UNIT-1

1.1 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 utilising 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. 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

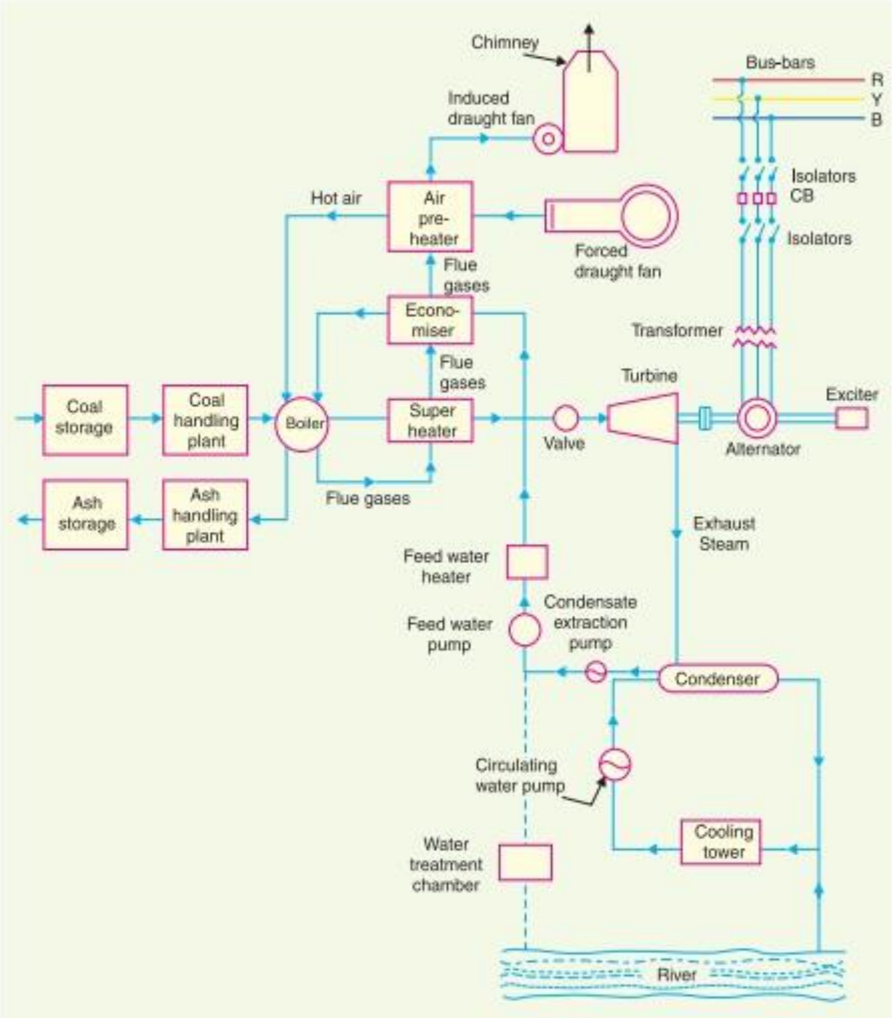
3. Steam turbine

4. Alternator

5. Feed water

6. Cooling arrangement

1. 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



Schematic arrangement of Steam Power Station

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

2. 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 super heater, 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.

3. 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.

4. 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.

5. 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 effi ciency of the plant.

6. 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.

Choice of Site for Steam Power Stations

In order to achieve overall economy, the following points should be considered while selecting a site for a steam power station :

(i) *Supply of fuel.*The steam power station should be located near the coal mines so that transportation cost of fuel is minimum. However, if such a plant is to be installed at a placewhere coal is not available, then care should be taken that adequate facilities exist for the transportation of coal.

(ii) *Availability of water.* As huge amount of water is required for the condenser, therefore, such a plant should be located at the bank of a river or near a canal to ensure the continuous supply of water.

(iii) *Transportation facilities.*A modern steam power station often requires the transportation of material and machinery. Therefore, adequate transportation facilities must exist *i.e.*, the plant should be well connected to other parts of the country by rail, road. etc.

(iv) *Cost and type of land.*The steam power station should be located at a place where land is cheap and further extension, if necessary, is possible. Moreover, the bearing capacity of the ground should be adequate so that heavy equipment could be installed.

