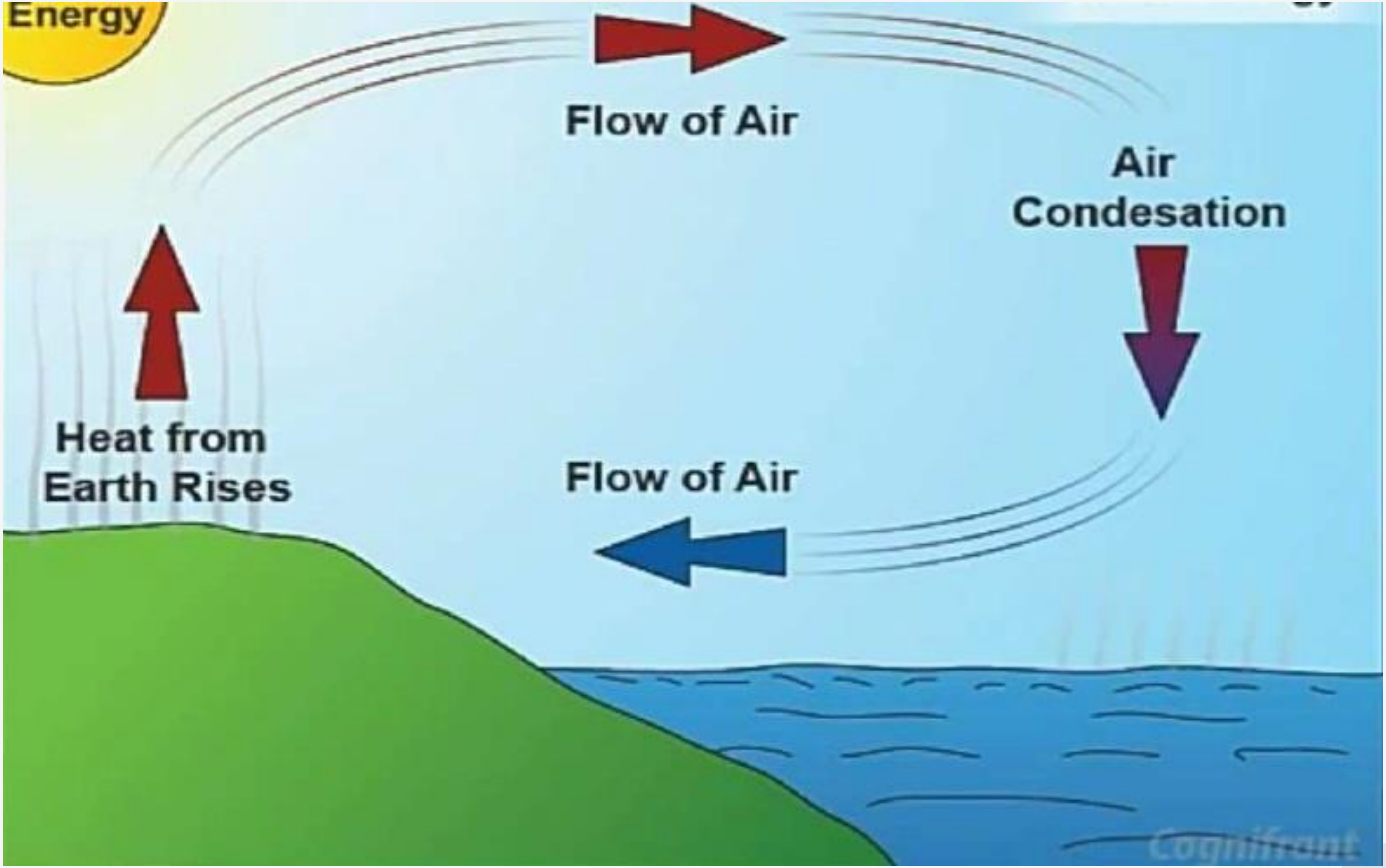
Wind Energy

- potential of India is about 45,000 MW out of which capacity of 8748 MW has been installed in India.
- India is one of the leading countries in generating the power through wind energy.
- Gujarat, AP, Karnataka, MP and Rajasthan are states having more than 5000 MW potential each.
- There are wind farms on sea generating as high as 160 MW of power.

Wind – Air flow



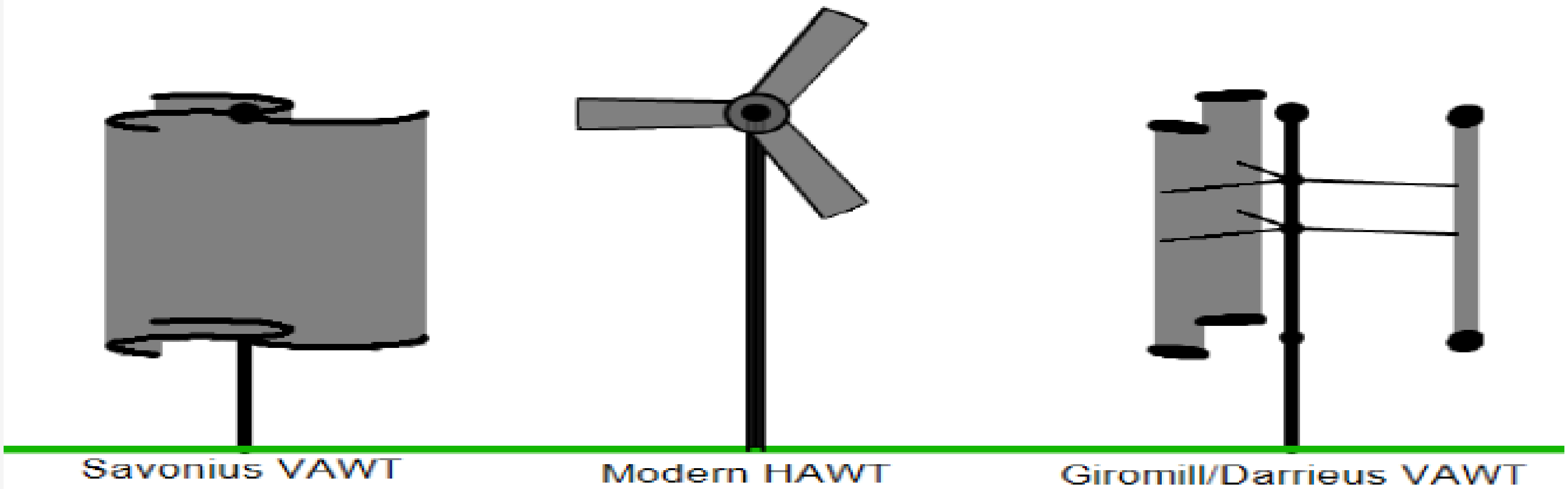
Wind Turbines - Types

Vertical axis

- Rotating axis of the wind turbine is vertical or perpendicular to the ground
- Primarily used in small wind projects and residential applications
- Powered by wind coming from all 360 degrees, no yaw mechanism
- Ideal for installations where wind conditions are not consistent, or due to public ordinances the turbine cannot be placed high enough to benefit from steady wind

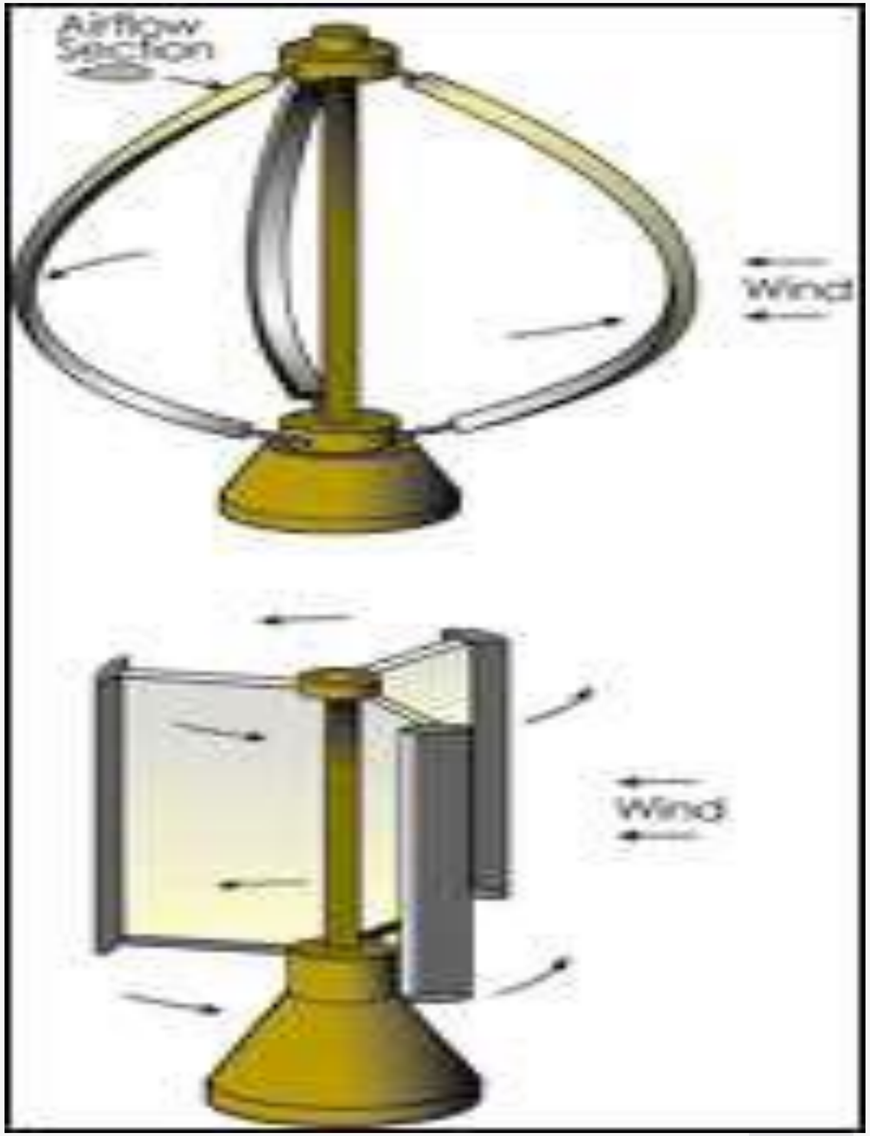
Horizontal axis

- Rotating axis of the wind turbine is horizontal or parallel to the ground
- Primarily used in big wind application
- Able to produce more electricity from a given amount of wind
- Disadvantage of horizontal axis however is that it is generally heavier and it does not produce well in turbulent winds
- Yaw mechanism



Vertical Axis Wind Turbines

The main reason for this is that they do not take advantage of the higher wind speeds at higher elevations above the ground as well as horizontal axis turbines



Vertical Axis Wind Turbines - Disadvantages

- These structures are low to the ground, where wind speeds are lowest.
- The overall efficiency is much lower than horizontal axis machines
- Most vertical axis machines are not self starting.
- Many vertical axis machines require guy wires which greatly increase the structural footprint.
- Maintenance is usually more difficult.
- For example, replacement of the generator typically requires disassembly of the entire machine.

Vertical Axis Wind Turbines - Advantages

- The generator and gearbox can be placed on the ground
- The structure is usually simpler
- do not need a yaw (pointing) mechanism to turn the rotor against the wind
- These are easier for hobbyists to build – little
- Detailed knowledge of aerodynamics is needed for simple designs.

Horizontal Axis Wind Turbines

One

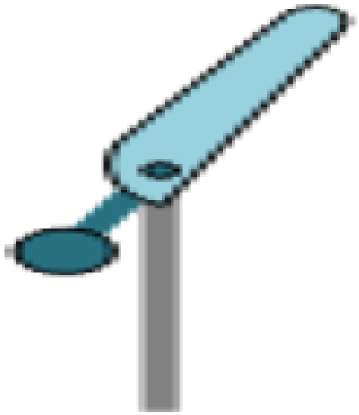
- Rotor must move more rapidly .
- Gearbox ratio reduced.
- Higher speed means more noise and other impacts.
- Captures 10% less energy than 2 blades design.
- Ultimately provide no cost savings.

Two

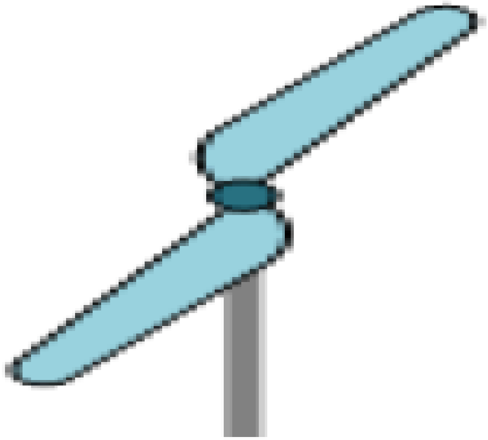
- Rotor must move more rapidly.
- Higher speed means more noise and other impacts.
- Needs shock absorber because of gyroscopic imbalances.
- Captures 5% less energy than three blades design.

Three

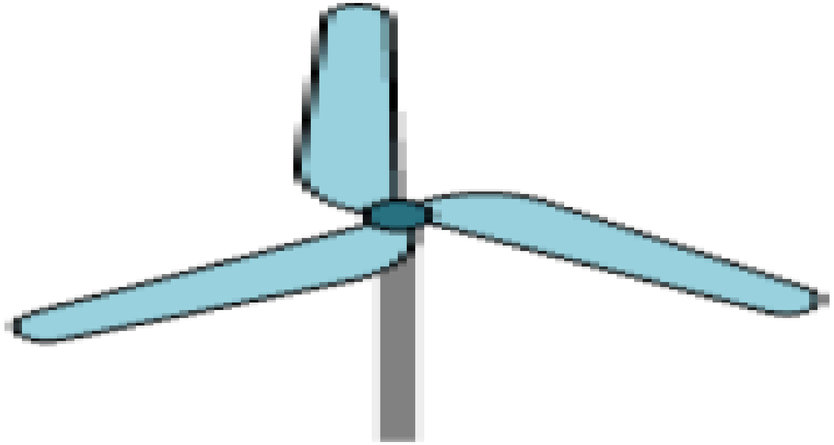
- Balances of gyroscopic forces.
- Slower rotation
- Increases gearbox and transmission cost
- More aesthetic, less noise , fewer bird strikes.



Single Blade



Double Bladed



Three Bladed

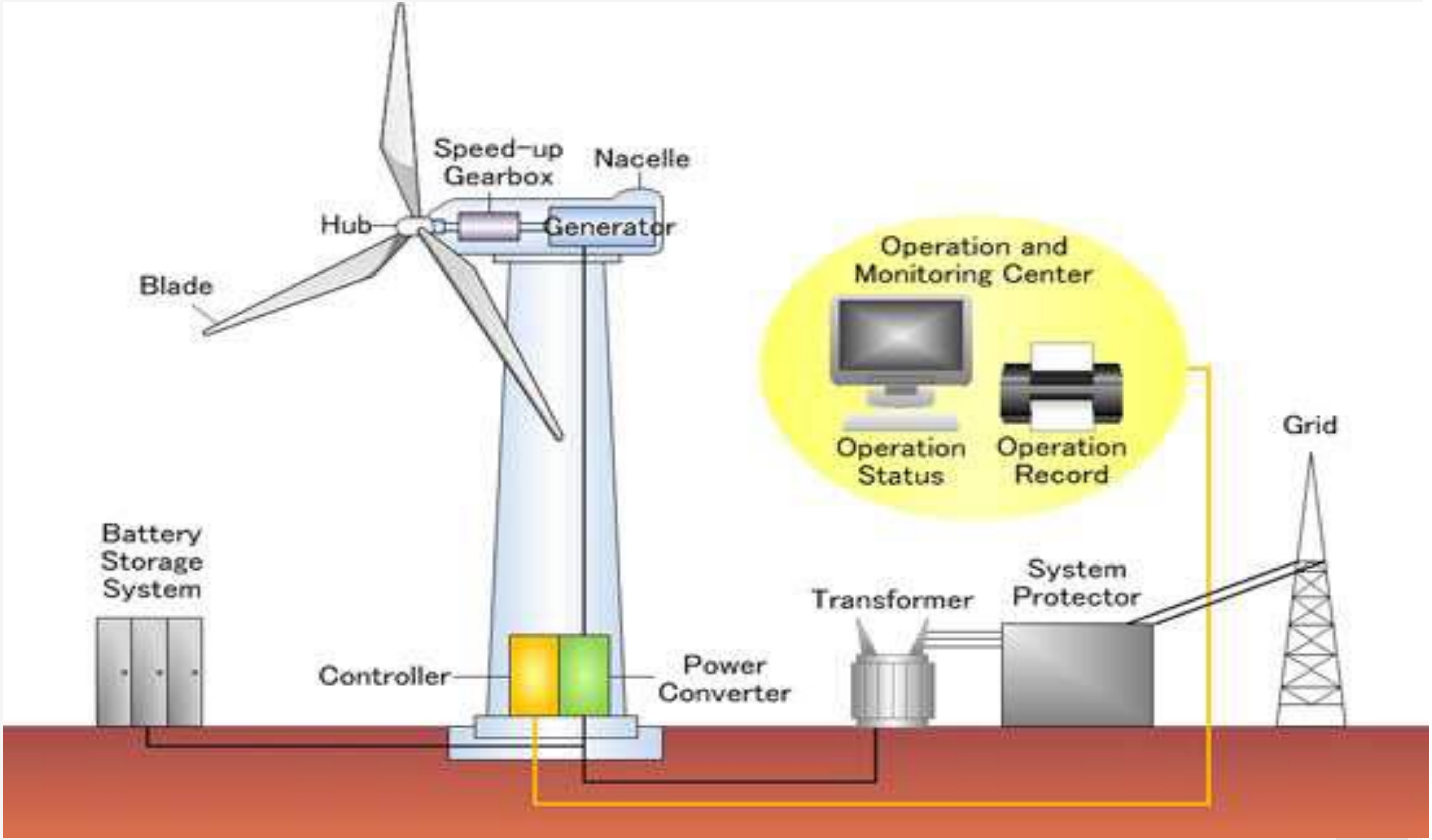
Horizontal Axis Wind Turbines - Advantages

- The efficiency is higher than that of vertical axis machines.
- They are easier to mount high enough to avoid much of the ground effect
- They are self starting
- They are less expensive
- The technology is better developed
- They are available commercially.

