

Lecture note

Semester- 4th

Subject – GENERATION TRANSMISSION AND DISTRIBUTION

Subject code- Th4

Branch- Electrical Engineering

Chapter1 Generation of electricity

IMPORTANCE OF ELECTRICAL ENERGY:

Energy may be needed as heat, as light, as motive power etc. The present-day advancement in science and technology has made it possible to convert electrical energy into any desired form. This has given electrical energy a place of pride in the modern world. The survival of industrial undertakings and our social structures depends primarily upon low cost and uninterrupted supply of electrical energy. In fact, the advancement of a country is measured in terms of per capita consumption of electrical energy. Electrical energy is superior to all other forms of energy due to the following reasons:

- (i) Convenient form. Electrical energy is a very convenient form of energy. It can be easily converted into other forms of energy. For example, if we want to convert electrical energy into heat, the only thing to be done is to pass electrical current through a wire of high resistance e.g., a heater. Similarly, electrical energy can be converted into light (e.g. electric bulb), mechanical energy (e.g. electric motors) etc.
- (ii) Easy control. The electrically operated machines have simple and convenient starting, control and operation. For instance, an electric motor can be started or stopped by turning on or off a switch. Similarly, with simple arrangements, the speed of electric motors can be easily varied over the desired range.
- (iii) Greater flexibility. One important reason for preferring electrical energy is the flexibility that it offers. It can be easily transported from one place to another with the help of conductors.
- (iv) Cheapness. Electrical energy is much cheaper than other forms of energy. Thus it is overall economical to use this form of energy for domestic, commercial and industrial purposes.
- (v) Cleanliness. Electrical energy is not associated with smoke, fumes or poisonous gases. Therefore, its use ensures cleanliness and healthy conditions.
- (vi) High transmission efficiency. The consumers of electrical energy are generally situated quite away from the centres of its production. The electrical energy can be transmitted conveniently and efficiently from the centres of generation to the consumers with the help of overhead conductors known as transmission lines.

The conversion of energy available in different forms in nature into electrical energy is known as generation of electrical energy. Electrical energy is a manufactured commodity like clothing, furniture or tools. Just as the manufacture of a commodity involves the conversion of raw materials available in nature into the desired form, similarly electrical energy is produced from the forms of energy available in nature. However, electrical energy differs in one important respect. Whereas other commodities may be produced at will and consumed as needed, the electrical energy must be produced and transmitted to the point of use at the instant it is needed. The entire process takes only a fraction of a second. This instantaneous production of electrical energy introduces technical and economic considerations unique to the electrical power industry. Energy is available in various forms from different natural sources such as pressure head of water, chemical energy of fuels, nuclear energy of radioactive substances etc. All these forms of energy can be converted into electrical energy by the use of suitable arrangements. The arrangement essentially employs (see Fig. 1.1) an alternator coupled to a prime mover. The prime mover is driven by the energy obtained from various sources such as burning of fuel, pressure of water, force of wind etc. For example, chemical energy of a fuel (e.g., coal) can be used to produce steam at high temperature and pressure. The steam is fed to a prime mover which may be a steam engine or a steam turbine. The turbine converts heat energy of steam into mechanical energy which is further converted into electrical energy by the alternator. Similarly, other forms of energy can be converted into electrical energy by employing suitable machinery and equipment.

Generating Stations Bulk electric power is produced by special plants known as generating stations or power plants. A generating station essentially employs a primemover coupled to an alternator for the production of electric power. The prime mover (e.g., steam turbine, water turbine etc.) converts energy from some other form into mechanical energy. The alternator converts mechanical energy of the prime mover into electrical energy. The electrical energy produced by the generating station is transmitted and distributed with the help of conductors to various consumers. It may be emphasized here that apart from prime mover-alternator combination, a modern generating station employs several auxiliary equipment and instruments to ensure cheap, reliable and continuous service. Depending upon the form of energy converted into electrical energy, the generating stations are classified as under:

- (i) Steam power stations
- (ii) Hydroelectric power stations
- (iii) Diesel power stations
- (iv) Nuclear power stations

Steam power station:

Steam Power Station (Thermal Station) A generating station which converts heat energy of coal combustion into electrical energy is known as a steam power station. A steam power station basically works on the Rankine cycle. Steam is produced in the boiler by utilizing the heat of coal combustion. The steam is then expanded in the prime mover (i.e., steam turbine) and is condensed in a condenser to be fed into the boiler again. The steam turbine drives the alternator which converts mechanical energy of the turbine into electrical energy. This type of power station is suitable where coal and water are available in abundance and a large amount of electric power is to be generated.

Advantages

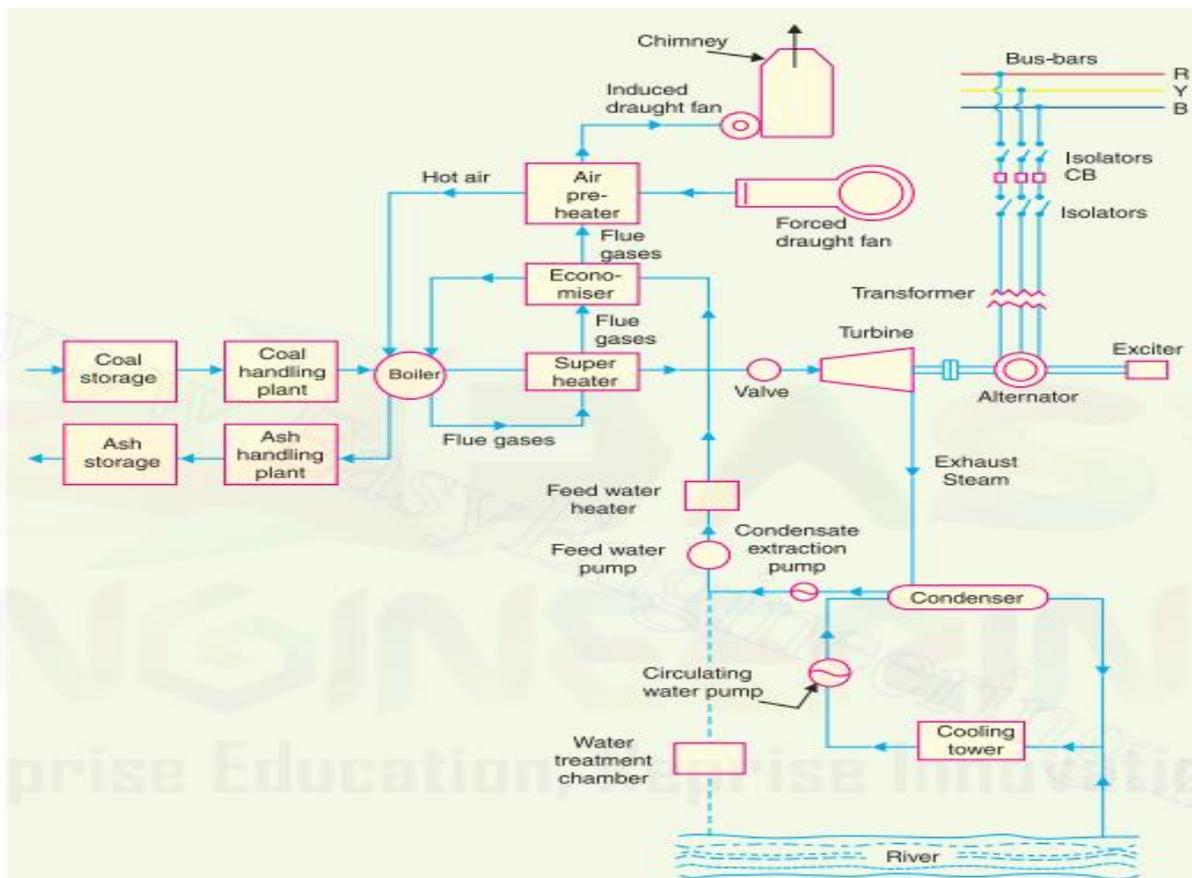
- (i) The fuel (i.e., coal) used is quite cheap.
- (ii) Less initial cost as compared to other generating stations.
- (iii) It can be installed at any place irrespective of the existence of coal. The coal can be transported to the site of the plant by rail or road.
- (iv) It requires less space as compared to the hydroelectric power station.
- (v) The cost of generation is lesser than that of the diesel power station.