(v) *Nearness to load centres.* In order to reduce the transmission cost, the plant should be located near the centre of the load. This is particularly important if *d.c.* supply system is adopted. However, if *a.c.* supply system is adopted, this factor becomes relatively less important. It is because *a.c.* power can be transmitted at high voltages with consequent reduced transmission cost. Therefore, it is possible to install the plant away from the load centres, provided other conditions are favourable.

(vi) *Distance from populated area.*As huge amount of coal is burnt in a steam power station, therefore, smoke and fumes pollute the surrounding area. This necessitates that the plant should be located at a considerable distance from the populated areas.

Conclusion. It is clear that all the above factors cannot be favourable at one place. However, keeping in view the fact that now-a-days the supply system is *a.c.* and more importance is being given to generation than transmission, a site away from the towns may be selected. In particular, a site by river side where sufficient water is available, no pollution of atmosphere occurs and fuel can be transported economically, may perhaps be an ideal choice

1.2.Hydro-electric Power Station

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.

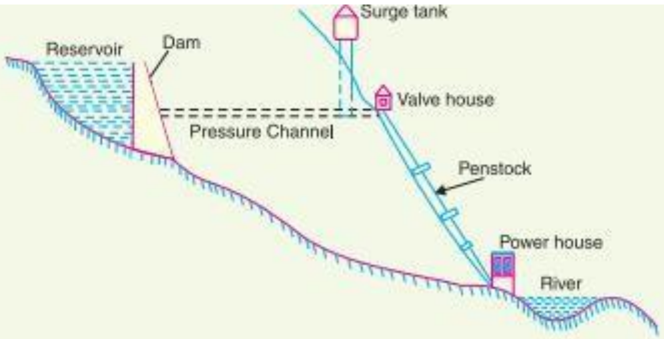
(iv) It requires high cost of transmission lines as the plant is located in hilly areas which are quite away from the consumers.

2.82.8

2.8 Schematic Arrangement of Hydro-electric 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 thegates 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.



Schematic arrangement of a Hydro-electric plant

Fig. 2.2

2.9

Choice of Site for Hydro-electric Power Stations

The following points should be taken into account while selecting the site for a hydro-electric power station :

(i) *Availability of water.* Since the primary requirement of a hydro-electric power station is the availability of huge quantity of water, such plants should be built at a place (*e.g.*, river, canal) where adequate water is available at a good head.

(ii) *Storage of water.*There are wide variations in water supply from a river or canal during the year. This makes it necessary to store water by constructing a dam in order to ensure the generation of power throughout the year. The storage helps in equalising the flow of water so that any excess quantity of water at a certain period of the year can be made available during times of very low flow in the river. This leads to the conclusion that site selected for a hydro-electric plant should provide adequate facilities for erecting a dam and storage of water.

(iii) *Cost and type of land.*The land for the construction of the plant should be available at a reasonable price. Further, the bearing capacity of the ground should be adequate to with stand the weight of heavy equipment to be installed.

(iv) *Transportation facilities.*The site selected for a hydro-electric plant should be accessible by rail and road so that necessary equipment and machinery could be easily transported.

It is clear from the above mentioned factors that ideal choice of site for such a plant is near a river in hilly areas where dam can be conveniently built and large reservoirs can be obtained.

2.10

Constituents of Hydro-electric Plant

The constituents of a hydro-electric plant are **(1)** hydraulic structures **(2)** water turbines and **(3)** electrical equipment. We shall discuss these items in turn.

1. 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 masonary, earth or rock fill. The type and arrangement depends upon the

topography of the site. A masonary 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 con

duit. 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.

(v) *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 pen stocks can be designed for any head; the thickness of the penstock increases with the head or working pressure.

Various devices such as automatic butterfly valve, air valve and surge tank (See Fig. 2.3) are provided for the protection of penstocks. Automatic butterfly valve shuts off water flow through the penstock promptly if it ruptures. Air valve maintains the air pressure inside the penstock equal to outside atmospheric pressure. When water runs out of a penstock faster than it enters, a vacuum is created which may cause the penstock to collapse. Under such situations, air valve opens and admits air in the penstock to maintain inside air pressure equal to the outside air pressure.