Horizontal Axis Wind Turbines - Disadvantages

- ❖ Many of the important parts that require maintenance are high off the ground
- ❖ They are easier to mount high enough to avoid much of the ground effect
- ❖ A yaw mechanism must be in place to turn the turbine into the wind.

Parts Operating In Wind Turbine



Parts Operating In Wind Turbine

Nacelle:

The nacelle contains large primary components such as the main axle, gearbox, generator, transformer and control system.

Parts Operating In Wind Turbine

Shaft:- **Two different shafts turn the generator.** One is used for low speeds while another is used in high speeds

Gear Box:- **Gears connect the high and low** speed shafts and increase the rotational speeds from about 10-60 rotations per minute to about 1200-1800 rpm, the rotational speed required by most generators to produce power.

Parts Operating In Wind Turbine

Generator

• Different generator designs produce either alternating current (AC) or direct current (DC), and they are available in a large range of output power ratings.

•The generator's rating, or size, is dependent on the length of the wind turbine's blades because more energy is captured by longer blades.

Controller:- Turns the blades on at 8-16 mph and shuts them down around 65 to prevent any high wind damage

Tower:- Tall tubular metal shaft. The taller the tower, the more power produced.

Brake:- If something is wrong or it is going to fast. Then it will brake and stop the wind turbine.

Site selection of wind Turbine

- How good is the wind resource on the site?
- How much does electricity cost, and is there enough demand for the power?
- Who has site control?
- Are there other potential barriers based on utility rules?
- Are there permitting, zoning, or other related barriers?

Advantages of wind power

1. The wind is free and with modern technology it can be captured efficiently.
2. Once the wind turbine is built the energy it produces does not cause green house gases or other pollutants.
3. Although wind turbines can be very tall each takes up only a small plot of land. This means that the land below can still be used. This is especially the case in agricultural areas as farming can still continue.
4. Many people find wind farms an interesting feature of the landscape

Advantages of wind power

5. Remote areas that are not connected to the electricity power grid can use wind turbines to produce their own supply.

6.Wind turbines have a role to play in both the developed and third world.

7. Wind turbines are available in a range of sizes which means a vast range of people and businesses can use them. Single households to small towns and villages can make good use of range of wind turbines available today.

Disadvantages of wind power

1.The strength of the wind is not constant and it varies from zero to storm force. This means that wind turbines do not produce the same amount of electricity all the time. There will be times when they produce no electricity at all

2.Many people feel that the countryside should be left untouched, without these large structures being built. The landscape should left in its natural form for everyone to enjoy

3.Wind turbines are noisy. Each one can generate the same level of noise as a family car travelling at 70 mph.

Disadvantages of wind power

4.Many people see large wind turbines as unsightly structures and not pleasant or interesting to look at. They disfigure the countryside and are generally ugly

5.When wind turbines are being manufactured some pollution is Produced. Therefore wind power does produce some pollution

6.Large wind farms are needed to provide entire communities with enough electricity. For example, the largest single turbine available today can only provide enough electricity for 475 homes, when running at full capacity. How many would be needed for a town of 100 000 people?

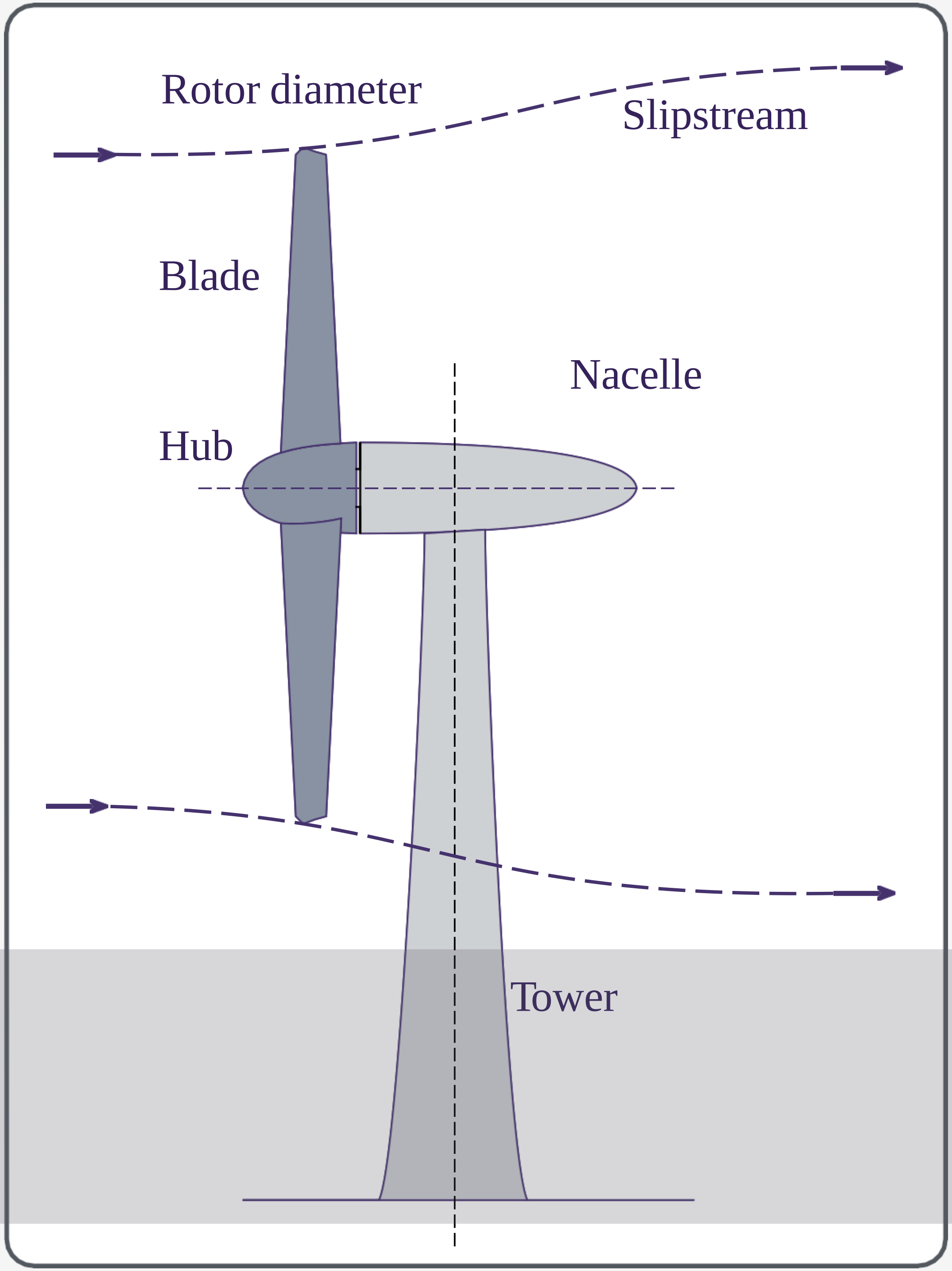
WIND SOURCE & CHARACTERISTICS

The primary source of wind is Solar Radiation

Approximately *1-2%* of the incident solar power $(1.4\ kW{\cdot}m^{-2})$ is converted into wind

Radius of the Earth ~ 6000 km therefore the CS area receiving solar radiation is about $1.13{\times}10^{14}\ m^2$

Winds are variable in time and location



WIND TURBINE CONFIGURATION

ENERY AVAILABLE IN THE WIND

Determining the energy and power available in the wind requires an understanding of basic geometry & the physics of kinetic energy (KE).

"Kinetic Energy is the motion of waves, electrons, atoms, molecules, substances and objects"

Considering this statement and identifying air has mass, it will therefore move as a result of wind i.e. it has kinetic energy (KE).

The KE of an object (or a collection of objects,
i.e. a car, train, etc...) with a total mass M and velocity v is given by;

V

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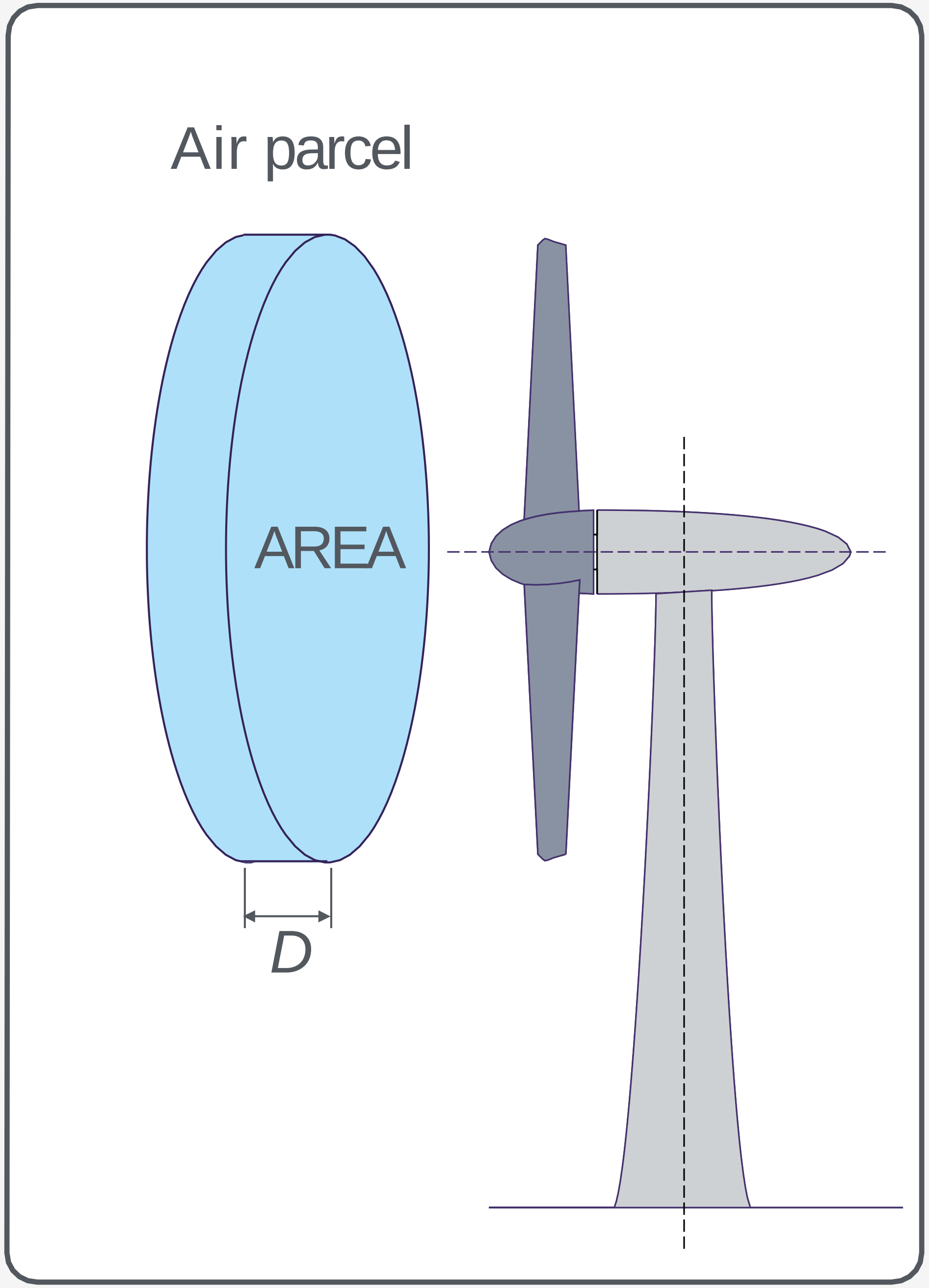
The KE of an object (or a collection of objects,
i.e. a car, train, etc...) with a total mass M and velocity v is given by;

In order to determine the KE of moving air molecules (i.e. wind), we can take a large air parcel in the shape of cylinder.This geometry will contain a collection of air molecules which will pass through the plane of the a wind turbines blades over a given time frame.

The volume of air contained within this parcel can be determined using established theory;



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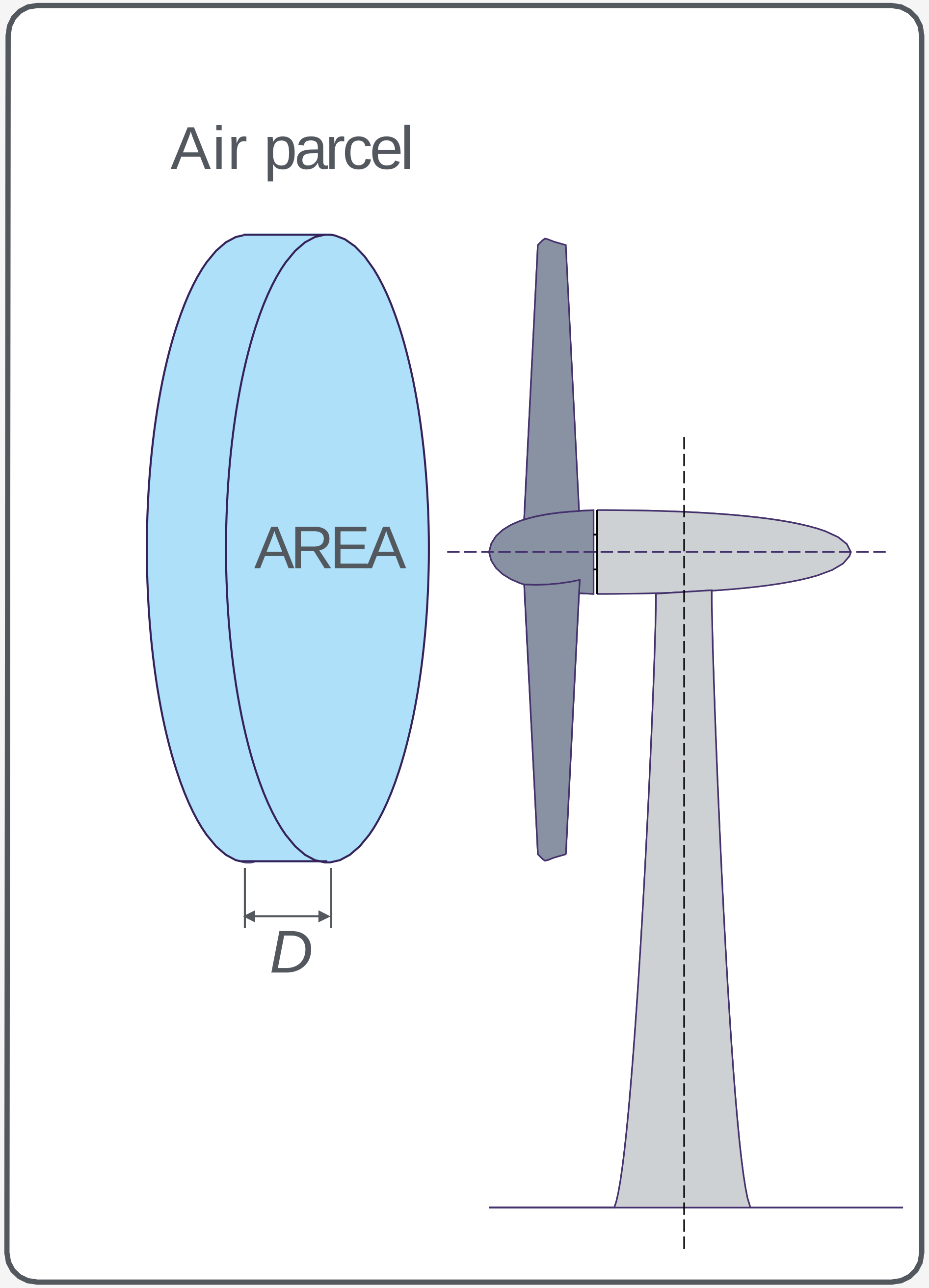
$$Vol = A \times D$$