Disadvantages

- (i) It pollutes the atmosphere due to the production of large amount of smoke and fumes.
- (ii) It is costlier in running cost as compared to hydroelectric plant.

Schematic Arrangement of Steam Power Station:

Although steam power station simply involves the conversion of heat of coal combustion into electrical energy, yet it embraces many arrangements for proper working and efficiency. The schematic arrangement of a modern steam power station is shown in Fig. 2.1.



Schematic arrangement of Steam Power Station

Fig. 2.1

The whole arrangement can be divided into the following stages for the sake of simplicity :

1. Coal and ash handling arrangement
2. Steam generating plant
3. Steam turbine
4. Alternator
5. Feed water
6. Cooling arrangement

Coal and ash handling plant:

The coal is transported to the power station by road or rail and is stored in the coal storage plant. Storage of coal is primarily a matter of protection against coal strikes, failure of transportation system and general coal shortages. From the coal storage plant, coal is delivered to the coal handling plant where it is pulverised (i.e., crushed into small pieces) in order to increase its surface exposure, thus promoting rapid combustion without using large quantity of excess air. The pulverised coal is fed to the boiler by belt conveyors. The coal is burnt in the boiler and the ash produced after the complete combustion of coal is removed to the ash handling plant and then delivered to the ash storage plant for disposal. The removal of the ash from the boiler furnace is necessary for proper burning of coal. It is worthwhile to give a passing reference to the amount of coal burnt and ash produced in a modern thermal power station. A 100 MW station operating at 50% load factor may burn about 20,000 tons of coal per month and ash produced may be to the tune of 10% to 15% of coal fired i.e., 2,000 to 3,000 tons. In fact, in a thermal station, about 50% to 60% of the total operating cost consists of fuel purchasing and its handling.

Steam generating plant:

The steam generating plant consists of a boiler for the production of steam and other auxiliary equipment for the utilisation of flue gases.

- (i) **Boiler.** The heat of combustion of coal in the boiler is utilised to convert water into steam at high temperature and pressure. The flue gases from the boiler make their journey through superheater, economiser, air pre-heater and are finally exhausted to atmosphere through the chimney.
- (ii) **Superheater.** The steam produced in the boiler is wet and is passed through a superheater where it is dried and superheated (i.e., steam temperature increased above that of boiling point of water) by the flue gases on their way to chimney. Superheating provides two principal benefits. Firstly, the overall efficiency is increased. Secondly, too much condensation in the last stages of turbine (which would cause blade corrosion) is avoided. The superheated steam from the superheater is fed to steam turbine through the main valve.
- (iii) **Economiser.** An economiser is essentially a feed water heater and derives heat from the flue gases for this purpose. The feed water is fed to the economiser before supplying to the

boiler. The economiser extracts a part of heat of flue gases to increase the feed water temperature.

- (iv) **Air preheater.** An air preheater increases the temperature of the air supplied for coal burning by deriving heat from flue gases. Air is drawn from the atmosphere by a forced draught fan and is passed through air preheater before supplying to the boiler furnace. The air preheater extracts heat from flue gases and increases the temperature of air used for coal combustion. The principal benefits of preheating the air are: increased thermal efficiency and increased steam capacity per square metre of boiler surface.

Steam turbine:

The dry and superheated steam from the superheater is fed to the steam turbine through main valve. The heat energy of steam when passing over the blades of turbine is converted into mechanical energy. After giving heat energy to the turbine, the steam is exhausted to the condenser which condenses the exhausted steam by means of cold-water circulation.

Alternator:

The steam turbine is coupled to an alternator. The alternator converts mechanical energy of turbine into electrical energy. The electrical output from the alternator is delivered to the bus bars through transformer, circuit breakers and isolators.

Feed water:

The condensate from the condenser is used as feed water to the boiler. Some water may be lost in the cycle which is suitably made up from external source. The feed water on its way to the boiler is heated by water heaters and economiser. This helps in raising the overall efficiency of the plant.

Cooling arrangement:

In order to improve the efficiency of the plant, the steam exhausted from the turbine is condensed* by means of a condenser. Water is drawn from a natural source of supply such as a river, canal or lake and is circulated through the condenser. The circulating water takes up the heat of the exhausted steam and itself becomes hot. This hot water coming out from the condenser is discharged at a suitable location down the river. In case the availability of water from the source of supply is not assured throughout the year, cooling towers are used. During the scarcity of water in the river, hot water from the condenser is passed on to the cooling towers where it is cooled. The cold water from the cooling tower is reused in the condenser.

Equipment of Steam Power Station A modern steam power station is highly complex and has numerous equipment and auxiliaries. However, the most important constituents of a steam power station are:

1. Steam generating equipment
2. Condenser
3. Prime mover
4. Water treatment plant
5. Electrical equipment.

Hydro power plant:

A generating station which utilises the potential energy of water at a high level for the generation of electrical energy is known as a **hydro-electric power station**.

Hydro-electric power stations are generally located in hilly areas where dams can be built conveniently and large water reservoirs can be obtained. In a hydro-electric power station, water head is created by constructing a dam across a river or lake. From the dam, water is led to a water turbine. The water turbine captures the energy in the falling water and changes the hydraulic energy (*i.e.*, product of head and flow of water) into mechanical energy at the turbine shaft. The turbine drives the alternator which converts mechanical energy into electrical energy. Hydro-electric power stations are becoming very popular because the reserves of fuels (*i.e.*, coal and oil) are depleting day by day. They have the added importance for flood control, storage of water for irrigation and water for drinking purposes.

Advantages

- (i) It requires no fuel as water is used for the generation of electrical energy.
- (ii) It is quite neat and clean as no smoke or ash is produced.
- (iii) It requires very small running charges because water is the source of energy which is available free of cost.
- (iv) It is comparatively simple in construction and requires less maintenance.
- (v) It does not require a long starting time like a steam power station. In fact, such plants can be put into service instantly.
- (vi) It is robust and has a longer life.
- (vii) Such plants serve many purposes. In addition to the generation of electrical energy, they also help in irrigation and controlling floods.
- (viii) Although such plants require the attention of highly skilled persons at the time of construction, yet for operation, a few experienced persons may do the job well.

Disadvantages

- (i) It involves high capital cost due to construction of dam.
- (ii) There is uncertainty about the availability of huge amount of water due to dependence on weather conditions.
- (iii) Skilled and experienced hands are required to build the plant.
- (iv) It requires high cost of transmission lines as the plant is located in hilly areas which are quite away from the consumers.

