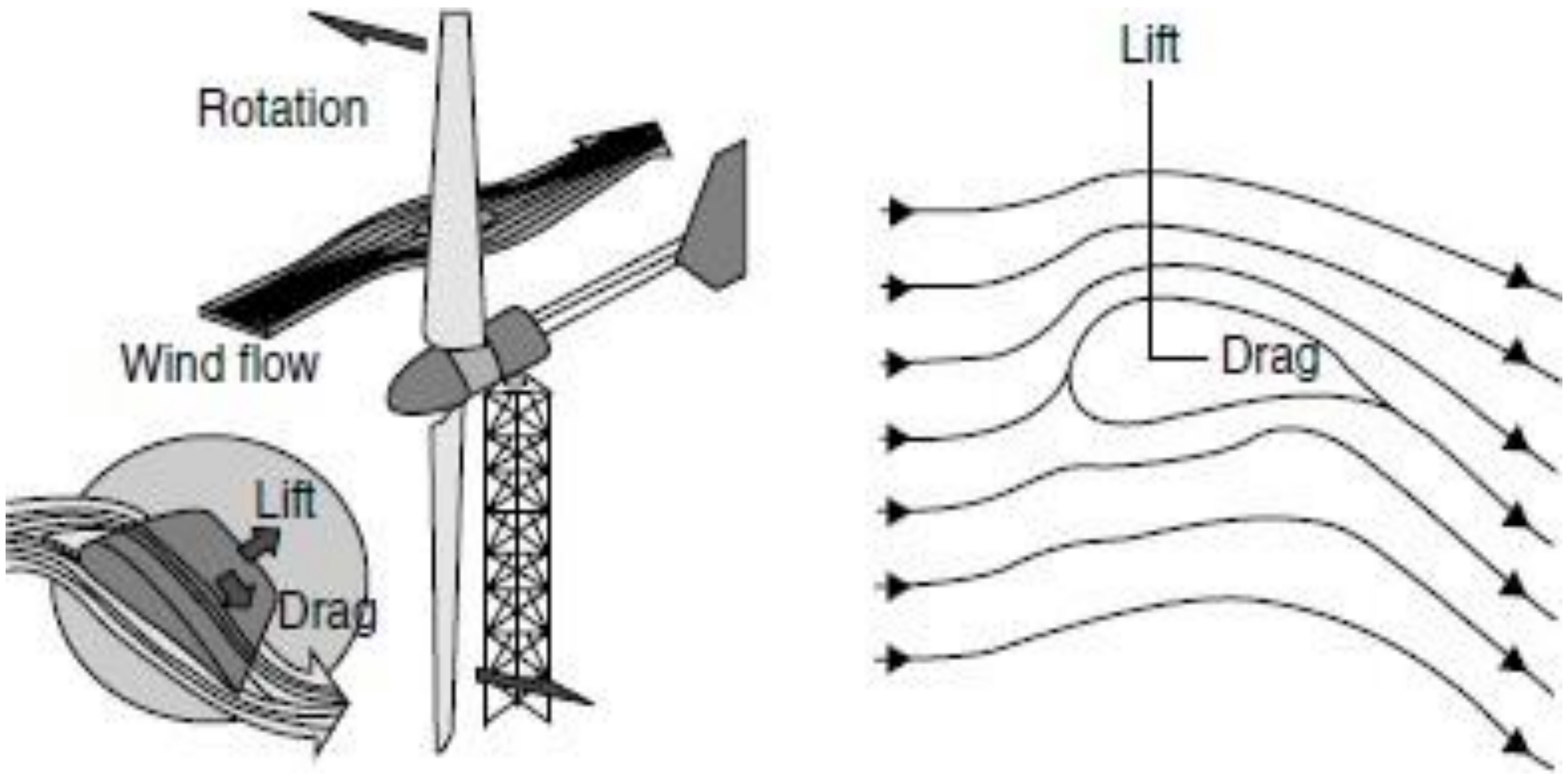

Fig : Principles of wind turbine aerodynamics

- Air flow over a stationary airfoil produces two forces, a lift force perpendicular to the air flow and a drag force in the direction of air flow, as shown in the above figure.
- The existence of the lift force depends upon laminar flow over the airfoil, which means that the air flows smoothly over both sides of the airfoil.
- If turbulent flow exists - then little or no lift force.
- The pressure difference across the airfoil yields the lift force, which is perpendicular to the direction of air flow.
- The air moving over the airfoil also produces a drag force in the direction of the air flow.
- This is a loss term and is minimized as much as possible in high- performance wind turbines.