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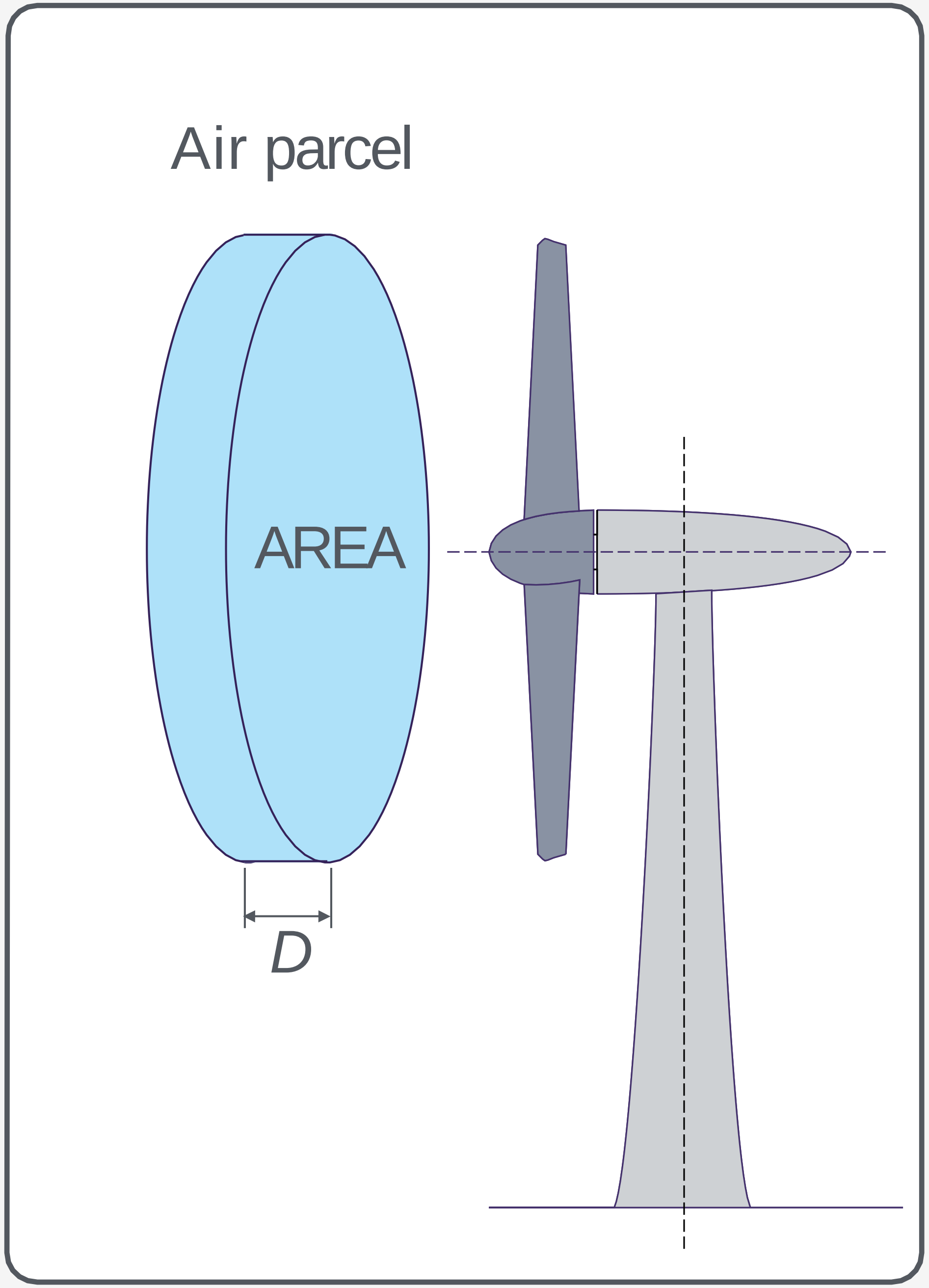
The volume of air contained within this parcel can be determined using established theory;

$$Vol = A \times D$$

$$Vol = \frac{\pi d^2}{4} \times D \quad \text{or} \quad Vol = \pi r^2 \times D$$



The air within this parcel also has a density ρ, and as density is mass per unit volume the density can therefore be expressed as;

$$\rho = \frac{m}{Vol}$$

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Transposing this formula to get it in terms of *m*, yields;

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Given that we have determined the *Volume* and the the density of the air parcel, we now must turn our attention to the velocity (*u*). If a time frame *T* is required for the parcel of air with thickness *D* to pass through the plane of the the wind turbine blades, then the parcel's velocity can be expressed as;

$$u = \frac{D}{T}$$

The air within this parcel also has a density ρ, and as density is mass per unit volume the density can therefore be expressed as;

Transposing this formula to get it in terms of *m*, yields;

$$m = \rho \times Vol$$

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Transposing this formula

$$D = u \times T$$

Substituting expressions into original formula for kinetic energy

$$KE = \frac{1}{2} mu^2$$

Substituting for *m*;

$$KE = \frac{1}{2} \times (\rho \times Vol) \times u^2$$

Vol can be replaced;

$$KE = \frac{1}{2} \times \left(\rho \times \left(\frac{\pi d^2}{4} \right) \times D \right) \times u^2$$

D can be replaced;

$$KE = \frac{1}{2} \times \left(\rho \times \left(\frac{\pi d^2}{4} \right) \times v \times T \right) \times u^2$$

Rewriting

$$KE = \frac{1}{2} \times \left(\rho \times \left(\frac{\pi d^2}{4} \right) \times T \right) \times u^3$$

Let us now consider the *Power* that can be achieved

$$Power = \frac{Energy}{Time}$$

$$Power = \frac{KE}{T}$$

$$Power = \frac{\frac{1}{2} \times \left(\rho \times \left(\frac{\pi d^2}{4} \right) \times T \right) \times u^3}{T}$$

Dividing by T

$$Power = \frac{1}{2} \times \left(\rho \times \left(\frac{\pi d^2}{4} \right) \right) \times u^3$$

if we divide the *Power* by the cross-sectional area (A) of the parcel, then we are left with the expression;

$$\frac{Power}{\left(\frac{\pi d^2}{4} \right)} = \frac{1}{2} \times (\rho) \times u^3$$

Examining this equation two important things can be identified

- the Power is proportional to the cube of the wind speed
- by dividing the Power by the area, an expression that is independent of the size of the wind turbines rotor is achieved

The Source of Wind Energy is the Day-Night Cycle Due to Temperature Variations. It is Renewable and Provides Clean Mechanical and Electrical Power to Meet the Needs of Human Beings without Disturbing the Ecosystem.

CHAPTER 7

Wind Energy

7.1 INTRODUCTION

In the past, wind energy was used (i) to propel ships (ii) to produce mechanical energy for pulling up underground water from wells and (iii) grinding agriculture products. There is also evidence that suggests that the ancient Egyptians used windmills to pump water for irrigating agricultural lands and to grind grains during 3600 B.C. Wind is simply air in motion that carries kinetic energy with it. The kinetic energy is converted into first mechanical and then electrical energy by generation. The mechanical energy of wind can be used for driving ships, pumping water, grinding grains, *etc*.

The harnessing of electrical power from wind is gaining momentum due to the depletion of fossil fuels and their rising running cost. Moreover, wind energy is considered to be a green/clean power technology. It has minor impacts on the economy and environment. Hence, wind energy, which is a renewable sources of energy, can be harnessed to provide an environmentally friendly and reliable source of energy without producing any air pollutants or greenhouse gases. The kinetic energy of wind is captured by the wind turbine that is mechanically coupled to an electrical generator. The turbine is mounted on a tall pillar to enhance the energy capture. In the 19th century, wind turbines contributed greatly to the economic development of many countries like the Netherlands, Denmark and the USA. The use of wind energy declined very fast everywhere due to the cheap availability and exploitation of coal, oil and gas resources.

The old wind turbines were no longer economically competitive with conventional sources of energy. Therefore, very little research was done to develop new and more efficient wind turbines. Due to the energy crisis during 1973 the development of new and more efficient wind turbines was resumed to generate electricity. As a result, the cost of electricity produced by wind turbines decreased dramatically due to improved technology. Nowadays, the extraction of electrical power with modern turbines from the wind is an established industry. A device for direct mechanical work is often called a windmill or just wind turbines. If electricity is produced, the combination of turbine and generator may be called a wind generator or aerogenerator that is also referred as a **wind energy-conversion system (WECS)**.

Generated electricity from wind has been used in three modes namely (a) small wind electric generators below 4 kW capacity for battery chargers; (b) wind electric generators in the range of 20 to 100 kW in standalone model supplemented by power from diesel generator sets and (c) wind electric generators in the range of 50 to 300 kW capacities have been used in grid-connected wind farms.

Advanced Renewable Energy Sources
G. N. Tiwari and R. K. Mishra

Published by the Royal Society of Chemistry, www.rsc.org

Being a clean and ecofriendly, wind energy has the limitation of its intermittent nature, like solar energy. Wind potential is a localised concept in comparison with solar energy. Power fluctuations due to uncertainty of wind, variations in magnitude and directions of wind velocities, structural instability due to heavy gusts and cyclonic storms are also some of the problems associated with wind energy-conversion systems. It can be harnessed in a clean and inexhaustible manner through the application of technically advanced and efficient systems.

7.2 HISTORICAL DEVELOPMENT

The wind has played a long and important role in the history of human civilisation. Wind power has been harnessed by mankind for thousands of years. Since the earliest recorded history, wind power has been used to move ships, grind grain and pump water. There is evidence that wind energy was used to propel boats along the Nile River as early as 5000 B.C. The first true windmill, a machine with vanes attached to an axis to produce circular motion, may have been built as early as 2000 B.C. in ancient Babylon. By the 10th century A.D., windmills with wind-catching surfaces as long as 16 feet and as high as 30 feet were grinding grain in the area now known as eastern Iran and Afghanistan. The western world discovered the windmill much later. The earliest written references to working wind machines date from the 12th century. These were used for milling grain. It was not until a few hundred years later that windmills were modified to pump water and reclaim much of Holland from the sea. The first horizontal-axis windmill appeared in England around 1150, in France 1180, in Flanders 1190, in Germany 1222 and in Denmark 1259. This fast development was most likely influenced by the Crusaders, taking the knowledge about windmills from Persia to many places in Europe. The people of Holland improved the basic design of the windmill. They gave it propeller-type blades made of fabric sails and invented ways for it to change direction so that it could continually face the wind. Windmills helped Holland become one of the world's most industrialised countries by the 17th century. The first person, who generated in 1891 electricity from wind speed, was the Dane Poul LaCour, who lived in Denmark. He had also received meteorology education and used the wind tunnel for the first time in order to obtain some theoretical formulations. Danish engineers improved the technology during World Wars I and II and used the technology to overcome energy shortages.

In Europe, windmill performance was constantly improved between the 12th and 19th centuries. By 1800, about 20 000 modern European windmills were in operation in France alone. And in the Netherlands, 90% of the power used in industry was based on wind energy. Industrialisation then led to a gradual decline in windmills, but even in 1904 wind energy provided 11% of the Dutch industry energy and Germany had more than 18 000 units installed. American colonists used windmills to grind wheat and corn, pump water, and cut wood. As late as the 1920s, Americans used small windmills to generate electricity in rural areas without electric service. When power lines began to transport electricity to rural areas in the 1930s, local windmills were used less and less, though they can still be seen on some Western ranches. The popularity of windmills in the US reached its peak between 1920 and 1930 with about 600 000 units installed. Various types of American windmills are still used for agricultural purposes all over the world.

In the 1930s and 1940s, hundreds of thousands of electricity producing wind turbines were built in the US. They had two or three thin blades, which rotated at high speeds to drive electrical generators. These wind turbines provided electricity to farms beyond the reach of power lines and were typically used to charge storage batteries, operate radio receivers and power a light bulb or two. By the early 1950s, however, the extension of the central power grid to nearly every American household, *via* the Rural Electrification Administration, eliminated the market for these machines.

The popularity of using the energy in the wind has always fluctuated with the price of fossil fuels. When fuel prices fell after World War II, interest in wind turbines waned. But when the price of oil skyrocketed in the 1970s, so did worldwide interest in wind-turbine generators. The wind-turbine technology R&D that followed the oil embargoes of the 1970s refined old ideas and introduced new ways of converting wind energy into useful power. Many of these approaches have been demonstrated in "wind farms" or wind-power plants – groups of turbines that feed electricity into the utility grid – in the US and Europe. The wind technology has improved step by step since the early 1970s. By the end of the 1990s, wind energy had re-emerged as one of the most important sustainable energy resources.

Today, the lessons learned from more than a decade of operating wind power plants, along with continuing R&D, have made wind-generated electricity very close in cost to the power from conventional utility generation in some locations.

As for the background in Turkey, wind energy has always played an important role in the historical and economical development of Asia Minor and the geographical area covered by the Republic of Turkey today. The earliest documented evidence of this statement goes back to the ancient city of Troia. It is not known when the first windmills were installed in Anatolia. However, they must have been dominant landmarks already in the 14th century. A naval map dated 1389 AC shows windmills as landmarks along with the shallows and sand banks in the Bay of Izmir.[1]

In the 1940s windmills ground corn, pumped water to fields and even powered the first radio sets at the Anatolia countryside. Based on a survey performed by the Turkish Ministry of Agriculture between 1960 and 1961, there were 749 windmills. Of these, 718 were used for water pumping, while 41 were for generating electricity. Two surveys between 1966–1967 and 1978–1979 revealed 309 and 894 units, of which 2 and 23 were electricity-producing turbines with capacities lower than 1 kW, respectively. Since the 1960s, several universities have conducted studies on wind energy. The Turkish Scientific and Technologic Research Institution (TUBITAK) Marmara Research Centre has started with studies towards developing a wind atlas for Turkey since the 1980s. The General Directorate of Electrical Power Resources Survey Administration (EIE) has made some wind measurements. Electricity generation through wind energy for general use was first realised at the Cesme Altinyunus Resort Hotel (The Golden Dolphin Hotel) in Izmir, Turkey in 1986 with a 55-kW nominal wind power capacity. This hotel with 1000 beds consumes about 3 million kWh of electrical energy annually, while the windmill installed produces 130 000 kW h per year approximately. Between 1986 and 1996, there were some attempts to generate electricity from wind, but they were never successful. In 1994, the first build-operate-transfer (BOT) feasibility study for a wind energy project in Turkey was presented to the Ministry of Energy and Natural Resources of Turkey (MENR).[2] Apart from initial high investment costs in harnessing wind energy, lack of adequate knowledge on the wind-speed characteristics in the country is the main reason for the failure to harvest the energy from wind. In terms of generating electricity from wind, the development of wind energy in Turkey started in 1998 when some wind plants were installed at several locations in the country. By January 1998, there were 25 applications for wind energy projects recorded at the MENR. To date, three wind power plants have been installed with a total capacity of about 18.9 MW. Considering the installation of a wind plant with a capacity of 1.2 MW in November 2003, the total installed capacity will reach 20.1 MW. Recently, small wind-turbine systems with capacities ranging from 1.5 to 5 kW have also been installed in some Turkish universities for conducting wind energy investigations as well as for lighting purposes.[3] Wind energy projections made by some institutions and organisations, such as the International Energy Agency, European Commission and BTM Consult ApS, differ from each other, as given in detail elsewhere. These projections are based on the studies performed between 1997 and 2000.[4] According to a forecast of 2003 made by BTM Consult ApS for the period up to 2007, an average growth rate of 11.2% yearly is projected, while for 2003 a growth of 24% over 2001 is expected. Total demand during the 5-year period is estimated to be 51 000 MW. By the end of 2007, 83 000 MW of capacity will be on line, of which 58 600 MW is in Europe. According to long term prediction up to 2012, an annual installation level of 24 000 MW by 2012 is expected. Cumulative installation growth to 177 000 MW is projected to equal a penetration of wind power close to 2% of the world's electricity consumption by 2012.

7.3 BASIC CONCEPTS OF LIFT AND DRAG FORCES

Flowing of fluid air over the solid bodies frequently occurs in practice. It is responsible for numerous physical phenomena namely the lift force development by airplane wings, dust particles in high-wind turbines, *etc*., and the drag force acting on automobiles, trees, *etc*. The two processes, namely fluid moves over a stationary body and body moves through a quiescent fluid are equivalent to each other. The relative motion between the body and the fluid is important. These motions are referred to as flow over bodies or external flow.