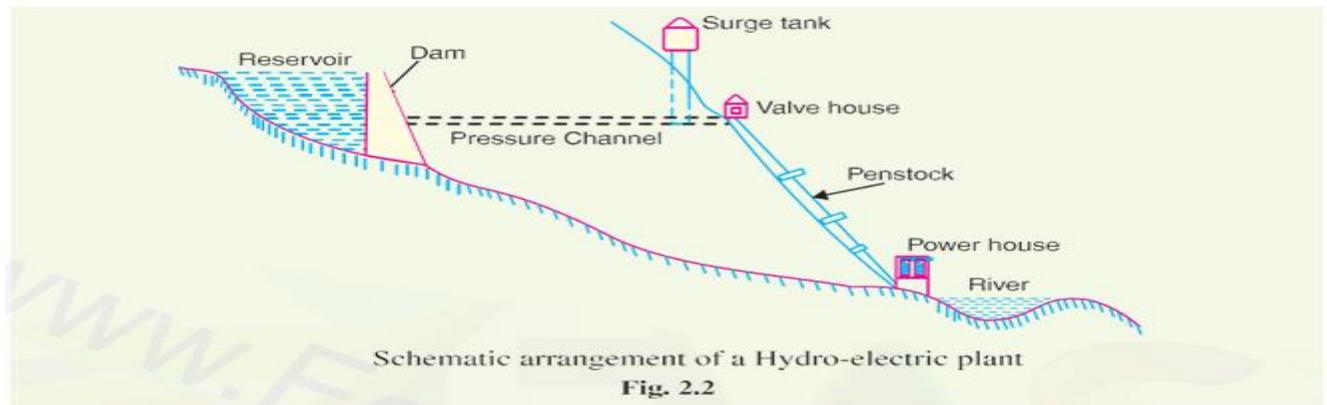
Schematic Arrangement of Hydroelectric Power Station

Although a hydro-electric power station simply involves the conversion of hydraulic energy into electrical energy, yet it embraces many arrangements for proper working and efficiency. The schematic arrangement of a modern hydro-electric plant is shown in Fig. 2.2.

The dam is constructed across a river or lake and water from the catchment area collects at the back of the dam to form a reservoir. A pressure tunnel is taken off from the reservoir and water brought to the valve house at the start of the penstock. The valve house contains main sluice valves and automatic isolating valves. The former controls the water flow to the power house and the latter cuts off supply of water when the penstock bursts. From the valve house, water is taken to water turbine through a huge steel pipe known as *penstock*. The water turbine converts hydraulic energy into mechanical energy. The turbine drives the alternator which converts mechanical energy into electrical energy.

A surge tank (open from top) is built just before the valve house and protects the penstock from bursting in case the turbine gates suddenly close* due to electrical load being thrown off. When

the gates close, there is a sudden stopping of water at the lower end of the penstock and consequently the penstock can burst like a paper log. The surge tank absorbs this pressure swing by increase in its level of water



Constituents of Hydroelectric Plant

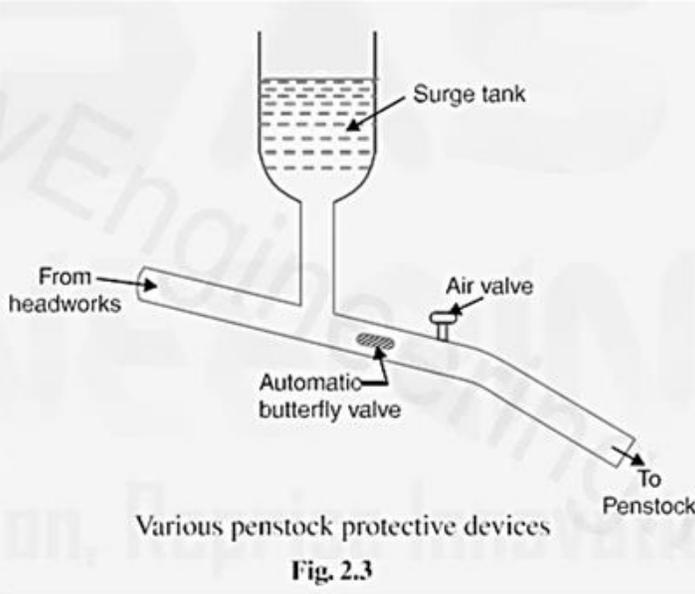
The constituents of a hydro-electric plant are

- (1) hydraulic structures
- (2) water turbines and electrical equipment.

Hydraulic structures. Hydraulic structures in a hydro-electric power station include dam, spillways, headworks, surge tank, penstock and accessory works.

- (i) **Dam.** A dam is a barrier which stores water and creates water head. Dams are built of concrete or stone masonry, earth or rock fill. The type and arrangement depend upon the topography of the site. A masonry dam may be built in a narrow canyon. An earth dam may be best suited for a wide valley. The type of dam also depends upon the foundation conditions, local materials and transportation available, occurrence of earthquakes and other hazards. At most of sites, more than one type of dam may be suitable and the one which is most economical is chosen.
- (ii) **Spillways.** There are times when the river flow exceeds the storage capacity of the reservoir. Such a situation arises during heavy rainfall in the catchment area. In order to discharge the surplus water from the storage reservoir into the river on the down-stream side of the dam, spillways are used. Spillways are constructed of concrete piers on the top of the dam. Gates are provided between these piers and surplus water is discharged over the crest of the dam by opening these gates.
- (iii) **Headworks.** The headworks consists of the diversion structures at the head of an intake. They generally include booms and racks for diverting floating debris, sluices for by-passing debris and sediments and valves for controlling the flow of water to the turbine. The flow of water into and through headworks should be as smooth as possible to avoid head loss and cavitation. For this purpose, it is necessary to avoid sharp corners and abrupt contractions or enlargements.

(iv) **Surge tank.** Open conduits leading water to the turbine require no* protection. However, when closed conduits are used, protection becomes necessary to limit the abnormal pressure in the conduit. For this reason, closed conduits are always provided with a surge tank. A surge tank is a small reservoir or tank (open at the top) in which water level rises or falls to reduce the pressure swings in the conduit.



A surge tank is located near the beginning of the conduit.

When the turbine is running at a steady load, there are no surges in the flow of water through the conduit *i.e.*, the quantity of water flowing in the conduit is just sufficient to meet the turbine requirements. However, when the load on the turbine decreases, the governor closes the gates of turbine, reducing water supply to the turbine. The excess water at the lower end of the conduit rushes back to the surge tank and increases its water level. Thus the conduit is prevented from bursting. On the other hand, when load on the turbine increases, additional water is drawn from the surge tank to meet the increased load requirement. Hence, a surge tank overcomes the abnormal pressure in the conduit when load on the turbine falls and acts as a reservoir during increase of load on the turbine.

(iv) **Penstocks.** Penstocks are open or closed conduits which carry water to the turbines. They are generally made of reinforced concrete or steel. Concrete penstocks are suitable for low heads (< 30 m) as greater pressure causes rapid deterioration of concrete. The steel penstocks can be designed for any head; the thickness of the penstock increases with the head or working pressure

Water turbines. Water turbines are used to convert the energy of falling water into mechanical energy. The principal types of water turbines are:

- (i) Impulse turbines (ii) Reaction turbines

Nuclear Power Station:

A generating station in which nuclear energy is converted into electrical energy is known as a nuclear power station.

In nuclear power station, heavy elements such as Uranium (U^{235}) or Thorium (Th^{232}) are subjected to nuclear fission in a special apparatus known as a *reactor*. The heat energy thus released is utilised in raising steam at high temperature and pressure. The steam runs the steam turbine which converts steam energy into mechanical energy. The turbine drives the alternator which converts mechanical energy into electrical energy.

The most important feature of a nuclear power station is that huge amount of electrical energy can be produced from a relatively small amount of nuclear fuel as compared to other conventional

types of power stations. It has been found that complete fission of 1 kg of Uranium (U^{235}) can produce as much energy as can be produced by the burning of 4,500 tons of high-grade coal. Although the recovery of principal nuclear fuels (*i.e.*, Uranium and Thorium) is difficult and expensive, yet the total energy content of the estimated world reserves of these fuels are considerably higher than those of conventional fuels, *viz.*, coal, oil and gas. At present, energy crisis is gripping us and, therefore, nuclear energy can be successfully employed for producing low cost electrical energy on a large scale to meet the growing commercial and industrial demands.