- Lift coefficient (C_L) is defined as follows,

$$CL = \{FL/SL\} / [(1/2)\ \rho V^2]$$

(FL) is the lift force in Newton,

(SL) is the cross-sectional area of airfoil in m2,

ρ is the air density in kg/m2, and

V is the wind speed in m/s2

- Drag coefficient(C_D) is given by,

$$CD = [FD/SD] / [(1/2)\ \rho V2]$$

Drag force (FD) and

SD = Effective area of airfoil in the direction of drag force.

Numerical Problems

1. The velocity of wind at a place is 18 m/s, where the conditions of pressure and temperature are 1 standard atmospheric and 15 degree C, respectively Determine the following,

a) The total power density of the wind stream.
b) The maximum power density that can be absorbed
c) The possible power absorption with efficiency 35%.
d) The total power if turbine diameter is 125m.
e) The torque if N is 42/min, and f) The axial thrust.

Solution:

$p = 1 \text{ atm} = 1.01325 \times 10^5$ Pa.

$T = 15^0 C = 15 + 273 = 288K.$

$Vi = 18$ m/s.

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

where, R = gas constant

$= 0.287$ kJ/kg.K. $= 287$ J/kg.K.

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

a) Total power in the wind stream (P_{total})

$$(P_{total}) = \frac{\rho A V_i^3}{2}$$

$$\text{Power Density} = \frac{P_{total}}{A} = \frac{1}{2} \rho V_i^3$$

$$= \frac{1}{2} \times 1.226 \times 18^3 = \mathbf{3575} \text{ W/m}^2.$$

b) Maximum power (P_{max})

We have, $P_{max} = \dfrac{8}{27} \rho A. V_i^3$

$$\text{Max. power density, } \frac{P_{max}}{A} = \frac{8}{27} \rho V_1^3$$

$$= \frac{8}{27} \times 1.226 \times 18^3$$

$$= \mathbf{2118} \text{ W/m}^2$$

c) Possible power absorption

With an efficiency $\eta = 35\%$

Possible power absorption, $\frac{P_{total}}{A} \times \eta$

$= 3575 \times 0.35 = \mathbf{1251}\ W/m^2$

d) Total power

$$\text{Total power, } P = \text{Power density} \times \text{Area.}$$

$$= 1251 \times \frac{\pi D^2}{4} = 1251 \times \frac{\pi\, 125^2}{4}$$

$$= 15352079\ W$$

$$= \mathbf{15352}\ kW = \mathbf{15.3}\ MW$$

e) Torque at maximum efficiency

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

$$= \frac{2}{27} \times \frac{1.226 \times 125 \times 18^3}{42/60} = \mathbf{94577}\ N.$$

f) Maximum axial thrust

$$F_{a.max} = \frac{\pi}{9} \rho D^2 V_i^2$$

$$= \frac{\pi}{9} 1.226 \times 125^2 \times 18^2$$

$$= \mathbf{2166520}\ N$$

$$= \mathbf{2166}\ kN.$$

Example 6-13: A 10 m/s wind is at 1 standard atmospheric pressure at 15°C temperature.

Calculate:

i) the total power density in the wind stream.

ii) maximum obtainable power density

iii) a reasonable obtainable power density in W/m^2

iv) total power (in kW) if the turbine diameter is 120 m.

Assume, conversion efficiency = 40%. **(VTU: Jun 2012)**

Solution:

$P = 1 \text{ atm} = 1.01325 \times 10^5$ Pa.

$T = 15^0 C = 15+273 = 288K$.

$Vi = 10$ m/s.

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

where, R = gas constant = 0.287 kJ/kg.K. = 287 J/kg.K.

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

a) Total power in the wind stream (P_{total})

$$(P_{total}) = \frac{\rho A V_i^3}{2}$$

$$\text{Power Density} = \frac{P_{total}}{A} = \frac{1}{2}\rho V_i^3$$

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

b) Maximum power (P_{max})

We have, $$P_{max} = \frac{8}{27} \rho A. V_i^3$$

Max. power density, $$\frac{P_{max}}{A} = \frac{8}{27} \rho V_1^3$$

$$= \frac{8}{27} \times 1.226 \times 10^3$$

$$= \mathbf{363.26} \text{ W/m}^2$$

c) Possible power absorption

With an efficiency $\eta = 40\%$

Possible power absorption,

$$\frac{P_{total}}{A} \times \eta = 613 \times 0.4 = \mathbf{245.2} \text{ W/m}^2$$

d) Total power

Total power, P = Power density × Area.

$$= 245.2 \times \frac{\pi D^2}{4} = 245.2 \times \frac{\pi 120^2}{4}$$

$$= 2773146 \text{ W}$$

$$= \mathbf{2773} \text{ kW}$$