7.3.1 Drag Force (*D*)

When a body is forced to move through a fluid especially through a liquid, it is found that the body meets some resistance. It is well known that it is very difficult to walk in water because of the much greater resistance offered by water to motion as compared to air. It is also felt that the strong push is exerted by the flowing wind on the human body. **The force exerted by a flowing fluid on a body in the flow direction is called drag force**. It can be directly measured by attaching the body subjected to fluid flow to a calibrated spring and measuring the displacement in the flow direction of. Drag is usually an undesirable effect, like friction and is minimised as far as practicable. Reduction of drag is closely associated with the reduction of fuel consumption in automobiles, submarines, aircraft, *etc*. In some cases drag produces a very beneficial effect and is maximised. Friction for example is a life saver in the brakes of automobiles. Likewise, it is the drag that helps people to parachute, pollen to fly to distant locations, *etc*.

7.3.2 Lift Force (*L*)

A stationary fluid exerts only normal forces on the surface of a body immersed in it. A moving fluid, however, also exerts tangential shear forces on the surface of a body. Both of these forces have the components in the direction of the flow. Hence, drag force is due to the combined effects of pressure and wall shear forces in the flow direction. The components of pressure and wall-shear forces in the direction normal to the fluid flow that tend to move the body in that direction are called lift.

In a moving car when a hand is extended out of the window, the hand is moved towards the rear side of the car and due to lift force, it is moved towards the ceiling of the car. Hence, both the lift and drag forces act on a body immersed in a mass of moving fluid, as shown in Figure 7.1.

Let P and τ be pressure (N/m^2) and wall shear stress (viscous force) acting at M, as shown in the Figure 7.2. The θ is an angle of incidence of wind on a body. The net pressure and shear force on a differential area dA are $P\mathrm{d}A$ and $\tau\mathrm{d}A$, respectively. Let a body held stationary in a stream of air (fluid) moving at a uniform velocity v_0. The pressure force $P\mathrm{d}A$ acts normal to the surface and the shear force $\tau\mathrm{d}A$ acts along the tangential direction of the body. The drag force on the body is therefore the sum of the components of both pressure force ($P\mathrm{d}A$) and shear force ($\tau\mathrm{d}A$) acting over the entire surface of the body in the direction of motion.

The component of the shear force in the direction of flow of fluid is called the friction drag ($\mathrm{d}F_{\mathrm{Df}}$) that may be expressed as

$$\text{Friction drag } \mathrm{d}F_{\mathrm{Df}} = \tau \mathrm{d}A \cos\theta$$

Similarly, the components of the pressure forces in the direction of the fluid motion is called the pressure drag $\mathrm{d}F_{\mathrm{DP}}$ and is expressed as

$$\text{Pressure drag } \mathrm{d}F_{\mathrm{DP}} = P \mathrm{d}A \sin\theta$$

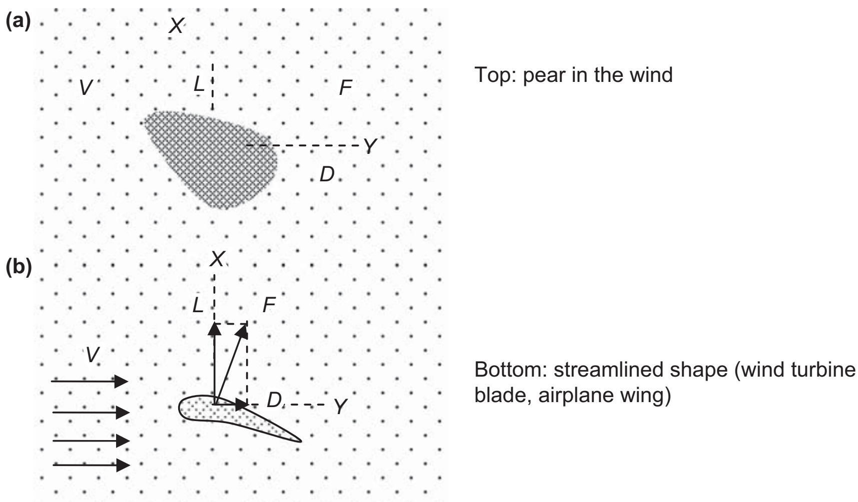


Figure 7.1 View of lift and drag forces in the immersed bodies (V = wind velocity, F = net force exerted by the wind on blade).

The net differential drag force dF_D acting on the body is therefore equal to the sum of the friction drag and the pressure drag. Thus

$$dF_D = dF_{DF} + dF_{DP} = \tau dA \cos\theta + PdA \sin\theta \tag{7.1}$$

The relative magnitude of the total drag depends on the shape and position of the immersed body.

For example:

(i) if a thin flat plate is held immersed in a fluid, parallel to the direction of flow, the pressure drag ($PdA \sin\theta$) is practically equal to zero due to minimum value of dA, hence the differential drag force (dF_D), which is only the friction drag (dF_{DF}) becomes

$$dF_D = \tau dA \cos\theta$$

(ii) if the same plate is held perpendicular to the air flow, the friction drag ($\tau dA \cos\theta$) is equal to zero and the total drag is due to the pressure difference between the upstream and downstream sides of the plate hence the differential drag force (dF_D) becomes

$$dF_D = PdA \sin\theta$$

In between these two extreme cases, there are several shapes of the body for which the contribution of each of the two components to the total drag varies considerably depending on the shape and position of the immersed body and the flow and fluid characteristics.

Similarly, the net lift force (dF_L) on the differential body is given by the sum of the components of shear and the pressure forces acting over the surface of the body (dA) in the direction perpendicular to the direction of the fluid motion. Thus,

$$dF_L = \tau dA \sin\theta - PdA \cos\theta \tag{7.2}$$

The total drag and lift forces acting on the body can be determined by integrating Eq. (7.1) over the entire surface of the body. This is not practical since the detailed distributions of pressure and

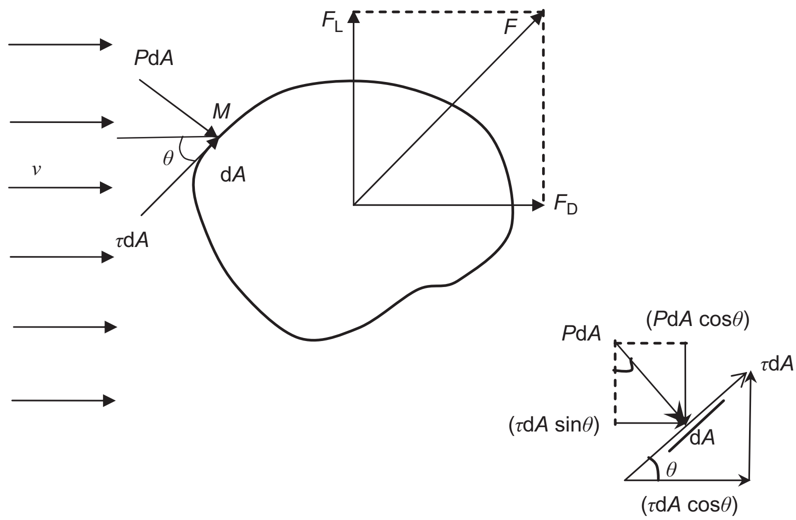


Figure 7.2 View of components of pressure and frictional forces on an element of surface of an immersed body.

shear forces over the entire surface are difficult to obtain by analysis or measurement. In practice, the resultant drag and lift forces acting on the entire body can be measured directly in a wind tunnel.

The airfoil of the wind turbine is shaped specifically to produce the maximum lift force when coming into contact with the flowing air. This is achieved by making the top surface of the airfoil curved and the bottom surface nearly flat. The fluid flowing over the airfoil travels a longer distance to reach the end of the airfoil causing a pressure difference, as mentioned earlier. The pressure difference generates an upward force that tends to lift the airfoil and thereby the rotation of the rotor of the wind turbine. The drag and lift forces depend on the density (ρ) of the fluid, the upstream velocity of the wind (v_0), size, shape and orientation of the body. It is better to work with appropriate dimensionless numbers that represents the drag and lift characteristics of the body. These numbers are the drag coefficients (C_D) and lift coefficients (C_L) and they are defined as

$$\text{Drag coefficient, } C_D = \frac{F_D}{\frac{1}{2}\rho v_0^2 A} \tag{7.3}$$

$$\text{Lift coefficient, } C_L = \frac{F_L}{\frac{1}{2}\rho v_0^2 A} \tag{7.4}$$

where A is the frontal area projected on a plane normal to the direction of the flow of the body. The frontal area of a cylinder of diameter D and length L, for example is $A = LD$.

For an airfoil of width (or span) b and chord length c (the length between the leading edge and trailing edge), the platform area $A = bc$. In most cases the drag and lift coefficients are functions of the shape and roughness of the body. The term $\frac{1}{2}\rho v_0^2$ is the dynamic pressure due to wind.

It is desirable for airfoils to generate the most lift force while producing the least drag. Therefore, a measure of performance of airfoil is the lift to drag ratio, which is equivalent to the ratio of lift to drag coefficients C_L/C_D. This information is provided by either plotting C_L versus C_D for different values of the angles of attack as shown in Figure 7.3. The ratio C_L/C_D increases with the angle of attack, until the airfoil stalls. Similarly, the variations of C_D as well as C_L/C_D with the angle of attack for an airfoil NACA 0012 are shown in Figures 7.4 and 7.5. From these figures it is seen that

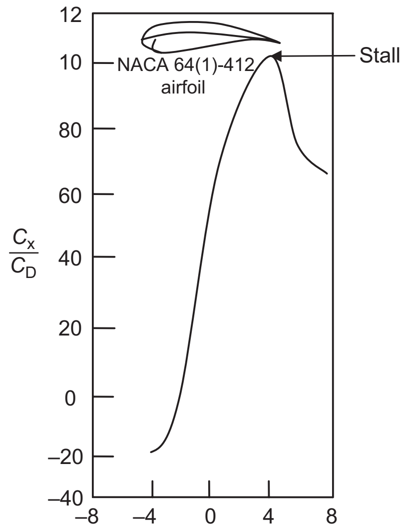


Figure 7.3 Effect of the angle of attack of an airfoil on lift-to-drag ratio.

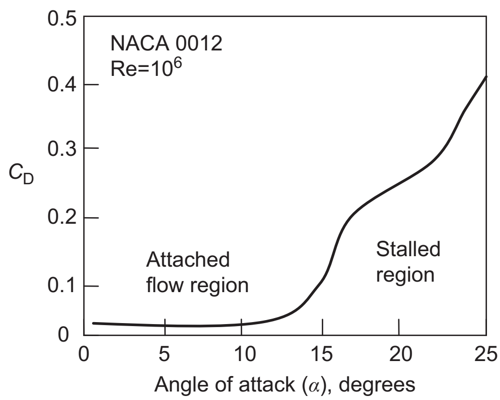


Figure 7.4 Effect of the angle of attack of an airfoil on C_D for the NACA 0012 aerofoil.

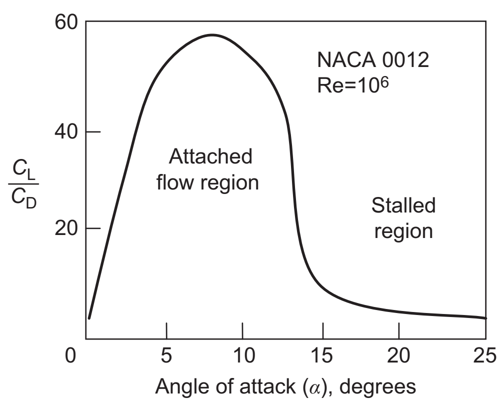


Figure 7.5 Effect of the angle of attack of an airfoil on Lift/Drag ratio for the NACA 0012 aerofoil.

there is no significant variation of C_D with the increase of the angle of attack. C_D increases abruptly when the angle of attack exceeds 13° and the airfoil stalls. The values C_L/C_D from Figure 7.5 are seen to be highest at around a 10° angle of attack. Therefore, the lift/drag ratio has a significant effect upon the efficiency of a wind turbine and it is desirable that a turbine blade must operate at the maximum ratio for better energy extraction from the wind.

7.4 TYPES OF TURBINE

There are two types of wind energy-conversion devices namely, aerodynamic lift and aerodynamic drag, which is also referred to as wind turbines (rotors).

7.4.1 Lift Type Wind Turbine

A high-speed turbine depends on lift forces to move the blades of the wind turbine. The linear speed of the blades is usually several times higher than the wind speed. The torque of lift force is low as compared to the drag type.

7.4.2 Drag Type Wind Turbine

Low-speed turbines are slower than the wind. They are mainly driven by the drag force. The torque at the rotor shaft is relatively high. Wind turbines are classified as (a) horizontal axis and (b) vertical axis wind turbines. In horizontal-axis turbines the axis of rotation is horizontal with respect to the ground. In this case, the rotating shaft is parallel to the ground and the blades are perpendicular to the ground. In vertical-axis turbines, the axis of rotation is vertical with respect to the ground. The configurations of horizontal- and vertical-axis turbines are shown in Figure 7.6. Horizontal-axis or propeller-type turbines are more common and highly development than the vertical-axis designs.

Vertical-axis machines operate independently in the wind direction. Gear box and generating machinery can be directly coupled to the axis at the ground level, as shown in Figure 7.6. Vertical-axis machines have the following disadvantages: they are not self-starting, the speed regulation in high winds is difficult; the torque fluctuates with each revolution as the blades move into and away

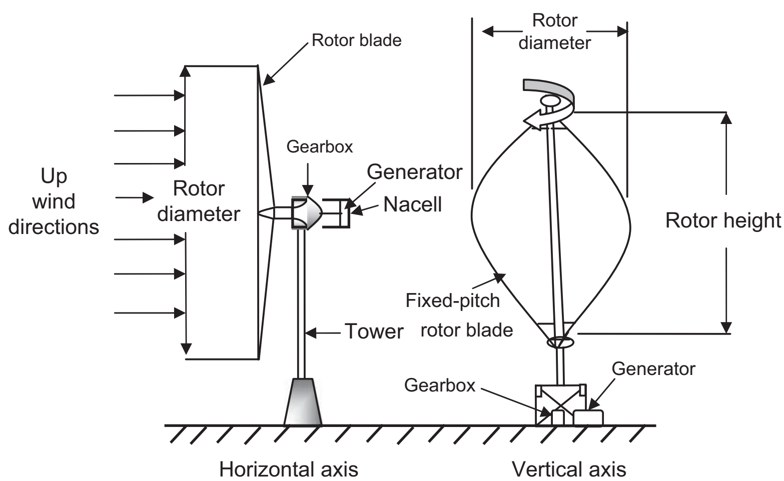


Figure 7.6 View of horizontal-axis and vertical-axis wind turbine.

from the wind. Due to these disadvantages, most working machines are of the horizontal-axis type. The various types of vertical-axis wind turbines are as follows:

(a) **Anemometer:** This rotates by drag force. Due to the small size of the cup, there is a linear relationship between rotational frequency and wind speed ($v = r\omega$).
(b) **Savonius rotor (turbo machine):** There is a complicated motion of wind through and around the two curved sheet airfoils rotates by drag force, has a simple construction and is inexpensive.
(c) **Darrieus rotor:** This rotator consists of two or three curved blades; the driving forces are lifting forces. The maximum torque occurs when a blade is moving across the wind of a speed much high than the wind speed. Initial movement may be initiated with the electrical generator used as a motor.
(d) **Musgrove rotor:** In this rotor, the blades are vertical for normal power generation. This rotor has an advantage of fail-safe shut down in strong winds.
(e) **Evans rotor:** Vertical blades twist about a vertical axis speed for control and a fail-safe shut down.

Rotors can also be classified on the basis of their movement at variable speed or constant speed. For water pumping and small-battery operation, it is desirable to allow the rotor speed to vary. However, for the large scale generation of electricity, it is common to operate wind turbines at constant speed. This allows the use of simple generators whose speed is fixed by the frequency of the electrical network. Variable-speed wind turbines are sometimes used for electricity generation but a power electronic frequency converter is then required to connect the variable frequency output of the wind turbine to the fixed frequency of the electrical system.

7.5 AERODYNAMICS OF WIND TURBINE

In wind turbines, aerodynamics deals with the relative motion between the moving air and the stationary airfoil. The airfoil is the cross section of the blade of the wind turbine. It is the shape designed to create maximum lift force when air flows over it. In the wind turbine, linear kinetic energy associated with the wind is converted into the rotational motion that is required to turn the electrical generator for power generation. This change is accomplished by a rotor that has one, two or three blades or airfoils attached to the hub. The wind flowing over the surfaces of these airfoils generates the forces that cause the motor to run. The basic principle of aerodynamics of a horizontal-axis wind turbine is shown in Figure 7.7a.

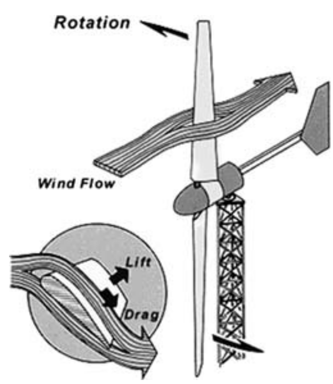


Figure 7.7a View of wind turbine aerodynamic lift.