Advantages

- (i) The amount of fuel required is quite small. Therefore, there is a considerable saving in the cost of fuel transportation.
- (ii) A nuclear power plant requires less space as compared to any other type of the same size.
- (iii) It has low running charges as a small amount of fuel is used for producing bulk electrical energy.
- (iv) This type of plant is very economical for producing bulk electric power.
- (v) It can be located near the load centres because it does not require large quantities of water and need not be near coal mines. Therefore, the cost of primary distribution is reduced.
- (vi) There are large deposits of nuclear fuels available all over the world. Therefore, such plants can ensure continued supply of electrical energy for thousands of years.
- (vii) It ensures reliability of operation.

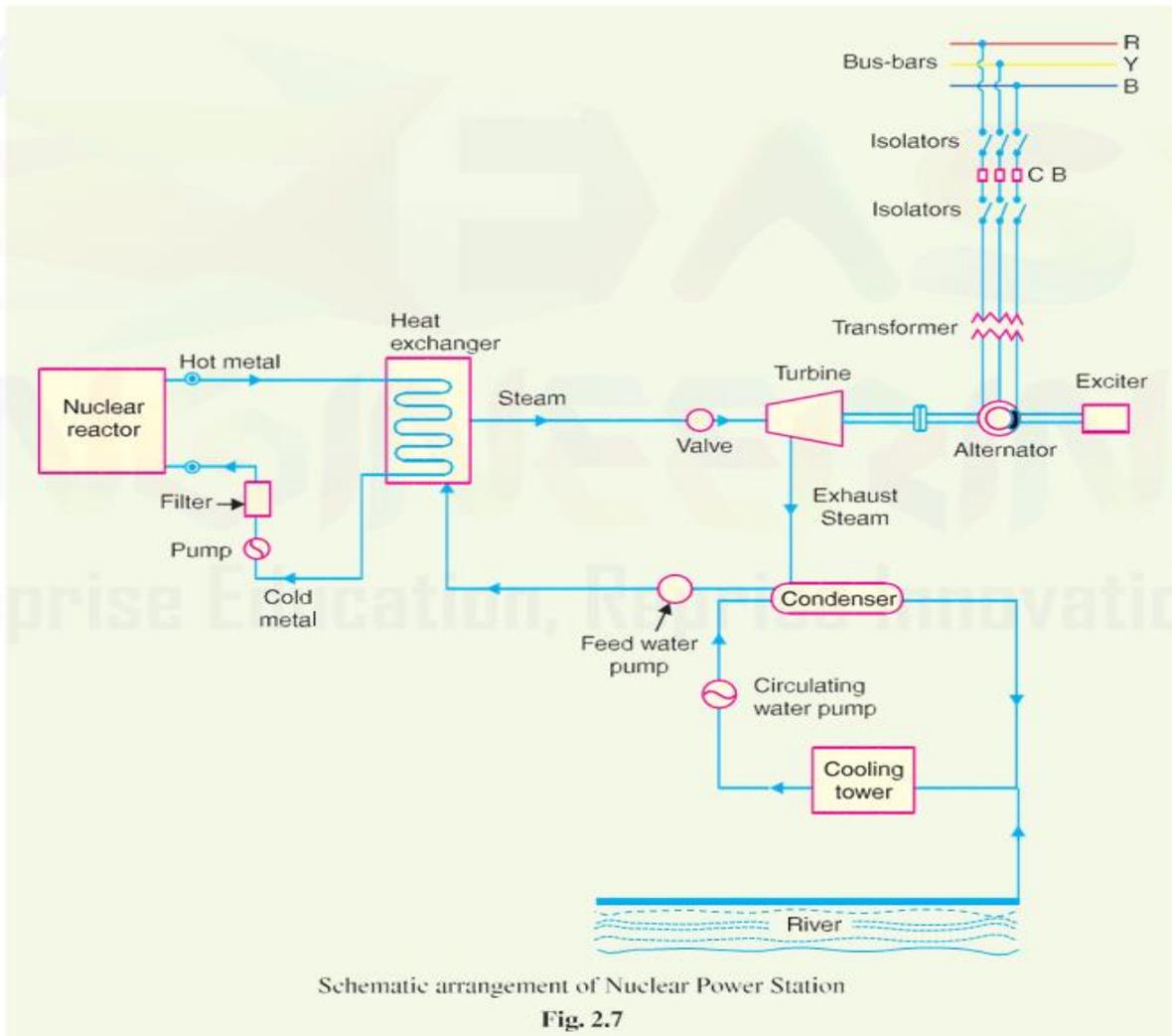
Disadvantages

- (i) The fuel used is expensive and is difficult to recover.
- (ii) The capital cost on a nuclear plant is very high as compared to other types of plants.
- (iii) The erection and commissioning of the plant requires greater technical know-how.
- (iv) The fission by-products are generally radioactive and may cause a dangerous amount of radioactive pollution.
- (v) Maintenance charges are high due to lack of standardization. Moreover, high salaries of specially trained personnel employed to handle the plant further raise the cost.
- (vi) Nuclear power plants are not well suited for varying loads as the reactor does not respond to the load fluctuations efficiently.
- (vii) The disposal of the by-products, which are radioactive, is a big problem. They have either to be disposed of in a deep trench or in a sea away from sea-shore.

Schematic Arrangement of Nuclear Power Station

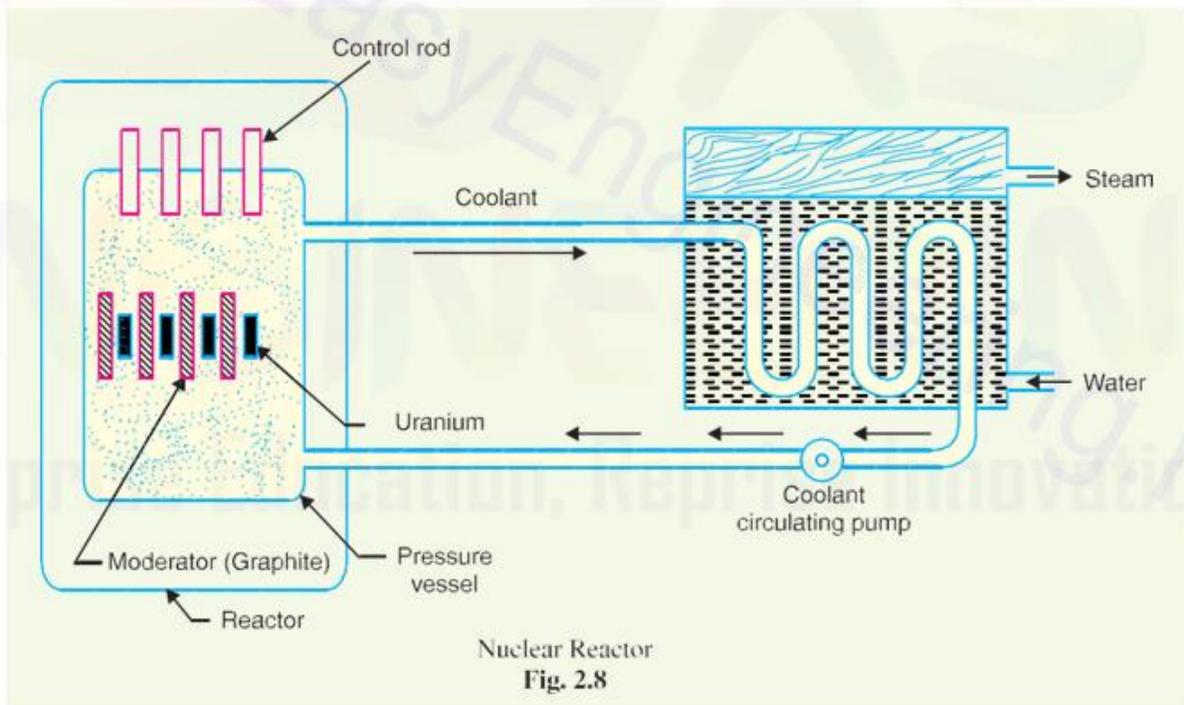
The schematic arrangement of a nuclear power station is shown in Fig. 2.7. The whole arrangement can be divided into the following main stages :

- (i) Nuclear reactor (ii) Heat exchanger (iii) Steam turbine (iv) Alternator.