2. 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

(i) *Impulse turbines.* Such turbines are used for high heads. In an impulse turbine, the entire pressure of water is converted into kinetic energy in a nozzle and the velocity of the jet drives the wheel. The example of this type of turbine is the Pelton wheel.

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 (U235) or Thorium (Th232) 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 (U235) 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.

) Maintenance charges are high due to lack of standardisation. 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 off in a deep trench or in a sea away from sea-shore.

2.14 Schematic Arrangement of Nuclear Power Station

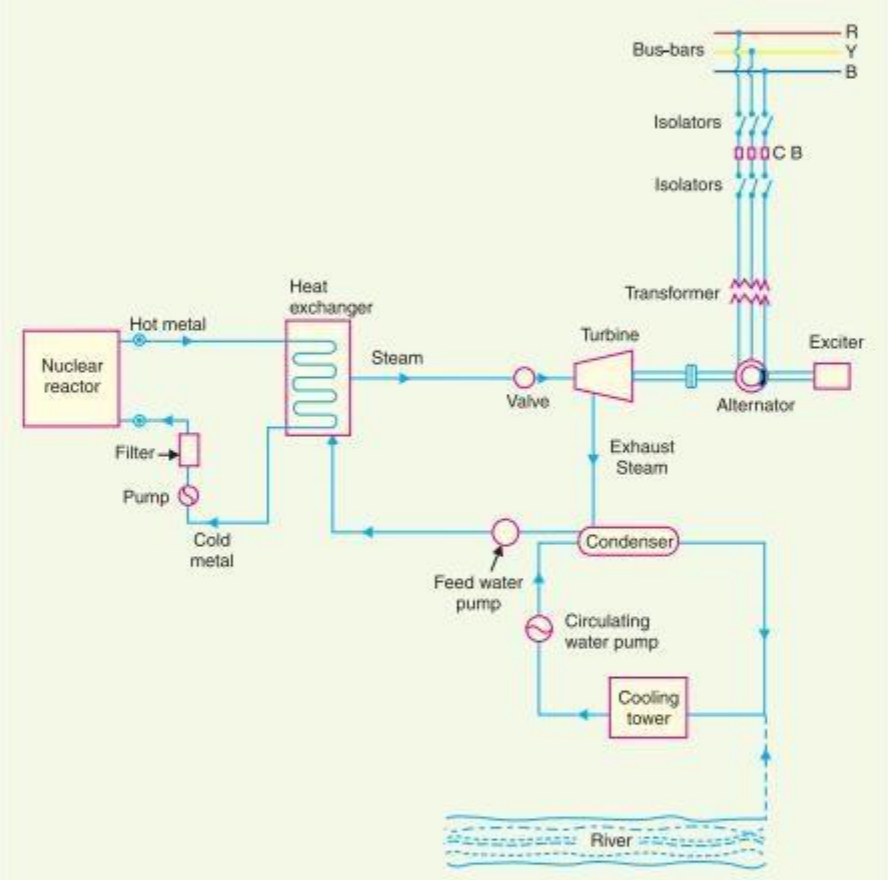
The schematic arrangement of a nuclear power station is shown in Fig. 2.7. The whole arrangement can be divided into the following main stages :

(i) Nuclear reactor

(ii) Heat exchanger

(iii) Steam turbine

(iv) Alternator.