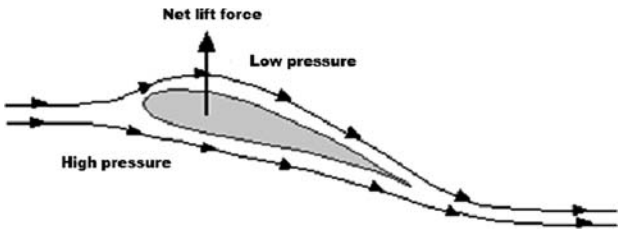


Figure 7.7b View of aerodynamic lift force on an airfoil section of wind turbine.

Wind passes more rapidly over the longer (upper) path of the airfoil in comparison to the shorter (lower) path, as shown in Figure 7.7b. High- and low-pressure regions can be identified by using Bernoulli's equation (Chapter 1). The pressure is low at locations where the flow velocity is high and the pressure is high at locations where flow velocity is low. Therefore, low pressure is created in the upper surface of the airfoil and high pressure in its lower surface. The pressure difference between the top and bottom surfaces of the airfoil results in a force called the aerodynamic lift as air moves from the high-pressure region to the low-pressure region. The upward force due to aerodynamic lift pushes the blades to move up. Since the blades of the wind of the wind turbine are constrained to move up with the hub at its centre, the lift force causes the rotation of the blade about the hub. Air flowing smoothly over an airfoil produces two forces; the force perpendicular to the air flow and drag, which acts in the direction of flow.

In wind turbines, the drag force perpendicular to the lift force also acts on the blade causing the impediment or rotor rotation. The prime objective in wind-turbine design is for the blade (airfoil-shaped) to have a relatively high lift to drag ratio. This ratio can be varied along the length of the blade to optimise the output energy of the turbine at various wind speeds. Hence, in aerodynamic analysis of wind turbines, both lift and drag forces are important for their optimisation in efficient design. In the next section, the basic concept of lift and drag forces are discussed.

7.6 MOMENTUM THEOREM

The simplest model for wind-turbine aerodynamics is the momentum theorem. In this model, the rotor is approximated by an actuator disk. The kinetic energy of the wind is extracted in the wind turbines. After extraction of kinetic energy, the velocity of flowing wind decreases. Further, the affected mass of air due to the rotor disk remains separate from the air that does not pass through the rotor disk. Pressure energy can be extracted in a step-like manner. Hence, the model assumes a sudden drop in pressure at the rotor disk. The variation in velocity is assumed to be smooth from far upstream. The air then proceeds downstream with reduced speed and static pressure. This region of flow is called the **wake**. Eventually, the static pressure in the wake becomes the atmospheric level at far downstream. The rise of static pressure is at the expense of the kinetic energy and thereby wind speed further decreases. Thus, between the far-upstream and far-wake conditions, no change in static pressure exists, but there is a reduction in kinetic energy.

The device that carries out the extraction process is called an actuator disk, as shown in the Figure 7.8.

The assumptions for this model are as follows:

- flow is regarded as an incompressible fluid;
- sudden drop in pressure occurs at the rotor disk;
- the flow velocity varies smoothly and in a continuous manner from far upstream to far downstream;

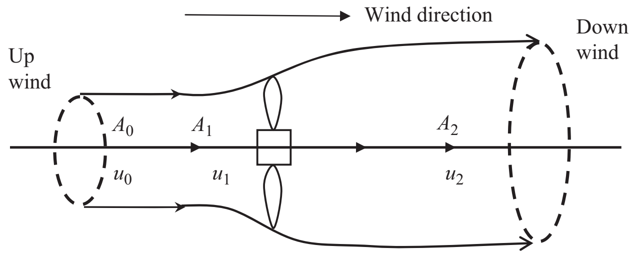


Figure 7.8 Flow diagram of energy extraction actuator disk of wind turbine.

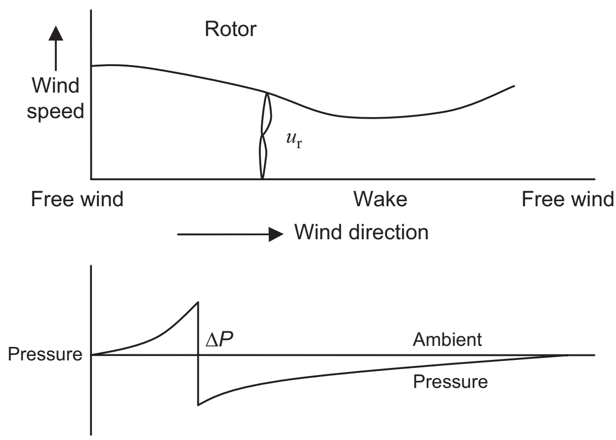


Figure 7.9 Conditions in traversing a wind turbine.

- the rotation of wake after rotor is ignored;
- the flow is steady;
- the mass flow rate is constant at far upstream, at the rotor and at far downstream.

The variations of wind speed as well as pressure in the actuator disk (rotor) are shown in Figure 7.9.

7.6.1 Energy Extraction

The kinetic energy of the air stream passing through the turbine rotor as shown in Figure 7.10 of cross-sectional area A per unit time is expressed as

$$\text{kinetic energy per unit time} = \frac{1}{2}\left(\frac{m}{t}\right)v_0^2 = \frac{1}{2}(\rho A_1 v_0)(v_0^2) = \frac{1}{2}\rho A_1 v_0^3$$

Here, ρ is the air density and v_0 is the free wind speed in the upstream side of the airflow. The above expression also represents the power in the wind at the speed v_0.

Hence, the initial power associated with wind is given by

$$P_0 = \frac{1}{2}\rho A_1 v_0^3 \tag{7.5}$$

For $\rho = 1.2$ kg/m^3 at sea level and
(i) $v_0 = 10$ m/s, $P_0 = 600$ W/m^2 and (ii) $v_0 = 25$ m/s, $P_0 = 10\ 000$ W/m^2

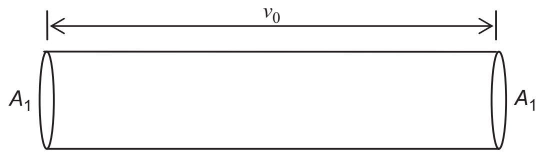


Figure 7.10 Cross-sectional view of the wind-turbine rotor.

In case (i), the input power in 600 W/m^2, which is equivalent to the average daily insolation on horizontal surface, *i.e*. 500 W/m^2. Hence, the optimum wind velocity for power extraction should be 10 m/s.

In Figure 7.8, A_1 is the rotor swept area and A_0 and A_2 are area of upwind and downwind enclose the stream of constant air mass passing through A_1.

The force (F) or thrust on the wind turbine (actuator) is the rate of change of momentum from the air mass flow rate $\dot{m}$, which is given by

$$F = \dot{m}v_0 - \dot{m}v_2 \tag{7.6}$$

The power extracted by the wind turbine is obtained by multiplying force/thrust and v_1 as

$$P_T = Fv_1 = (\dot{m}v_0 - \dot{m}v_2)v_1 \tag{7.7}$$

The rate of loss of kinetic energy of wind flowing across the wind turbine is given by

$$P_w = \frac{1}{2}\dot{m}(v_0^2 - v_2^2) \tag{7.8}$$

By equating Eqs. (7.7) and (7.8), one gets

$$(v_0 - v_2)v_1 = \frac{1}{2}(v_0^2 - v_2^2) = \frac{1}{2}(v_0 - v_2)(v_0 + v_2) \tag{7.9}$$

or,

$$v_1 = \frac{v_0 + v_2}{2} \tag{7.10}$$

The mass of air flowing through the disk per unit time is given by

$$\dot{m} = \rho A_1 v_1 \tag{7.11}$$

Substituting the expression for $\dot{m}$ from Eq. (7.11) in Eq. (7.12) one gets,

$$P_T = \rho A_1 v_1^2(v_0 - v_2) \tag{7.12}$$

Now, substituting the expression for v_2 from Eq. (7.10) in Eq. (7.12), one gets

$$P_T = \rho A_1 v_1^2\{v_0 - (2v_1 - v_0)\} = 2\rho A_1 v_1^2(v_0 - v_1) \tag{7.13}$$

If the interference factor or perturbation factor (a) is defined as the fractional decrease of wind speed at the wind turbine as,

$$a = \left(\frac{v_0 - v_1}{v_0}\right) \Rightarrow v_1 = (1 - a)v_0 \tag{7.14a}$$

Sometimes $b = \dfrac{v_2}{v_0}$ is also referred to as the interference factor (7.14b)

Now, using Eq. (7.10) in Eq. (7.13),

$$a = \left(\frac{v_0 - v_2}{2v_0}\right) \Rightarrow v_2 = (1 - 2a)v_0 \tag{7.15a}$$

From Eqs. (7.14b) and (7.15a) one can get

$$b = 2a \tag{7.15b}$$

Now, using Eq. (7.14) in Eq. (7.13)

$$P_T = 2\rho A_1(1 - a^2)v_0^2[v_0 - (1 - a)v_0]$$

or,

$$P_T = \frac{1}{2}\rho A_1 v_0^3\left[4a(1 - a)^2\right] \tag{7.16}$$

or,

$$P_T = C_P P_0 \tag{7.17}$$

where,

$$C_P = 4a(1 - a)^2 \tag{7.18a}$$

P_0 is the power of free wind and C_P, the fraction of power extracted, also called the power coefficient.

In order to maximise the value of C_P, differentiate Eq. (7.18a) with respect to "a", we have

$$\frac{dC_p}{da} = 1 + 3a^2 - 4a = 0$$

Thus, $a = 1$ or $1/3$, $a \neq 1$ as $C_p = 0$ when $a = 1$ and hence $a = 1/3$

Putting the value of $a = 1/3$ in Eq. (7.18a) one can get

$$C_{p\max} = \frac{16}{27} = 0.59$$

With the help of Eq. (7.14b), an expression for C_p can also be written as

$$C_P = \frac{1}{2}(1 - b)(1 + b)^2 \tag{7.18b}$$

EXAMPLE 7.1

By using Eq. (7.18b), find the condition for maximum "C_p".

Solution: From Eq. (7.18b), one has

$$C_P = \frac{1}{2}(1-b)(1+b)^2$$

For the maximum value of "C_p", differentiate the above equation with respect to "b" and equate it to zero, one gets

$$\frac{dC_p}{dt} = \frac{1}{2}\left[(1-b)\times 2(1+b) + (1+b)^2 \times (-1)\right]$$
$$= \frac{1}{2}(1+b)(1-3b) = 0 \Rightarrow b = -1 \text{ or } \frac{1}{3}$$

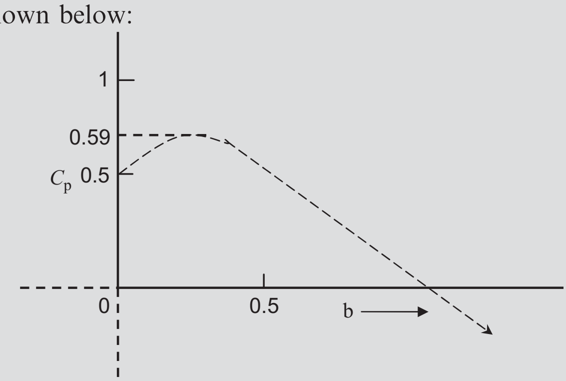
Since v_2 is not negative, condition $b = 1/3$ is valid.

For $b = 1/3, C_p = \frac{1}{2}\times\frac{2}{3}\times\frac{4}{3}\times\frac{4}{3} = \frac{16}{27} = 0.59$

EXAMPLE 7.2

Plot the curve between "C_p" and "b" (Example 7.1) and compare it with Figure 7.15.

Solution: The variation of "C_p" and "b" can be obtained by using Eq. (7.18b). The variation of "C_p" and "b" is shown below:



The above figure shows that

(i) The C_p is maximum at $b = 1/3$ and the same at $a = 1/3$.
(ii) The C_p is zero at b = 1 or $v_2 = v_0$ as expected.
(iii) The turbine loses power for $b > 1$.

7.6.2 The Betz Limit

The Betz limit is the maximum achievable value of the power coefficient. This limit is applied to all types of wind turbine set in an extended fluid stream. This is also applied to power extraction from tidal and river sources. With conventional hydropower system, water reaches the turbine from a

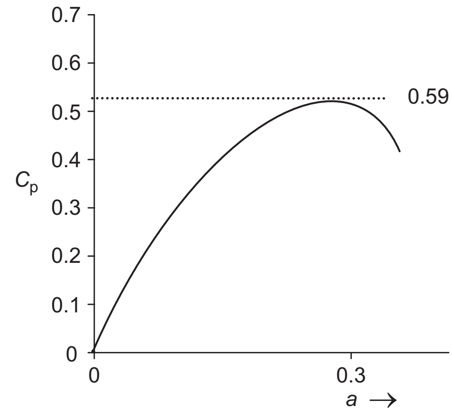


Figure 7.11 Effect of interference factor 'a' on power coefficient (C_p).

pipe and therefore this limit is inapplicable for a wind turbine which is not in extended flow condition. The variation of "C_p" with "a" has been shown in Figure 7.11.

Modern designs of wind turbines for electricity generation operate at C_p values of about 0.4. The major losses in efficiency for a real wind turbine arise from the viscous drag on the blades. While deriving C_p, the power coefficient, the extraction of power has to be taken from the mass of air in the stream to be through the activator disk of area A_1.

The power extracted per unit area of cross section equal to A_0 in the upstream side is greater than the power extracted per unit area of A_1. This is due to the fact that $A_0 < A_1$ and $v_0 > v_1$.

For maximum power extraction, we have $a = 1/3$

$$a = \frac{v_0 - v_1}{v_0} = \frac{1}{3} \Rightarrow 2v_0 = 3v_1 \Rightarrow v_0 = \frac{3}{2}v_1 \Rightarrow \frac{v_0}{v_1} = \frac{3}{2} \Rightarrow v_0 = \frac{3}{2}v_1$$

The mass flow rate is constant throughout, *i.e.*

$$\rho A_0 v_0 = \rho A_1 v_1 = \rho A_2 v_2 = \dot{m} \Rightarrow \frac{v_0}{v_1} = \frac{A_1}{A_0}$$

After substituting the value of $\frac{v_0}{v_1}$ in the above equation we get

$$\frac{A_1}{A_0} = \frac{v_0}{v_1} = \frac{3}{2} \Rightarrow A_1 = \frac{3}{2}A_0$$

For $C_p = \frac{16}{27}$ the maximum mechanical power output $= \frac{16}{27}\left(\frac{1}{2}\rho A_1 v_0^3\right)$ (Eq. (7.17))

The power of the wind at the upstream side is $\left(\frac{1}{2}\rho A_1 v_0^3\right)$

Thus, an overall mechanical efficiency of wind turbine is given by

$$\eta_m = \frac{\textit{output maximum mechanical power}}{\textit{input power}} = \frac{\left(\frac{16}{27}\right)\left(\frac{1}{2}\rho A_1 v_0^3\right)}{\left(\frac{1}{2}\rho A_0 v_0^3\right)} = \frac{16}{27}\left(\frac{A_1}{A_0}\right)$$

or,

$$\eta_m = \left(\frac{16}{27}\right)\left(\frac{3}{2}\right) = \frac{8}{9} = 0.89 \tag{7.19}$$

Therefore, the maximum mechanical power extraction per unit area of A_0 is 8/9 of the power in the wind.

7.6.3 Thrust on Turbine

Bernoulli's equation can be used for evaluating the thrust on a wind turbine (actuator disk) in a stream line flow, as shown in Figures 7.12a and b, respectively.

Referring to Figure 7.12a, Bernoulli's equation for no power extraction can be written for the above system per unit mass as follows:

$$\frac{P_0}{\rho_0} + gz_1 + \frac{v_0^2}{2} = \frac{P_2}{\rho_0} + gz_2 + \frac{v_2^2}{2} \tag{7.20}$$

Since the change in z and ρ with respect to height and temperature are negligible as compared to other terms, the static pressure difference across a wind turbine is given by

$$\Delta P = P_2 - P_0 = \frac{(v_0^2 - v_2^2)\rho}{2} \tag{7.21}$$

The term $v^2\rho/2$ is the **dynamic pressure**. The maximum value of static pressure difference occurs as v_2 tends to zero.

Therefore,

$$\Delta P_{\max} = \frac{\rho v_0^2}{2} \tag{7.22}$$

The maximum thrust on the turbine can be obtained by multiplying the above equation area of wind turbine (A_1)

$$F_{\max} = \rho A_1 v_0^2/2 \tag{7.23}$$

On a horizontal-axis machine, the thrust is centred on the turbine axis and is called the axial thrust F_A.