- (i) **Nuclear reactor.** It is an apparatus in which nuclear fuel (U^{235}) is subjected to nuclear fission. It controls the *chain reaction** that starts once the fission is done. If the chain reaction is not controlled, the result will be an explosion due to the fast increase in the energy released.

A nuclear reactor is a cylindrical stout pressure vessel and houses fuel rods of Uranium, moderator and control rods (See Fig. 2.8). The fuel rods constitute the fission material and release huge amount of energy when bombarded with slow moving neutrons. The moderator consists of graphite rods which enclose the fuel rods. The moderator slows down the neutrons before they bombard the fuel rods. The control rods are of cadmium and are inserted into the reactor. Cadmium is strong neutron absorber and thus regulates the supply of neutrons for fission. When the control rods are pushed in deep enough, they absorb most of fission neutrons and hence few are available for chain reaction which, therefore, stops. However, as they are being withdrawn, more and more of these fission neutrons cause fission and hence the *intensity* of chain reaction (or heat produced) is increased. Therefore, by pulling out the control rods, power of the nuclear reactor is increased, whereas by pushing them in, it is reduced. In actual practice, the lowering or raising of control rods is accomplished automatically according to the requirement of load. The heat produced in the reactor is removed by the coolant, generally a sodium metal. The coolant carries the heat to the heat exchanger.



- (ii) **Heat exchanger.** The coolant gives up heat to the heat exchanger which is utilised in raising the steam. After giving up heat, the coolant is again fed to the reactor.
- (iii) **Steam turbine.** The steam produced in the heat exchanger is led to the steam turbine through a valve. After doing a useful work in the turbine, the steam is exhausted to condenser. The condenser condenses the steam which is fed to the heat exchanger through feed water pump.
- (iv) **Alternator.** The steam turbine drives the alternator which converts mechanical energy into electrical energy. The output from the alternator is delivered to the bus-bars through trans- former, circuit breakers and isolators.

Solar power plant:

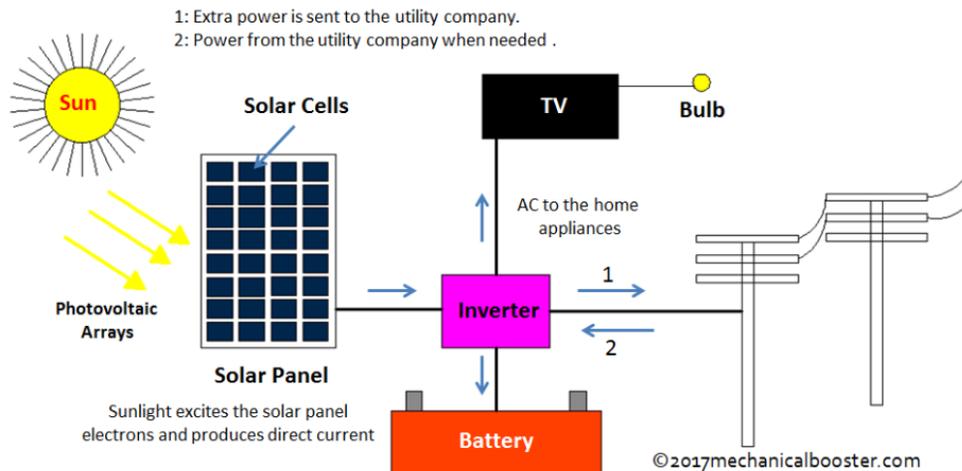
- **How does a Solar Panel Converts Sunlight into Electricity?**

Sunlight travels to earth in the form of small energy particles called photons. This photon strikes the p- type region and transfer its energy to hole and electron pair thus exciting the electron and it gets away from hole. The electric field we have due to potential difference at p-n junction makes its electron to travel to n-type region thus causing the current to flow. But there a bit more to know, to make this electric field strong enough so that it must travel to n-type region and not recombine with the hole it has been separated from. To make this electric field strong the n-type and p-type regions are connected to negative and positive terminals of battery, this process is known as reverse bias condition. Doing this increases the probability of electron travelling all along the way to n-type region once separated from a hole. Thus increasing the efficiency of a solar panel.

- **Working Principle:**

The working principle is that we use the energy of photons to get the drift current flowing in the circuit using reversed bias p-n junction diode (p-type and n-type silicon combination).

- **Main Components:**



Working of Solar Power Plant

1. Solar Panels

It is the heart of the solar power plant. Solar panels consist a number of solar cells. We have got around 35 solar cells in one panel. The energy produced by each solar cell is very small, but combining the energy of 35 of them we have got enough energy to charge a 12-volt battery.

2. Solar Cells

It is the energy generating unit, made up of p-type and n-type silicon semiconductor. It's the heart of solar power plant.

3. Battery

Batteries are used to produce the power back or store the excess energy produced during day, to be supplied during night.

4. D.C. to A.C. Converter (Inverter)

Solar panels produce direct current which is required to be converted into alternating current to be supplied to homes or power grid.

Working of Solar Power Plant

As sunlight falls over a solar cell, a large number of photons strike the p-type region of silicon. Electron and hole pair will get separated after absorbing the energy of photon. The electron travels from p-type region to n-type region due to the action of electric field at p-n junction. Further the diode is reversed biased to increase this electric field. So, this current start flowing in the circuit for individual solar cell. We combine the current of all the solar cells of a solar panel, to get a significant output.

Solar power plant has a large number of solar panels connected to each other to get a large voltage output. The electrical energy coming from the combined effort of solar panels is stored in the Lithium ion batteries to be supplied at night time, when there is no sunlight.

Energy Storage

Storage of the energy generated by the solar panels is a important issue. Sometimes the unused energy generated during daytime is used to pump water to some height, so that it could be used to generate electricity using its potential energy when required or mainly at night time.

For current being Tesla is providing its industrial energy pack to store energy and currently it is lighting up an entire island. Tesla has also made an offer to Australia that it could provide its battery pack for emergency blackouts.

The cost of manufacturing of solar panels has decreased rapidly in last few years, same is said to be true with the industrial energy pack (Lithium ion batteries), as the production and demand increases their cost is going to decrease in coming few years.

Chapter2 Transmission of electric power

Layout of transmission and distribution scheme:

The conveyance of electric power from a power station to consumers' premises is known as **electric supply system**.