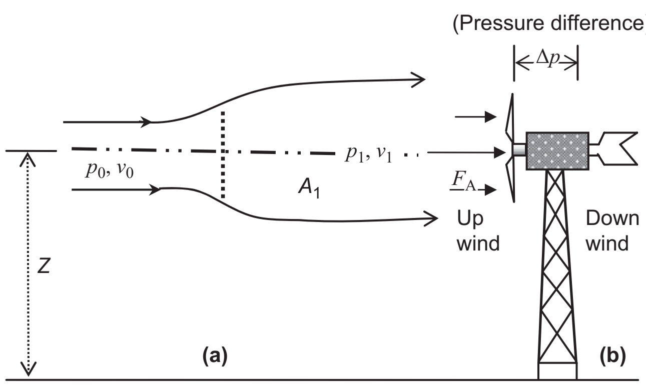


Figure 7.12 Force on turbine (a) air flow speed v, pressure p, height z, (b) axial force F_A, and pressure.

The thrust is also equal to the rate of loss of momentum of the air stream across the wind turbine and hence,

$$F_A = \dot{m}\,(v_0 - v_2)$$

Using Eqs. (7.11), (7.14) and (7.15), the above equation reduces to

$$F_A = (\rho A_1 v_1)\,(2v_0 a) = 2\rho A_1 v_0 (1-a) a v_0$$

$$F_A = \frac{\rho A_1 v_0^2}{2} 4a(1-a) \tag{7.24}$$

or,

$$F_A = C_F \frac{\rho A_1 v_0^2}{2} \tag{7.25}$$

The term $\frac{\rho A_1 v_0^2}{2}$ is the maximum force given by the actuator disk model (Eq. (7.23)) for wind hitting a solid disk. C_F is the axial force coefficient, *i.e*. the fraction of this force experienced by the actual turbine

$$C_F = 4a(1-a) \tag{7.26}$$

The maximum value of C_F would be 1 when $a = 1/2$, equivalent to $v_2 = 0$ from Eq. (7.19).

EXAMPLE 7.3

Determine the condition for maximum axial force coefficient (C_F) by using "b" as an interference factor.

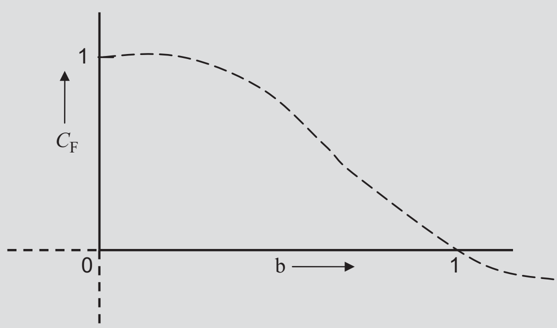
Solution: From Eq. (7.26), we have an expression for an axial force coefficient as

$$C_F = 4a(1-a)$$

Substituting $b = (1-a)/2$ in above equation one gets

$$C_F = 4 \times \frac{1-b}{2}\left[1 - \frac{1-b}{2}\right] = (1-b)\,(1+b)$$

Differentiating "C_F" with respect to "b" and equating it to zero, one gets



$$\frac{dC_F}{db} = (1-b) \times 1 + (1+b) \times (-1) = 0 \Rightarrow b = 0$$

EXAMPLE 7.4

Determine the condition for maximum "C_F" with respect to "a".
Solution: From Eq. (7.26) $C_F = 4a(1 - a)$
Differentiating "C_F" with respect to "a" and equating it to zero, one gets

$$\frac{dC_F}{da} = 4(1 - 2a) = 0 \Rightarrow a = \frac{1}{2}$$

Substituting the value of $a = 1/2$ in the expression of C_F, $C_F = 1$

EXAMPLE 7.5

Calculate C_F value of C_p at $a = 1/2$ and value of C_F at $a = 1/3$.
Solution: From Eq. (7.18a) $C_P = 4a(1 - a)^2$
Hence,

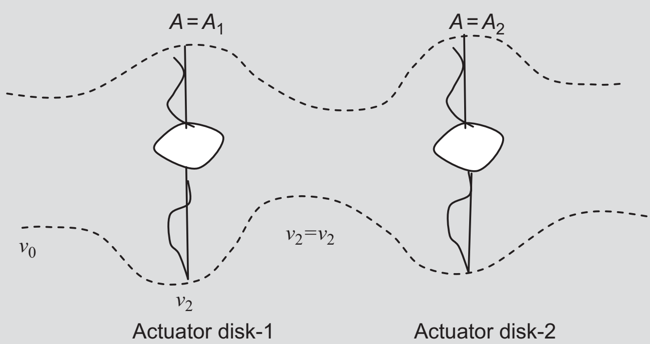
$$C_p \text{ at } a = \frac{1}{2} = 4 \times \frac{1}{2} \times \left(1 - \frac{1}{2}\right)^2 = 4 \times \frac{1}{2} \times \frac{1}{4} = \frac{1}{2}$$

From Eq. (7.26) $C_F = 4a(1 - a)$
Hence,

$$C_F \text{ at } a = \frac{1}{3} = 4 \times \frac{1}{3} \times \left(1 - \frac{1}{3}\right) = 4 \times \frac{1}{3} \times \frac{2}{3} = \frac{8}{9}$$

EXAMPLE 7.6

Derive an expression for the power coefficient for two activator disks (WECS) connected in series.
Solution: The two activator disks (WECS) connected in series are shown in the figure below:



Let us consider the prime notation for activator disk-1 and double prime notation for activator disk-2.

The overall power extraction from two activator disks connected in series as shown in the figure above, can be written as

$$P = P' + P'' = \frac{1}{2}\rho A v_0^3 C'_P + \frac{1}{2}\rho A {v'_2}^3 C''_P$$
$$= \frac{1}{2}\rho A v_0^3\left[C'_P + \left(\frac{v'_2}{v_0}\right)^3 . C''_P\right] = \frac{1}{2}\rho A v_0^3 . C_{Peff}$$

where,

$$C_{Peff} = C'_P + \left(\frac{v'_2}{v_0}\right)^3 . C''_P \text{ with } C'_P = 4a'(1-a')^2$$

From Eqs. (7.14b) and (7.15b), $\frac{v'_2}{v_0} = b' = 1 - 2a'$, so we have

$$C_{Peff} = C'_P + (1-2a')^3 . C''_P$$

For
$$C''_P = \frac{16}{27},\ C_{Peff} = 4a'(1-a')^2 + (1-2a')^3 . \frac{16}{27}$$

For the maximum value of C_{Peff}, differentiating C_{Peff} with respect to a' and equating to zero.

$$\frac{dC_{Peff}}{da'} = 0 \Rightarrow a' = 0.2$$

For $a' = 0.2$, $C_{Peff} = 0.64$

Here, we see that there is a small increase (0.04) in the value of C_{Peff} and hence it is not economical to have two disks connected in series.

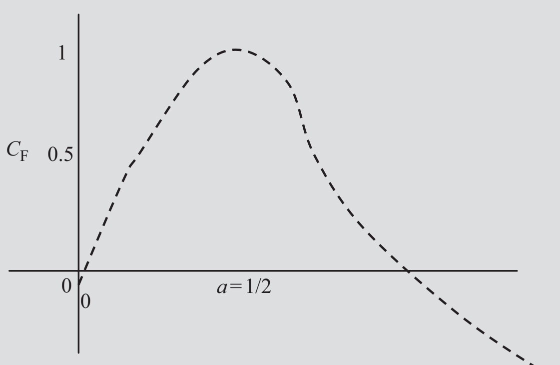
EXAMPLE 7.7

Plot the curve between an axial force coefficient (C_F) and "a". Compare the results obtained in Example 7.3.

Solution: From Eq. (7.26) an expression for C_F can be written as

$$C_F = 4a(1-a)$$

The variation of C_F with "a" is shown below:



7.6.4 Torque on Turbine

The maximum torque (Γ) on a wind turbine rotor occurs when the maximum force is applied at the blade tip farthest from the axis. For a parallel turbine of radius R, the maximum torque (Γ_{max}) is given by

$$\Gamma_{max} = F_{max} R$$

From Eq. (7.23), one has

$$F_{max} = \rho A_1 \frac{v_0^2}{2}$$

After substituting the expression of F_{max} from the above equation in expression for Γ_{max}, we have,

$$\Gamma_{max} = \rho A_1 v_0^2 R/2 \tag{7.27}$$

For a working wind machine producing a shaft torque Γ proportional to Γ_{max}

$$\Gamma \propto C_\Gamma \Gamma_{max}$$

or,

$$\Gamma = C_\Gamma \Gamma_{max} \tag{7.28}$$

where C_Γ is the torque coefficient.

The tip-speed ratio (λ) is defined as the ratio of the outer blade tip speed (v_t) to the unperturbed (free) up wind speed v_0, *i.e.*

$$\lambda = \frac{v_t}{v_0} = \frac{R\omega}{v_0} \Rightarrow R = \frac{\lambda v_0}{\omega} \tag{7.29}$$

where R and ω are the outer blade radius and the rotation frequency of the rotor.

Substituting the expression of R from Eq. (7.29) into Eq. (7.27), one gets

$$\Gamma_{max} = \rho A_1 v_0^2 \left(\frac{v_0 \lambda}{2\omega}\right) = P_0 \frac{\lambda}{\omega} \tag{7.30}$$

where $P_0 = \frac{1}{2}\rho A_1 v_0^3$ is the maximum power from the wind turbine.

Further, the shaft power from the wind turbine can be expressed as

$$P_T = \Gamma\omega = C_\Gamma \Gamma_{max} \omega \tag{7.31}$$

Since, $P_T = C_P P_0$ from Eq. (7.17)

Then,

$$C_P P_0 = C_\Gamma \Gamma_{max} \omega = C_\Gamma \frac{P_0 \lambda}{\omega} \omega$$

or,

$$C_P = \lambda C_\Gamma \tag{7.32}$$

For the Betz limit, the maximum value of C_P is 0.59, then

$$(C_\Gamma)_{max} = \frac{0.59}{\lambda} \tag{7.33}$$

7.7 WIND ENERGY SOURCES

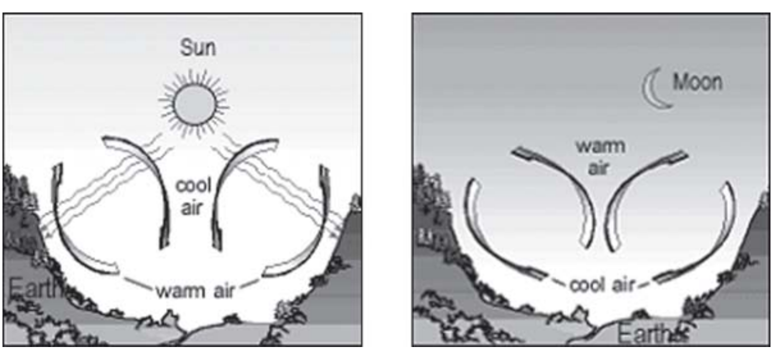
Before the analysis of the possible contribution of wind energy to the energy supply, the characteristics of wind energy sources need to be investigated.

7.7.1 The Origin of Wind

Wind is produced by the uneven heating of the Earth's surface by energy from the Sun. Since the Earth's surface is made of very different types of land and water, it absorbs the Sun's radiant energy at different rates. Much of this energy is converted into heat as it is absorbed by land areas, bodies of water, and the air over these formations. On a global scale, the nonuniform thermal effects combine with the dynamic effects from the Earth's rotation to produce prevailing wind patterns. There are also minor changes in the flow of the air as a result of the differential heating of sea and land. The nature of terrain ranging from mountain and valleys to more local obstacles such as buildings and trees also has an important effect on the origin of wind. Generally, during the day time the air above the land mass tends to heat up more rapidly than the air above water. In coastal regions this manifests itself in a strong onshore wind. In the night time the process is reversed because of the air cools down more rapidly over the land and the breeze therefore blows offshore, as shown in Figures 7.13a and b. A similar process occurs in mountains and valleys, creating local wind. The speed of wind is affected by the surface over which it blows. Rough surfaces such as areas with trees and buildings produce more friction and turbulence than smooth surface such as lakes or open cropland. The greater friction means the wind speed near the ground is reduced, as shown in Figure 7.14.

7.7.2 The Characteristics of the Wind

The power in the wind is proportional to the cube of the wind speed, as given by Eq. (7.5). It is well known that the highest wind velocities are generally found on hill tops, exposed coasts and out at sea. Various parameters need to be known regarding wind, including the mean wind speed directional data, variations about the mean in the short-term (gusts), daily, seasonal and annual variations as well as variations with height. These parameters are highly site specific and can only be determined with sufficient accuracy by measurements at a particular site over a sufficiently long period. They are used to assess the performance and economics of a wind energy-conversion system. General meteorological statistics may overestimate wind speed at a specific site. Therefore, not only the mean wind speed published by the meteorological organisations but also the wind-frequency



(a) Sunshine hour **(b)** Off-sunshine hour

Figure 7.13 Generation of wind sources (a) during day and (b) night time.

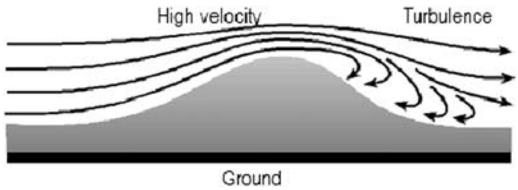


Figure 7.14 Wind sources due to the different ground surface conditions.

distribution, described by a Weibull distribution have to be taken into account in order to calculate the amount of electricity that can be produced by wind turbines in a certain region. A standard meteorological measurement of wind speed measures the speed of wind at a height of 10 m. But the height of the hub in a wind turbine is generally kept at more than 10 m. In that condition, the variations in speed of the wind with height are to be incorporated for predicting the energy available in the wind.

7.7.3 Vertical Wind Speed Gradient

The wind speed varies with the height above the ground. This is called the **wind shear**. The wind speed at the surface due to the friction between the air and the surface of the ground is zero. The wind speed increases most rapidly near the ground with height, increasing less rapidly with greater height. The change in wind speed becomes nearly zero at a height of about 1 km above the ground. The vertical variation of the wind speed and the wind-speed profile can be expressed by many functions. The two more common functions that have been developed to describe the change in mean wind speed with height are based on experiments. This is explained below:

Power exponent function: The power exponent function is given by

$$\mathrm{V}(z) = \mathrm{V}_r \left(\frac{z}{z_r} \right)^{\alpha} \tag{7.34}$$

where z is the height above the ground level, V_r is the wind speed at the reference height z_r above the ground level. A typical value of α is 0.1.

Although the power exponent law is a convenient approximation as given in Eq. (7.34), has no theoretical basis. Instead, aerodynamic theory suggests that when the atmosphere is thermally natural, which is the case on a cloudy day for the strong wind, air flow within the boundary layer varies logarithmically with height, so that the logarithmic function can be expressed as[5]

$$\frac{\mathrm{V}(z)}{\mathrm{V}_r} = \frac{\ln\left(\dfrac{z}{z_0} \right)}{\ln\left(\dfrac{z_r}{z_0} \right)} \tag{7.35}$$

where V_r is the wind speed at the reference height z_r above the ground level and z_0 is the roughness length. The parameters α and z_0 for different types of terrain are shown in Table 7.1.

7.7.4 Wind Speed Distribution

For the wind industry it is very necessary to be able to describe the variation of wind speeds. Turbine designers need the information to optimise the design of their wind turbines in order to minimise the generator cost. Turbine investors need the information to estimate their income from

Table 7.1 Wind-speed parameters for calculating a vertical profile.

Types of terrain	*Roughness class*	*Roughness length z_0 (m)*	*Exponent (α)*
Water areas	0	0.001	0.01
Open country, few surface features	1	0.12	0.12
Farmland with building and hedges	2	0.05	0.16
Farmland with many trees, forests, villages	3	0.3	0.28

electricity generation. Wind-speed variations and their distributions at any given site can be described in terms of a Weibull distribution.

The probability that the wind will blow at some wind speed including zero must be 100%, since the area under the curve is always 1. The Weibull function can be expressed as

$$P(\mathrm{V}) = \frac{k}{\mathrm{V}}\left(\frac{\mathrm{V}}{C}\right)^{k-1} \exp\left\{-\left(\frac{\mathrm{V}}{C}\right)^{k}\right\} \tag{7.36}$$

where $P(V)$ is the frequency of the wind at wind speed V, C is the scale parameter or characteristic wind speed and k is the shape parameter.

The Weibull distribution also expresses the proportion of time for which the wind speed exceeds the value V and is expressed as

$$P(\mathrm{V}) = \exp\left\{-\left(\frac{\mathrm{V}}{C}\right)^{k}\right\} \tag{7.37}$$

For a typical value of $k = 1$, the distribution is called a **cumulative Rayleigh distribution**.

The probability of wind distribution between V_1 and V_2 can be given as

$$P(\mathrm{V}_1 < \mathrm{V} < \mathrm{V}_2) = \exp\left\{-\left(\frac{\mathrm{V}_1}{C}\right)^{k}\right\} - \exp\left\{-\left(\frac{\mathrm{V}_2}{C}\right)^{k}\right\} \tag{7.38}$$

The plot of ln V versus ln $\{-(\ln V)\}$ gives the parameters C and k for the Weibull frequency distribution. The graph gives a straight line in which the slope is equal to k and parameter C is equal to exp (ln V) or V, where ln $\{-(\ln V)\}$ is zero.

7.8 COMPONENT OF WIND ENERGY-CONVERSION SYSTEM

The main components of the turbine are:

- nacelle;
- rotor that is the assembly of blades, hub and shaft;
- transmission system that includes a gearbox and a breaking mechanism;
- electric generator;
- yaw and control system;
- tower to support the rotor system.

Nacelle: This includes the gearbox, low- and high-speed shafts, generator controller and brake. It is placed on the top of the tower and is connected to the rotor.

Rotor: Most of the horizontal-axis wind turbines use two or three blades in an upwind design. Blades are manufactured form fibreglass-reinforced polyester (FRD), wood laminates, steel or aluminium. A FRD blade is comparatively lighter and exerts less stress on bearing and rotor hubs. Hence, it is used by most of the wind-turbine manufacturers. Other manufacturers use steel blades because of the ease of fabrication, greater strength and lower cost. Sometimes, wood laminates blades are also used due to their excellent fatigue resistance properties. Vertical-axis wind-turbine manufacturers often use extruded aluminium blades.

Rotor power control: While designing a wind turbine one of the important issue is to limit the power output at high wind speed. There are two options for constant speed machines (i) stall regulation and (ii) pitch control.

(i) For **stall-regulated wind turbines**, the pitch angle distribution along the blades is constant for all wind speeds. The angle of attack of the airfoil over the blades increases until flow separation (stall) occurs at high wind speeds. This results in a loss of lift but drag forces rise. The effect of this process can be influenced by appropriate choice of blade profile, the thickness and chord distribution and the blade twist. The great advantage of stall regulation is its simplicity and relatively low cost.
(ii) For **pitch-regulated wind turbines**, the blades can be rotated about their radial axis during the operation as the wind speed changes. It is therefore possible to have an optimum pitch angle at all wind speeds and a relatively low cut-in wind velocity. The pitch angle changes in order to decrease the angle of attack at high wind speeds. This ensures that the power output from the rotor is limited to the rated power of the generator. Pitch regulation is more expansive and it requires a relatively complicated control system. It is more efficient than stall regulation.

Transmission system: The mechanical power generated by the wind turbine (rotor blades) is transmitted to the electric generator by a transmission system located in the nacelle. The transmission system contains a gearbox, a clutch and a braking system to stop the rotor in an emergency. The purpose of the gearbox is to increase the speed of the rotor typically from 20 to 50 revolutions per minutes (rpm) or from 1000 to 1500 rpm which is required for driving most types of electric generators. There are two main types of gearbox (i) a planetary shaft and (ii) a parallel shaft. The transmission system must be designed for high dynamic torque loads due to the fluctuating power output from the rotor. Some designers have made an attempt to control the dynamic loads by adding (a) mechanical compliances and (b) damping into the drive train. This is particularly important for very large wind turbines.

Electric generator: There are two main options for the generator used in constant-speed wind turbines namely asynchronous (induction) or synchronous generators. Most of the grid-connected wind turbines installed so far use induction generators. These turbines have to be connected to the electricity grid before they can generate electricity. The generator is sometimes used as a motor to run the wind turbine up to synchronous speed, a feature that is utilised by stall-regulated wind turbines. The major disadvantage of the induction generators is that they draw reactive power from the grid system. Synchronous generators do not require reactive power so they are favoured by utilities. Wind turbines driving electrical generators operate at either variable or constant speed. In variable-speed operations, rotor speed varies with wind speed. In constant speed machines, rotor speed remains constant despite changes in the wind speed.

Yaw control: This is used to continuously orient the rotor in the direction of the wind. The horizontal-axis wind turbine has a yaw control system that turns the nacelle according to the actual wind direction, using a rotary actuator attached to the gear ring at the top of the wind tower. The wind direction must be perpendicular to the swept rotor area during normal operation of the wind turbine. A slow closed-loop control system is used to control the yaw drives. A wind vane mounted on the top of the nacelle, senses the relative wind direction and the wind-turbine controller then operates the yaw drives.

Wind tower: The most common types of wind tower are the lattice or tubular types constructed from steel or concrete. The towers are designed to withstand wind loads and gravity loads. The wind tower has to be mounted to a strong foundation in the ground. It is designed so that either its resonant frequencies do not coincide with induced frequencies from the rotor or they can be damped out.

7.9 WIND TURBINE GENERATOR CLASSIFICATION

Table 7.2 gives the classification of the wind-turbine electricity system. The classification depends on the relative size of the aerogenerator capacity (P_T) and other electricity generators capacity (P_G) connected in parallel with it.

Class A: For $P_T \geq 5P_G$, an aerogenerator represents a single autonomous standalone machine without any form of grid linking.

The control of output is very important for efficient cost effective systems. One choice is to have little control so that the output is of variable voltage for use as heat or rectified power, as shown in Figure 7.15a. Such a type of power supply is very useful. The relatively small amount of power that usually has to be controlled at say 240 V/50 Hz or 110 V/60 Hz can be obtained from batteries by inverters. However, it is preferred to have electricity at constant frequency. Two extreme options are:

(a) **Mechanical control of the turbine blades:** With change of wind speed, the pitch of the blades is adjusted to control the frequency of wind-turbine rotation. The power in the wind is wasted. The control method can be expensive and unreliable. This control system is shown in Figure 7.15b.
(b) **Mechanical control of the turbine blades:** With change of wind speed, the pitch of the blades is adjusted to control the frequency of wind-turbine rotation. The power in the wind is wasted. The control method can be expensive and unreliable. This control system is shown in Figure 7.15b.

Class B: $P_T \sim P_G$. This type of aerogenerator classification is common for remote areas and small grid systems. It is considered that "other generators" of capacity P_G are powered by a diesel engine. The basic aim of the wind turbine is to be a diesel saver. The diesel generator supplies power in windless periods. In this case, there are two extreme modes of operation.

(a) **Single-mode electricity supply distribution:** This is usually a three-phase supply that takes single phase to domestic dwellings with a single set of distribution cables, the system operates in a single mode at fixed voltage. A 24-h maintained supply without load-management control depends usually on diesel generation due to nonavailability of wind. The diesel is either left on continuously or switched off when excessive wind blows. Generally, a

Table 7.2 Classification of wind-turbine electricity generator system.

A	*B*	*C*
$P_T \gg P_G$ autonomous (a) blade pitch (b) load matching	$P_T \sim P_G$ wind/diesel (a) wind or diesel (b) wind and diesel together	$P_T \ll P_G$ grid stand (a) direct induction generator (b) to DC then AC

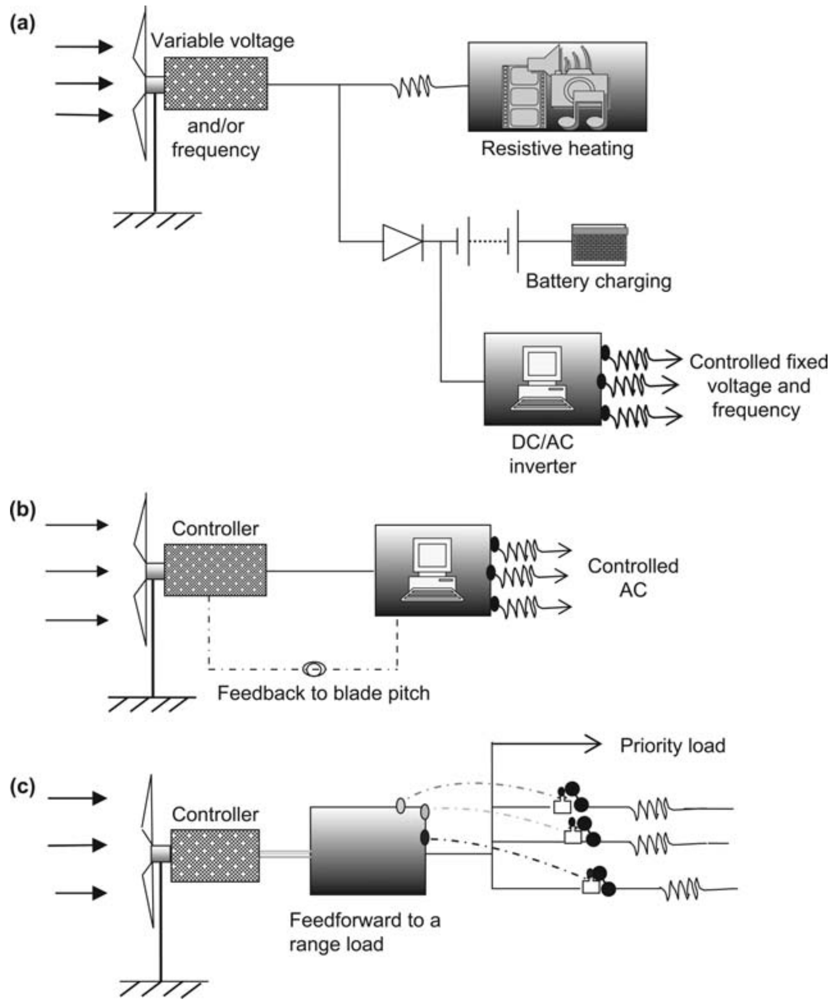


Figure 7.15 Classification of electricity supply options with the aerogenerator.

large amount (over 70%) of the wind generated power is to be dumped into an outside resistor banks owing to the mismatch of supply and demand in windy conditions. This is shown in Figure 7.16a.

(b) **Multiple-mode distribution:** In this case, every effort is made to use all the wind-generated power. Economic electricity for many applications in windy conditions is offered. The economic service loads are automatically switched off to decrease the demand due to wind drop. Only the loads on the expensive supply are enabled for supply by the diesel generator without availability of wind. The economic advantage of multiple mode operation is used at all times. This is shown in Figure 7.16b.

Class C: $5P_T \leq P_G$ (grid linked). This is common arrangement for (i) large capacity ($\sim$3 MW), (ii) medium capacity ($\sim$250 kW) and (iii) small capacity ($\sim$50 kW) machines. The owner of the wind machine uses the wind power directly and sells any excess electric power to the grid. Electricity is purchased from the grid at periods of low or no wind. This is depicted in Figure 7.17.

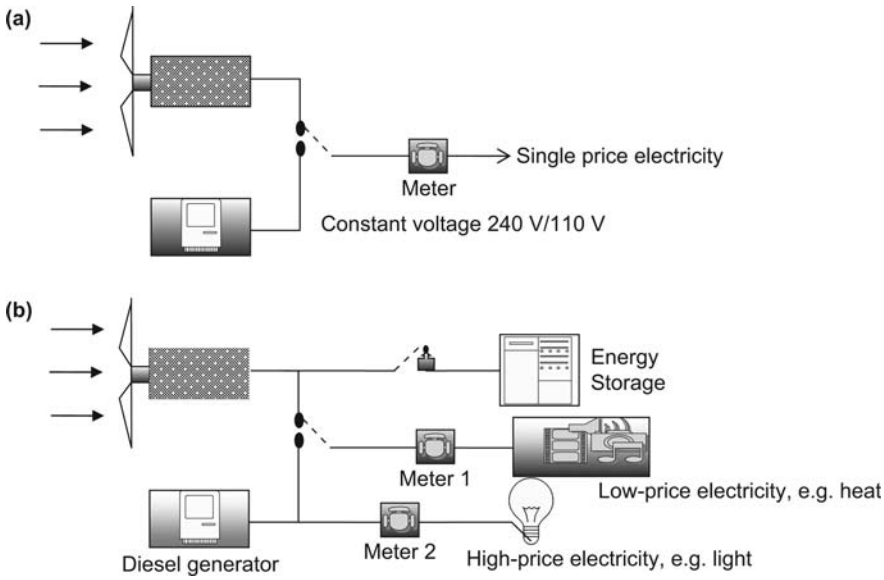


Figure 7.16 Wind/diesel supply modes (a) single-mode supply (b) multiple-mode supply.

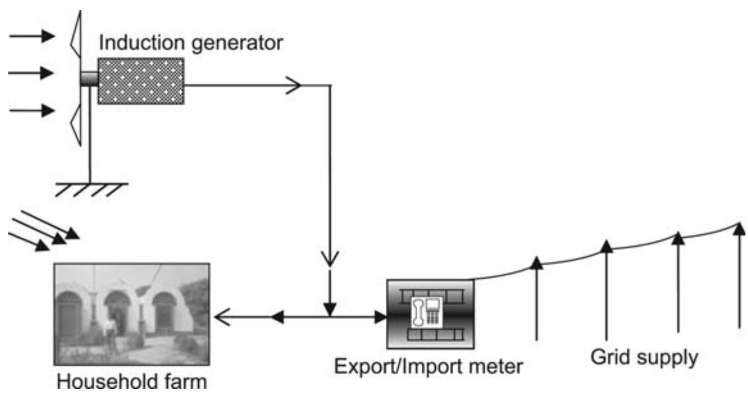


Figure 7.17 Grid-linked aerogenerator slaved in a large system.

7.10 APPLICATION OF WIND TURBINES

The followings are the main application of wind turbines

(a) Drag Machine

This consists of a device with wind-driven surfaces or flaps moving parallel to the undisturbed wind having wind speed v_0 as shown in Figure 7.18.

The pressure difference (ΔP) across a stationary flap held perpendicular to the wind velocity is given by Eq. (7.19). The maximum driving drag force for a loop can be given as

$$F_{max} = \rho A(v_0 - v^2)/2 \tag{7.39}$$

where A and v are the cross-sectional area and moving speed of the flap. Here, v_0 and v are in the same direction.

Figure 7.18 View of drag machine with hinged flaps on rotating belt.

The drag force can also be written as,

$$F_D = C_D \rho A(v_0 - v^2)/2 \tag{7.40}$$

where C_D is a dimensional quantity called the drag coefficient.

The power transmitted to the flap can be given as

$$P_D = F_D.v = C_D \rho A(v_0 - v^2)v/2 \tag{7.41}$$

For maximum transmitted power, differentiating Eq. (7.41) w.r.t. v and making it equal to zero one can get,

$$\frac{dP_D}{dv} = 0 \Rightarrow v = \frac{v_0}{3}$$

After substituting the value of v form above equation in Eq. (7.41) and using Eq. (7.17), one gets

$$P_{D,max} = \frac{4}{27} C_D \frac{\rho A v_0^2}{2} = C_P \frac{\rho A v_0^2}{2}$$

so,

$$C_{p,max} = \left(\frac{4}{27}\right) C_D$$

$C_D \rightarrow$ 0 for a pointed object

$C_D \rightarrow$ 1.5 (maximum) foe a concave shape used in standard anemometers.

Thus, the maximum power coefficient for a drag machine can be given as

$$C_{p,max} = \left(\frac{4}{27}\right)(1.5) = \frac{6}{27} = 22\%$$

The maximum value of C_p for a wind turbine in an ideal case is 59%, as per the Betz limit. Hence, $C_{p,max}$ for a drag machine is less than $C_{p,max}$ for a lift forced wind turbine.

$C_{p,max}$ for a drag machine can be increased by incorporating more flaps or by arranging concentrated air flows.

The ratio of $C_{p,max}$ between the drag machine and the lift forced machine is

$$\frac{Drag\,machine}{Lift\,turbine} = \frac{22}{59} = 37\%$$

Therefore, drag-only devices have power extraction coefficients of only about 37% that of lift forced turbines for the same cross-sectional area.

(b) Wind Pump

Water pumping is the one of the main applications of wind energy. The most widely used type of wind pump is constructed of a steel, multibladed, high solidity, fan-like rotor that drives a reciprocating pump linkage usually *via* a reduction gearing that is directly connected with a piston pump located in a borehole directly under it.[6]

The design of wind turbines for water pumping is relatively simple compared to electricity-generating turbines. The mechanical power at the rotor shaft is used directly to drive a pumping device. Turbines with high starting torque are suitable for pumping and this requires high solidity rotors operating at a low tip ratio of 2 or less.

The most prevalent wind turbines for water pumping are of the horizontal-axis type and typically have rotors blades usually made from curved sheet metal and need not be of a complex aerofoil section.

The important components of a wind pump are as follows:

(i) Rotor: This can vary widely in both size and design. Diameters range from less than 2 m to 7 m. The number of blades can vary from 6 to 24. A rotor with more blades runs slower but is able to pump with more force.
(ii) Tail: This keeps the rotor pointing into the wind like a weather vane. The whole top assembly pivots on the top of the tower. It allows the rotor to face in any direction.
(iii) Transmission system: This turns the rotation of the rotor into reciprocating motion (up and down) in the pump rod. Normal types use a gearbox or are direct drive. In direct drive, the pump rod moves up and down once for each turn of the rotor.
(iv) Pump rod: This transmits the motion from the transmission at the top of the tower to the pump at the bottom of the well. The motion of the pump rod is reciprocating (up and down) and the distance it travels (called the stroke) is typically of about 30 cm, depending on the pump. It is usually made of steel.
(v) Pump: This is normally submerged below the water level on the downward stroke, the cylinder is filled with water and on the upward stroke, the water is lifted by the piston up the drop pipe. The pump hangs on the drop pipe.
(vi) Drop pipe: This is the pipe through which the water is pumped and also encloses the pump rod.
(vii) Well: The source of water pumped by the wind pump.
(viii) This is normally of galvanised steel with three or four legs. Its height varies from 5 m to 20 m. The bases of the legs are fixed, often bolted, to a concrete foundation.