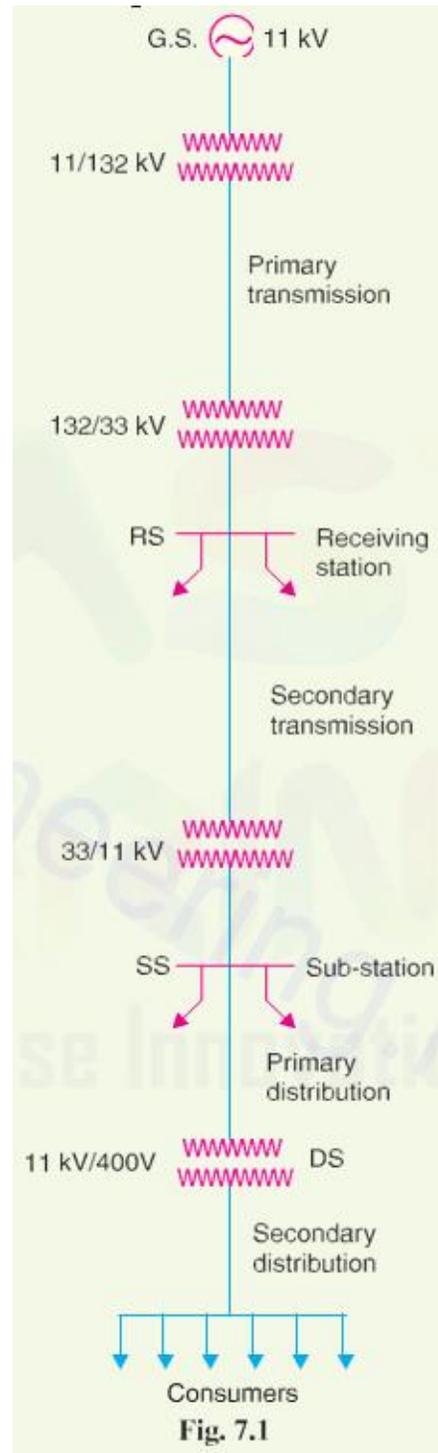
An electric supply system consists of three principal components viz., the power station, the transmission lines and the distribution system. Electric power is produced at the power stations which are located at favourable places, generally quite away from the consumers. It is then transmitted over large distances to load centres with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network

The electric supply system can be broadly classified into
(i) d.c. or a.c. system

(ii) overhead or underground system.

Now-a-days, 3-phase, 3-wire a.c. system is universally adopted for generation and transmission of electric power as an economical proposition. However, distribution of electric power is done by 3-phase, 4-wire a.c. system. The underground system is more expensive than the overhead system. Therefore, in our country, overhead system is mostly adopted for transmission and distribution of electric power.

Generating station: In Fig 7.1, G.S. represents the generating station where electric power is produced by 3-phase alternators operating in parallel. The usual generation voltage is 11 kV. For economy in the transmission of electric power, the generation voltage (*i.e.*, 11 kV) is stepped upto 132 kV (or more) at the generating station with the help of 3-phase transformers. The transmission of electric power at high voltages has several advantages including the saving of conductor material and high transmission efficiency. It may appear advisable to use the highest possible voltage for transmission of electric power to save conductor material and have other advantages. But there is a limit to which this voltage can be increased. It is because increase in transmission voltage introduces insulation problems as well as the cost of switchgear and transformer equipment is increased. Therefore, the choice of proper transmission voltage is essentially



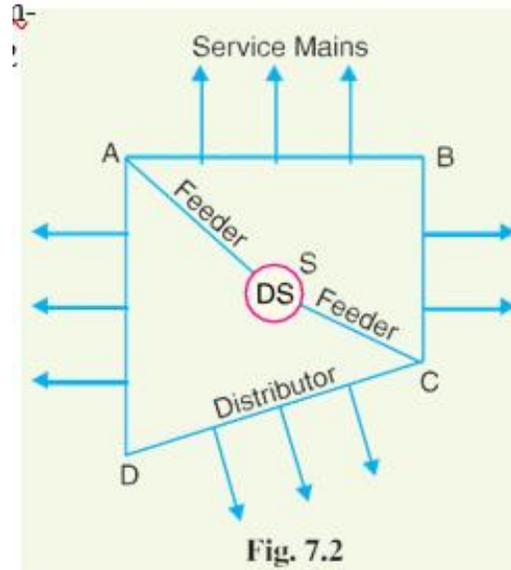
a question of economics. Generally, the primary transmission is carried at 66 kV, 132 kV, 220 kV or 400 kV.

Primary transmission. The electric power at 132 kV is transmitted by 3-phase, 3-wire overhead system to the out-skirts of the city. This forms the primary transmission.

Secondary transmission. The primary transmission line terminates at the receiving station (RS) which usually lies at the outskirts of the city. At the receiving station, the voltage is reduced to 33kV by step-down transformers. From this station, electric power is transmitted at 33kV by 3-phase, 3-wire overhead system to various sub-stations (SS) located at the strategic points in the city. This forms the secondary transmission.

Primary distribution. The secondary transmission line terminates at the sub-station (SS) where voltage is reduced from 33 kV to 11kV, 3-phase, 3-wire. The 11 kV lines run along the important road sides of the city. This forms the primary distribution. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations.

secondary distribution.: The electric power from primary distribution line (11 kV) is delivered to distribution sub-stations (DS). These sub-stations are located near the consumers' localities and step down the voltage to 400 V, 3-phase, 4-wire for secondary distribution. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single-phase residential lighting load is connected between any one phase and neutral, whereas 3-phase, 400 V motor load is connected across 3-phase lines directly.



It may be worthwhile to mention here that secondary distribution system consists of *feeders, distributors and service mains*. Fig. 7.2 shows the elements of low voltage distribution system. Feeders (SC or SA) radiating from the distribution sub-station (DS) supply power to the distributors (AB, BC, CD and AD). No consumer is given direct connection from the feeders. Instead, the consumers are connected to the distributors through their service mains.

Voltage regulation and efficiency of transmission:

Voltage regulation. When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending end voltage (V_S). This voltage drop ($V_S - V_R$) in the line is expressed as a percentage of receiving end voltage V_R and is called voltage regulation.

*The difference in voltage at the receiving end of a transmission line between conditions of no load and full load is called **voltage regulation** and is expressed as a percentage of the receiving end voltage.*

Mathematically,

$$\% \text{ age Voltage regulation} = (V_S - V_R) / V_R \times 100$$

Obviously, it is desirable that the voltage regulation of a transmission line should be low *i.e.*, the increase in load current should make very little difference in the receiving end voltage.

Transmission efficiency. The power obtained at the receiving end of a transmission line is generally less than the sending end power due to losses in the line resistance.

The ratio of receiving end power to the sending end power of a transmission line is known as the **transmission efficiency of the line** i.e.

$$\begin{aligned} & \% \text{ age Transmission efficiency, } \eta_T \\ & = \frac{\text{Receiving end power}}{\text{Sending end power}} \times 100 \\ & = \left(\frac{V_R I_R \cos \phi_R}{V_S I_S \cos \phi_S} \right) \times 100 \end{aligned}$$

where V_R , I_R and $\cos \phi_R$ are the receiving end voltage, current and power factor while V_S , I_S and $\cos \phi_S$ are the corresponding values at the sending end..

Kelvin's law for economical size of conductor:

Economic Choice of Conductor Size:

The cost of conductor material is generally a very considerable part of the total cost of a transmission line. Therefore, the determination of proper size of conductor for the line is of vital importance. The most economical area of conductor is that for which the total annual cost of transmission line is minimum*. This is known as *Kelvin's Law* after Lord Kelvin who first stated it in 1881. The total annual cost of transmission line can be divided broadly into two parts viz., annual charge on capital outlay and annual cost of energy wasted in the conductor.

(i)Annual charge on capital outlay. This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead system, it will be the annual interest and depreciation on the capital cost of conductors, supports and insulators and the cost of their erection. Now, for an overhead line, insulator cost is constant, the conductor cost is proportional to the area of X-section and the cost of supports and their erection is partly constant and partly proportional to area of X-section of the conductor. Therefore, annual charge on an overhead transmission line can be expressed as :

$$\text{Annual charge} = P_1 + P_2 a$$

where P_1 and P_2 are constants and a is the area of X-section of the conductor.