The size of a pump driven by the wind turbine is a function of the pump head, the required water flow rate and mean wind speed. The three main parameters that are needed are the total pumped head H (m), the pumped volume flow rate Q (m^3/s) and the expected mean wind speed v_0 (m/s). The actual power delivered by the rotor must be equal to the required hydraulic power.

$$C_p\left(\frac{1}{2}\rho A v_0^3\right) = \rho_w g H Q \tag{7.43}$$

where C_p is the power coefficient of wind turbine, ρ is the density of air, A is the swept area and v_0 is the mean velocity of air, $\rho_w = 1000$ kg/m^2 (the density of water) and $g = 9.81$ m/s^2 is the acceleration due to gravity.

Rearranging Eq. (7.43),

$$A = \frac{1000 \times 9.81 HQ}{0.06 c_p v_0^3} \tag{7.44}$$

The rotor diameter can be given as

$$D = \sqrt{\frac{4A}{\pi}}$$

7.11 ADVANTAGES/DISADVANTAGES OF WIND ENERGY SYSTEMS

The following are the advantages and disadvantages of wind turbine systems:

Advantages

(i) Wind is available free of cost.
(ii) Wind is helpful in supplying electric power to remote areas.
(iii) Wind power generation is cost effective and reliable.
(iv) Pollution free.
(v) Economical.
(vi) Reliable.

Disadvantages

(i) Wind energy has low energy density but is favorable in many geographical locations from cities and forests.
(ii) Requires energy storage batteries that indirectly and substantially contribute to environmental pollution.
(iii) Turbine rotors are not very efficient as they extract only 10 to 40% of the available wind energy.
(iv) Wind energy is capital intensive.

ADDITIONAL EXERCISES

Exercise 7.1 By using the Betz limit, plot the curve between the torque coefficient (C_Γ) and the tip speed ratio (λ)

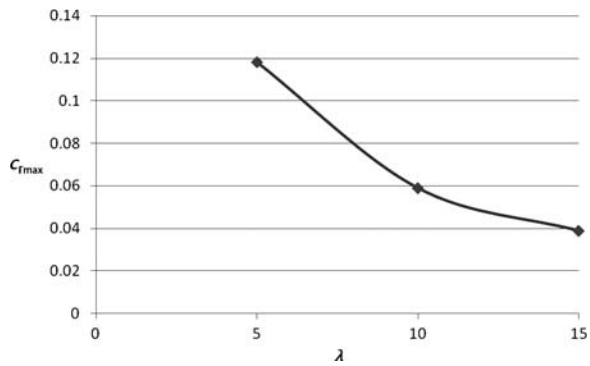
Solution:
We have, for the Betz limit, the maximum value of C_Γ is 0.59, then

$$(C_\Gamma)_{\max} = \frac{0.59}{\lambda}$$

$$\Rightarrow \lambda = 5: \; C_{\Gamma,max} = \frac{0.59}{\lambda} = \frac{0.59}{5} = 0.118$$

$$\Rightarrow \lambda = 10: \; C_{\Gamma,max} = \frac{0.59}{\lambda} = \frac{0.59}{10} = 0.059$$

$$\Rightarrow \lambda = 15: \; C_{\Gamma,max} = \frac{0.59}{\lambda} = \frac{0.59}{15} = 0.039$$



Statement: The value of C_Γ varies linearly with λ, if λ increases, C_Γ decreases, means that if wind turbine blades move faster, the torque coefficient will decrease. For modern high-speed turbines designed for electricity as low torque.

Exercise 7.2 Plot the curve between "C_p" and "C_F" w.r.t "a".
Solution:
The power coefficient C_p can be given in terms of "a" as

$$C_p = 4a(1-a)^2$$

For C_{pmax}, differentiate the above expression w.r.t "a" and equate it to 0, one gets

$$\frac{dC_p}{da} = \frac{d}{da}[4a(1-a)^2]$$

$$\frac{d}{da}[4a(a^2-2a+1)] = 0$$

$$\frac{d}{da}[4a+4a^3-8a^2] = 0$$

$$4+12a^2-16a = 0$$

$$1+3a^2-4a = 0$$

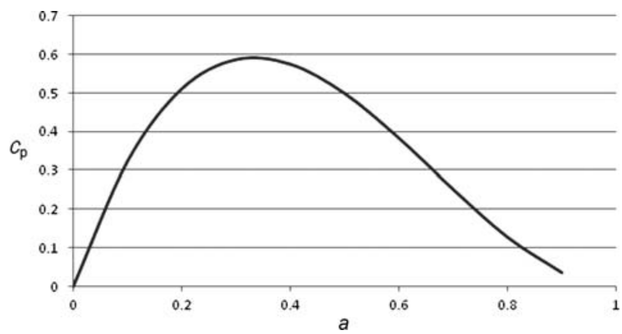
$$a = 1, \frac{1}{3}$$

$$\text{At } a = 1,\ C_p = 0$$

$$\text{At } a = \frac{1}{3},\ C_p = \frac{4}{3}\left(1-\frac{1}{3}\right)^2 = \frac{16}{27} = 0.592$$

$$C_{p,\max} = 0.592 \equiv \textit{Betz Criteria}$$

Now, the curve between "C_p" and "C_F" w.r.t. "a" can be plotted as



Statement: No wind turbine can generate power more than 59.2%, the value of a lies between 1/3 to 1. If we increase the value of a to more than 1/3, the C_p will decrease and at $a = 1$, it is 0.

Exercise 7.3 Plot the problem in Exercise 2 w.r.t. "b".
Solution:
We have an expression of "C_p" in terms of 'b' can be given as

$$C_p = 4a\,(1 - a)^2 \tag{i}$$

a = interference factor

$$a = \frac{(u_0 - u_1)}{u_0} \text{ and } u_1 = \frac{(u_0 + u_2)}{2} \tag{ii}$$

$$\Rightarrow u_1 = (1 - a)\,u_0 \tag{iii}$$

$b = u_2/u_0$ is also referred to as an interference factor

$$\Rightarrow u_1 = (1 - a)\,u_0$$

$$\Rightarrow \frac{(u_0 + u_2)}{2} = (1 - a)\,u_0$$

$$\Rightarrow (1 - a) = \frac{u_0 + u_2}{2u_0}$$

$$\Rightarrow a = 1 - \frac{(u_0 + u_2)}{2u_0} = \frac{(u_0 - u_2)}{2u_0} = \frac{1}{2}\left(1 - \frac{u_2}{u_0}\right)$$

$$a = \frac{1}{2}(1 - b)$$

$$C_p = 4a\,(1-a)^2$$

$$C_p = \frac{4}{2}(1-b)\left[1-\frac{1}{2}(1-b)\right]^2$$

$$C_p = 2(1-b)\left[\frac{1+b}{2}\right]^2$$

$$C_p = 2(1-b)\left[\frac{1+b}{2}\right]^2$$

$$C_p = \frac{1}{2}(1-b)(1+b)^2 \tag{iv}$$

For C_{pmax}, differentiate Eq. (iv) w.r.t. b and equate to 0.

$$\frac{dC_p}{db} = \frac{d}{db}\left[\frac{1}{2}(1-b)(1+b)^2\right]$$

$$\frac{d}{db}\left[\frac{1}{2}(1-b)(1+b)^2\right] = 0$$

$$\frac{d}{db}\left[\frac{1}{2}(1-b)(b^2+2b+1)\right] = 0$$

$$\frac{d}{db}\left[\frac{1}{2}(1+b^2+2b-b-b^3-2b^2)\right] = 0$$

$$\frac{d}{db}\left[\frac{1}{2}(1+b-b^2-b^3)\right] = 0$$

$$\Rightarrow 0+1-3b^2-2b=0$$

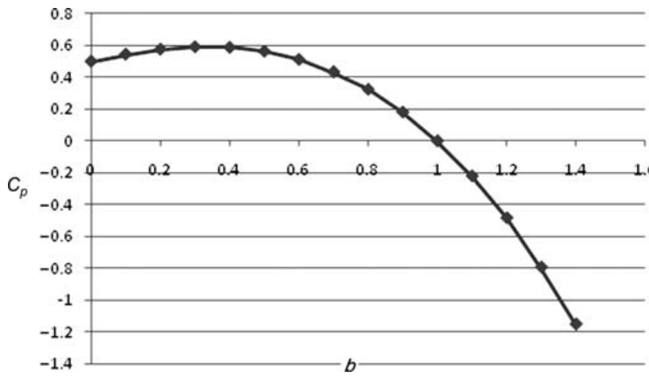
$$\Rightarrow 3b^2+2b-1=0$$

$$b=-1,\frac{1}{3}$$

$b\ =-1$ is not possible, as u_2 is not negative so it is invalid.

For $b = \frac{1}{3},\ C_p = \frac{1}{2}\left(1 - \frac{1}{3}\right)\left(1 + \frac{1}{3}\right)^2 = 0.592$

$$C_{p,max} = 0.592$$



Statements:

1. C_p is maximum at $b = 1/3$ or 0.33, same at $a = 1/3$.
2. C_p is zero at $b = 1$,

At $b > 1$, C_p is downfall (negative) means that turbine losses are present.

OBJECTIVE QUESTIONS

7.1 The drag force (C_D) in an immersed body in a fluid acts along the
(a) Horizontal direction
(b) Vertical direction
(c) Inclined surface at 45°
(d) None

7.2 The lift force (C_L) in an immersed body in a fluid acts along the
(a) Horizontal direction
(b) Vertical direction
(c) Inclined surface at 45°
(d) None

7.3 Pressure is defined as
(a) Force per unit area
(b) Work per unit area
(c) Velocity
(d) None

7.4 The shear force (tangential force) and pressure has the units of
(a) N/m^2
(b) W/m^2
(c) N/m
(d) N/m^3

7.5 The value of drag coefficient (C_D) is always
(a) <1
(b) >1
(c) $=1$
(d) $=0$
7.6 The ratio C_L/C_D has values of
(a) + ve to −ve
(b) +ve only
(c) −ve only
(d) zero only
7.7 The lift coefficient (C_L) is always
(a) Higher than the drag coefficient (C_D)
(b) Higher than the drag coefficient (C_D)
(c) Equal to the drag coefficient (C_D)
(d) None of the above
7.8 The horizontal-axis turbine works due to
(a) Lift force
(b) Drag force
(c) Both
(d) All
7.9 The vertical-axis turbine works due to
(a) Lift force
(b) Drag force
(c) Both
(d) All
7.10 The angle of attack will be
(a) Only positive
(b) Only negative
(c) Positive and negative
(d) None
7.11 The value of the lift coefficient is always
(a) $<C_D$
(b) $>C_L$
(c) $C_D=C_L$
(d) none
7.12 The numerical value of dynamic pressure ($\frac{1}{2}\rho v^2$) is
(a) $>C_D$
(b) $>C_L$
(c) $>C_D$ and C_L
(d) all true
7.13 The power associated with wind is
(a) $\propto v^2$
(b) $\propto v^3$
(c) $\propto v$
(d) none
7.14 The optimum wind speed for $P_0=600$ W/m^2 is
(a) 5 m/s
(b) 15 m/s
(c) 10 m/s
(d) None

7.15 The wind turbine gives
(a) Mechanical output
(b) Electrical output
(c) Chemical output
(d) None

7.16 The wind turbine gives maximum mechanical power if
(a) Wind is streamline
(b) Wind is turbulent
(c) Constant wind speed
(d) None

7.17 The power coefficient of horizontal axis wind turbine (C_p) is given by
(a) $4a(1–a)$
(b) $a(1–a)$
(c) $4a(a–a)^2$
(d) None

7.18 The maximum value of C_p for a horizontal-axis wind turbine is
(a) 0.49
(b) 0.59
(c) 0.39
(d) 0.29

7.19 The interface factor for a horizontal-axis wind turbine is given by
(a) $a = \frac{v_0 - v_2}{2v_0}$
(b) $a = \frac{v_2}{v_0}$
(c) $a = \frac{v_2}{v_0}$
(d) None

7.20 The value of C_p is maximum at
(a) $a = 1/2$
(b) $a = 3/4$
(c) $a = 1/3$
(d) None

7.21 The value of C_p is maximum at
(a) $a = 1/3$
(b) $b = 1/3$
(c) $a = b = 1/3$
(d) All of them

7.22 The power extracted by a horizontal-axis wind turbine depends on
(a) The rate of change of momentum
(b) The rate of kinetic energy of wind flow across the turbine
(c) The wind turbine speed
(d) All of them

7.23 The swept area (A_1) is related to unwind cross-sectional area (A_0) by
(a) 3/2
(b) 2/3
(c) 1
(d) None

7.24 The maximum power extraction per unit area of A_0 is
(a) 9/8
(b) 7/8
(c) 8/9
(d) 1

7.25 The wind turbine of a horizontal-axis wind turbine loses power for
(a) $b > 1$
(b) $b < 1$
(c) $b = 0$
(d) $b = 1$
7.26 The expression for the axial force coefficient of a horizontal-axis wind turbine (C_F) is given by
(a) $4a\ (1–a)2$
(b) $4a\ (1–a)$
(c) $4a\ (1–a)3$
(d) $4a$
7.27 The value of the maximum axial force coefficient of a horizontal-axis wind turbine (C_F) is
(a) 1/3
(b) 2/3
(c) 1/2
(d) 1
7.28 The maximum value of solidity of wind turbine is
(a) 10
(b) 1
(c) 0
(d) None
7.29 The maximum axial force coefficient occurs at
(a) $a = 1/2$
(b) $b = 0$
(c) $a = 1/3$
(d) $b = 1$
7.30 The origin of wind energy is
(a) Earth
(b) Ocean
(c) Sun
(d) None of them
7.31 The percentage of solar radiation converted into wind energy is
(a) 0.50%
(b) 0.25%
(c) 1%
(d) None
7.32 In which country was the first wind turbine connected to a grid?
(a) USA
(b) Denmark
(c) India
(d) Germany
7.33 Which of the following sources emits fewer pollutants?
(a) Coal
(b) Petroleum
(c) Charcoal
(d) Wind
7.34 The maximum energy conversion efficiency of a wind turbine for a given swept area is
(a) 25.1%
(b) 50.4%
(c) 59.3%
(d) 99.3%

7.35 If the velocity of was wind is doubled, then the power output will increase by
  (a) 10 times
  (b) 8 times
  (c) 2 times
  (d) 6 times
7.36 Windmills work on the principle of
  (a) Rotation
  (b) Momentum
  (c) Gravitation
  (d) Collision
7.37 Which of the following forces act on the blade of the wind-turbine rotors?
  (a) Lift force
  (b) Drag force
  (c) Both (a) & (b)
  (d) None of them
7.38 During the day the surface wind flows
  (a) From sea to land
  (b) From land to sea
  (c) On the surface of the sea
  (d) On the surface of the land
7.39 During the night, the direction of was wind reverses from was land surface to was sea surface because the
  (a) Land surface cools faster than water
  (b) Water surface cools faster than land
  (c) Water surface remains hot
  (d) None of the above
7.40 Wind-turbine conversion devices based on drag force
  (a) Move faster than was wind
  (b) Move slower than was wind
  (c) Move with equal velocity as was wind
  (d) Do not depend on the velocity of the wind

ANSWERS

7.1 **(a)**; 7.2 **(b)**; 7.3 **(a)**; 7.4 **(a)**; 7.5 **(a)**; 7.6 **(a)**; 7.7 **(a)**; 7.8 **(a)**; 7.9 **(b)**; 7.10 **(c)**; 7.11 **(b)**; 7.12 **(d)**; 7.13 **(b)**; 7.14 **(c)**; 7.15 **(a)**; 7.16 **(a)**; 7.17 **(c)**; 7.18 **(b)**; 7.19 **(a)**; 7.20 **(c)**; 7.21 **(d)**; 7.22 **(a)**; 7.23 **(c)**; 7.24 **(a)**; 7.25 **(b)**; 7.26 **(d)**; 7.27 **(b)**; 7.28 **(a) & (b)**; 7.29 **(a)**; 7.30 **(b)**; 7.31 **(a)**; 7.32 **(d)**; 7.33 **(d)**; 7.34 **(c)**; 7.35 **(b)**; 7.36 **(b)**; 7.37 **(c)**; 7.38 **(a)**; 7.39 **(a)**; 7.40 **(b)**

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