(ii) *Annual cost of energy wasted.* This is on account of energy lost mainly \dagger in the conductor due to I^2R losses. Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance. As resistance is inversely proportional to the area of X-section of the conductor, therefore, the energy lost in the conductor is inversely proportional to area of X-section. Thus, the annual cost of energy wasted in an overhead transmission line can be expressed as :

$$\text{Annual cost of energy wasted} = P_3/a \quad \dots(ii)$$

where P_3 is a constant.

$$\begin{aligned} \text{Total annual cost, } C &= \text{exp. (i)} + \text{exp. (ii)} \\ &= (P_1 + P_2 a) + P_3/a \end{aligned}$$

$$\therefore C = P_1 + P_2 a + P_3/a \quad \dots(iii)$$

In exp. (iii), only area of X-section a is variable. Therefore, the total annual cost of transmission line will be minimum if differentiation of C w.r.t. a is zero *i.e.*

$$\frac{d}{da} (C) = 0$$

$$\text{or } \frac{d}{da} (P_1 + P_2 a + P_3/a) = 0$$

$$\text{or } P_2 - \frac{P_3}{a^2} = 0$$

$$\text{or } P_2 = \frac{P_3}{a^2}$$

$$\text{or } P_2 a = \frac{P_3}{a}$$

i.e. Variable part of annual charge = Annual cost of energy wasted

Therefore Kelvin's Law can also be stated in another way *i.e. the most economical area of conductor is that for which the variable part* of annual charge is equal to the cost of energy losses per year.*

Graphical illustration of Kelvin's law. Kelvin's law can also be illustrated graphically by plotting annual cost against X-sectional area ' a ' of the conductor as shown in Fig. 7.28. In the diagram, the straight line (1) shows the relation between the annual charge (*i.e.*, $P_1 + P_2 a$) and the area of X-section a of the conductor. Similarly, the rectangular hyperbola (2) gives the relation between annual cost of energy wasted and X-sectional area a . By adding the ordinates of curves (1) and (2), the curve (3) is obtained. This latter curve shows the relation between total annual cost ($P_1 + P_2 a + P_3/a$) of transmission line and area of X-section a . The lowest point on the curve (*i.e.*, point P) represents the most economical area of X-section.

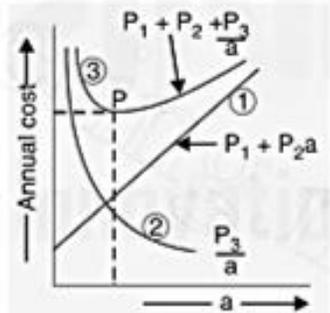


Fig. 7.28

Limitations of Kelvin's law. Although theoretically Kelvin's law holds good, there is often considerable difficulty in applying it to a proposed scheme of power transmission. In practice, the limitations of this law are :

- (i) It is not easy to estimate the energy loss in the line without actual load curves, which are not available at the time of estimation.
- (ii) The assumption that annual cost on account of interest and depreciation on the capital outlay is in the form $P_1 + P_2 a$ is strictly speaking not true. For instance, in cables neither the cost of cable dielectric and sheath nor the cost of laying vary in this manner.

(iii) This law does not take into account several physical factors like safe current density, mechanical strength, corona loss etc.

(iv) The conductor size determined by this law may not always be practicable one because it may be too small for the safe carrying of necessary current.

(v) Interest and depreciation on the capital outlay cannot be determined accurately.

Corona and corona loss in transmission lines:

Corona

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called *critical disruptive voltage*, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise. If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation.

*The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as **corona**.*

If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductors, otherwise the rough points will appear brighter. With d.c. voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation.

Some ionisation is always present in air due to cosmic rays, ultra-violet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles (*i.e.*, free electrons and +ve ions) and neutral molecules. When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons.

When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which in turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cumulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends:

1. Atmosphere. As corona is formed due to ionization of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

2. Conductor size. The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface

decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona than a solid conductor.

3. Spacing between conductors. If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

4. Line voltage. The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

8.12 Important Terms

The phenomenon of corona plays an important role in the design of an overhead transmission line. Therefore, it is profitable to consider the following terms much used in the analysis of corona effects:

(i) **Critical disruptive voltage.** *It is the minimum phase-neutral voltage at which corona occurs.*

Consider two conductors of radii r cm and spaced d cm apart. If V is the phase-neutral potential, then potential gradient at the conductor surface is given by:

$$g = \frac{V}{r \log_e \frac{d}{r}} \text{ volts/cm}$$

In order that corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25°C is 30 kV/cm (max) or _____

21.2 kV/cm (*r.m.s.*) and is denoted by g_o . If V_c is the phase-neutral potential required under these conditions, then,

$$g_o = \frac{V_c}{r \log_e \frac{d}{r}}$$

where

$$g_o = \text{breakdown strength of air at 76 cm of mercury and } 25^\circ\text{C} \\ = 30 \text{ kV/cm (max) or } 21.2 \text{ kV/cm (r.m.s.)}$$

$$\therefore \text{Critical disruptive voltage, } V_c = g_o r \log_e \frac{d}{r}$$

The above expression for disruptive voltage is under standard conditions *i.e.*, at 76 cm of Hg and 25°C . However, if these conditions vary, the air density also changes, thus altering the value of g_o . The value of g_o is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of b cm of mercury and temperature of $t^\circ\text{C}$ becomes δg_o where

$$\delta = \text{air density factor} = \frac{3.92b}{273 + t}$$

Under standard conditions, the value of $\delta = 1$.

$$\therefore \text{Critical disruptive voltage, } V_c = g_o \delta r \log_e \frac{d}{r}$$

Correction must also be made for the surface condition of the conductor. This is accounted for by multiplying the above expression by irregularity factor m_o .

$$\therefore \text{Critical disruptive voltage, } V_c = m_o g_o \delta r \log_e \frac{d}{r} \text{ kV/phase}$$

where

$$m_o = 1 \text{ for polished conductors} \\ = 0.98 \text{ to } 0.92 \text{ for dirty conductors} \\ = 0.87 \text{ to } 0.8 \text{ for stranded conductors}$$

(ii) **Visual critical voltage.** It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage V_c but at a higher voltage V_v , called *visual critical voltage*. The phase-neutral effective value of visual critical voltage is given by the following empirical formula :

$$V_v = m_v g_o \delta r \left(1 + \frac{0.3}{\sqrt{\delta r}} \right) \log_e \frac{d}{r} \text{ kV/phase}$$

where m_v is another irregularity factor having a value of 1.0 for polished conductors and 0.72 to 0.82 for rough conductors.

(iii) **Power loss due to corona.** Formation of corona is always accompanied by energy loss which is dissipated in the form of light, heat, sound and chemical action. When disruptive voltage is exceeded, the power loss due to corona is given by :

$$P = 242.2 \left(\frac{f+25}{\delta} \right) \sqrt{\frac{r}{d}} (V - V_c)^2 \times 10^{-5} \text{ kW / km / phase}$$

where

$$f = \text{supply frequency in Hz} \\ V = \text{phase-neutral voltage (r.m.s.)} \\ V_c = \text{disruptive voltage (r.m.s.) per phase}$$

Factors Affecting Corona

The phenomenon of corona is affected by the physical state of the atmosphere as well as by the conditions of the line. The following are the factors upon which corona depends :

- **Atmosphere.** As corona is formed due to ionisation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.
- **Conductor size.** The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona than a solid conductor.
- **Spacing between conductors.** If the spacing between the conductors is made very large as compared to their diameters, there may not be any corona effect. It is because larger distance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.
- **Line voltage.** The line voltage greatly affects corona. If it is low, there is no change in the condition of air surrounding the conductors and hence no corona is formed. However, if the line voltage has such a value that electrostatic stresses developed at the conductor surface make the air around the conductor conducting, then corona is formed.

Advantages and Disadvantages of Corona

Corona has many advantages and disadvantages. In the correct design of a high voltage overhead line, a balance should be struck between the advantages and disadvantages.

Advantages

- Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electro-static stresses between the conductors.
- Corona reduces the effects of transients produced by surges.

Disadvantages

- Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.
- Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.
- The current drawn by the line due to corona is nonsinusoidal and hence nonsinusoidal voltage drop occurs in the line. This may cause inductive interference with neighbouring communication lines.

Methods of Reducing Corona Effect

It has been seen that intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionised air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment. The corona effects can be reduced by the following methods:

- **By increasing conductor size.** By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the

reasons that ACSR conductors which have a larger cross-sectional area are used in transmission lines.

- **By increasing conductor spacing.** By increasing the spacing between conductors, the voltage at which corona occurs is raised and hence corona effects can be eliminated. However, spacing cannot be increased too much otherwise the cost of supporting structure (e.g., bigger cross arms and supports) may increase to a considerable extent.

Example A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart. If the dielectric strength of air is 30 kV (max) per cm, find the disruptive critical voltage for the line. Take air density factor $\delta = 0.952$ and irregularity factor $m_o = 0.9$.

Solution.

Conductor radius, $r = 2/2 = 1$ cm

Conductor spacing, $d = 1$ m = 100 cm

Dielectric strength of air, $g_o = 30$ kV/cm (max.) = 21.2 kV (r.m.s.) per cm

Disruptive critical voltage, $V_c = m_o g_o \delta r \log_e (d/r)$ kV*/phase (r.m.s. value)
 $= 0.9 \times 21.2 \times 0.952 \times 1 \times \log_e 100/1 = 83.64$ kV/phase

\therefore Line voltage (r.m.s.) = $\sqrt{3} \times 83.64 = 144.8$ kV

Example A 132 kV line with 1.956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionisation occurs can be taken as 30 kV per cm, find the spacing between the conductors.

Solution.

Assume the line is 3-phase.

Conductor radius, $r = 1.956/2 = 0.978$ cm

Dielectric strength of air, $g_o = 30/\sqrt{2} = 21.2$ kV (r.m.s.) per cm

Disruptive voltage/phase, $V_c = 210/\sqrt{3} = 121.25$ kV

Assume smooth conductors (i.e., irregularity factor $m_o = 1$) and standard pressure and temperature for which air density factor $\delta = 1$. Let d cm be the spacing between the conductors.

\therefore Disruptive voltage (r.m.s.) per phase is

$$\begin{aligned} V_c &= m_o g_o \delta r \log_e (d/r) \text{ kV} \\ &= 1 \times 21.2 \times 1 \times 0.978 \times \log_e (d/r) \end{aligned}$$

or $121.25 = 20.733 \log_e (d/r)$

or $\log_e \frac{d}{r} = \frac{121.25}{20.733} = 5.848$

or $2.3 \log_{10} d/r = 5.848$

or $\log_{10} d/r = 5.848/2.3 = 2.5426$

or $d/r = \text{Antilog } 2.5426$

or $d/r = 348.8$

\therefore Conductor spacing, $d = 348.8 \times r = 348.8 \times 0.978 = 341$ cm

Example A 3-phase, 220 kV, 50 Hz transmission line consists of 1.5 cm radius conductor spaced 2 metres apart in equilateral triangular formation. If the temperature is 40°C and atmospheric pressure is 76 cm, calculate the corona loss per km of the line. Take $m_o = 0.85$.

Solution.

As seen from Art. 8.12, the corona loss is given by :

$$P = \frac{242.2}{\delta} (f + 25) \sqrt{\frac{r}{d}} (V - V_c)^2 \times 10^{-5} \text{ kW/km/phase}$$

Now, $\delta = \frac{3.92 b}{273 + t} = \frac{3.92 \times 76}{273 + 40} = 0.952$

Assuming $g_o = 21.2$ kV/cm (r.m.s.)

\therefore Critical disruptive voltage per phase is

$$\begin{aligned} V_c &= m_o g_o \delta r \log_e d/r \text{ kV} \\ &= 0.85 \times 21.2 \times 0.952 \times 1.5 \times \log_e 200/1.5 = 125.9 \text{ kV} \end{aligned}$$

Supply voltage per phase, $V = 220/\sqrt{3} = 127$ kV

Substituting the above values, we have corona loss as:

$$\begin{aligned} P &= \frac{242.2}{0.952} (50 + 25) \times \sqrt{\frac{1.5}{200}} \times (127 - 125.9)^2 \times 10^{-5} \text{ kW/phase/km} \\ &= \frac{242.2}{0.952} \times 75 \times 0.0866 \times 1.21 \times 10^{-5} \text{ kW/km/phase} \\ &= 0.01999 \text{ kW/km/phase} \end{aligned}$$

\therefore Total corona loss per km for three phases

$$= 3 \times 0.01999 \text{ kW} = 0.05998 \text{ kW}$$

Example A certain 3-phase equilateral transmission line has a total corona loss of 53 kW at 106 kV and a loss of 98 kW at 110.9 kV. What is the disruptive critical voltage? What is the corona loss at 113 kV?

Solution.

The power loss due to corona for 3 phases is given by :

$$P = 3 \times \frac{242 \cdot 2 (f + 25)}{\delta} \sqrt{\frac{r}{d}} (V - V_c)^2 \times 10^{-5} \text{ kW/km}$$

As f , δ , r and d are the same for the two cases,

$$\therefore P \propto (V - V_c)^2$$

$$\text{For first case, } P = 53 \text{ kW and } V = 106/\sqrt{3} = 61.2 \text{ kV}$$

$$\text{For second case, } P = 98 \text{ kW and } V = 110.9/\sqrt{3} = 64 \text{ kV}$$

$$\therefore 53 \propto (61.2 - V_c)^2 \quad \dots(i)$$

$$\text{and } 98 \propto (64 - V_c)^2 \quad \dots(ii)$$

Dividing [(ii)/(i)], we get,

$$\frac{98}{53} = \frac{(64 - V_c)^2}{(61.2 - V_c)^2}$$

$$\text{or } V_c = 54 \text{ kV}$$

Let W kilowatt be the power loss at 113 kV.

$$\therefore W \propto \left(\frac{113}{\sqrt{3}} - V_c \right)^2$$

$$\propto (65.2 - 54)^2 \quad \dots(iii)$$

Dividing [(iii)/(i)], we get,

$$\frac{W}{53} = \frac{(65.2 - 54)^2}{(61.2 - 54)^2}$$

$$\therefore W = (11.2/7.2)^2 \times 53 = 128 \text{ kW}$$

TUTORIAL PROBLEMS

1. Estimate the corona loss for a three-phase, 110 kV, 50 Hz, 150 km long transmission line consisting of three conductors each of 10 mm diameter and spaced 2.5 m apart in an equilateral triangle formation. The temperature of air is 30°C and the atmospheric pressure is 750 mm of mercury. Take irregularity factor as 0.85. Ionisation of air may be assumed to take place at a maximum voltage gradient of 30 kV/cm. [316.8 kW]
2. Taking the dielectric strength of air to be 30 kV/cm, calculate the disruptive critical voltage for a 3-phase line with conductors of 1 cm radius and spaced symmetrically 4 m apart. [220 kV line voltage]
3. A 3-phase, 220 kV, 50 Hz transmission line consists of 1.2 cm radius conductors spaced 2 m at the corners of an equilateral triangle. Calculate the corona loss per km of the line. The condition of the wire is smoothly weathered and the weather is fair with temperature of 20°C and barometric pressure of 72.2 cm of Hg. [2.148 kW]