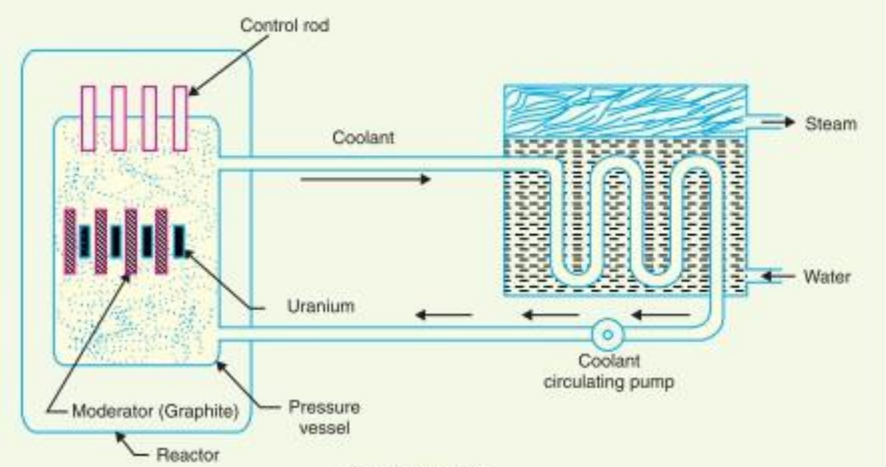


Schematic arrangement of Nuclear Power Station

Fig. 2.7

(i) Nuclear reactor. It is an apparatus in which nuclear fuel (U235) 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 modera tor 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 fis sion 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 accom plished automatically according to the requirement of load. The heat produced in the reac tor is removed by the coolant, generally a sodium metal. The coolant carries the heat to the heat exchanger.



Nuclear Reactor
Fig. 2.8

(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 transformer, circuit breakers and isolators.

2.15 Selection of Site for Nuclear Power Station

The following points should be kept in view while selecting the site for a nuclear power station :

(i) *Availability of water.* As sufficient water is required for cooling purposes, therefore, the plant site should be located where ample quantity of water is available, *e.g.*, across a river or by sea-side.

(ii) *Disposal of waste.* The waste produced by fission in a nuclear power station is generally radioactive which must be disposed off properly to avoid health hazards. The waste should either be buried in a deep trench or disposed off in sea quite away from the sea shore. Therefore, the site selected for such a plant should have adequate arrangement for the dis posal of radioactive waste.

(iii) *Distance from populated areas.*The site selected for a nuclear power station should be quite away from the populated areas as there is a danger of presence of radioactivity in the atmosphere near the plant. However, as a precautionary measure, *a dome* is used in the plant which does not allow the radioactivity to spread by wind or underground waterways.

(iv) *Transportation facilities.* The site selected for a nuclear power station should have adequate facilities in order to transport the heavy equipment during erection and to facilitate

the movement of the workers employed in the plant. From the above mentioned factors it becomes apparent that ideal choice for a nuclear power station would be near sea or river and away from thickly populated areas.

2.16 Gas Turbine Power Plant

A generating station which employs gas turbine as the prime mover for the generation of electrical energy is known as a **gas turbine power plant**

In a gas turbine power plant, air is used as the working fluid. The air is compressed by the compressor and is led to the combustion chamber where heat is added to air, thus raising its temperature. Heat is added to the compressed air either by burning fuel in the chamber or by the use of air heaters. The hot and high pressure air from the combustion chamber is then passed to the gas turbine where it expands and does the mechanical work. The gas turbine drives the alternator which converts mechanical energy into electrical energy. It may be mentioned here that compressor, gas turbine and the alternator are mounted on the same shaft so that a part of mechanical power of the turbine can be utilised for the operation of the compressor. Gas turbine power plants are being used as standby plants for hydro-electric stations, as a starting plant for driving auxiliaries in power plants etc.

Advantages

(i) It is simple in design as compared to steam power station since no boilers and their auxiliaries are required.

(ii) It is much smaller in size as compared to steam power station of the same capacity. This is expected since gas turbine power plant does not require boiler, feed water arrangement etc.

(iii) The initial and operating costs are much lower than that of equivalent steam power station.

(iv) It requires comparatively less water as no condenser is used.

(v) The maintenance charges are quite small.

(vi) Gas turbines are much simpler in construction and operation than steam turbines.

(vii) It can be started quickly form cold conditions.

(viii) There are no standby losses. However, in a steam power station, these losses occur because boiler is kept in operation even when the steam turbine is supplying no load.

Disadvantages

(i) There is a problem for starting the unit. It is because before starting the turbine, the com pressor has to be operated for which power is required from some external source. How ever, once the unit starts, the external power is not needed as the turbine itself supplies the necessary power to the compressor.

(ii) Since a greater part of power developed by the turbine is used in driving the compressor, the net output is low.

(iii) The overall efficiency of such plants is low (about 20%) because the exhaust gases from the turbine contain sufficient heat.

(iv) The temperature of combustion chamber is quite high (3000o F) so that its life is comparatively reduced.

Schematic Arrangement of Gas Turbine Power Plant

The schematic arrangement of a gas turbine power plant is shown in Fig. 2.9. The main components

of the plant are :

(i) Compressor

(ii) Regenerator

(iii) Combustion chamber

(iv) Gas turbine

(v) Alternator

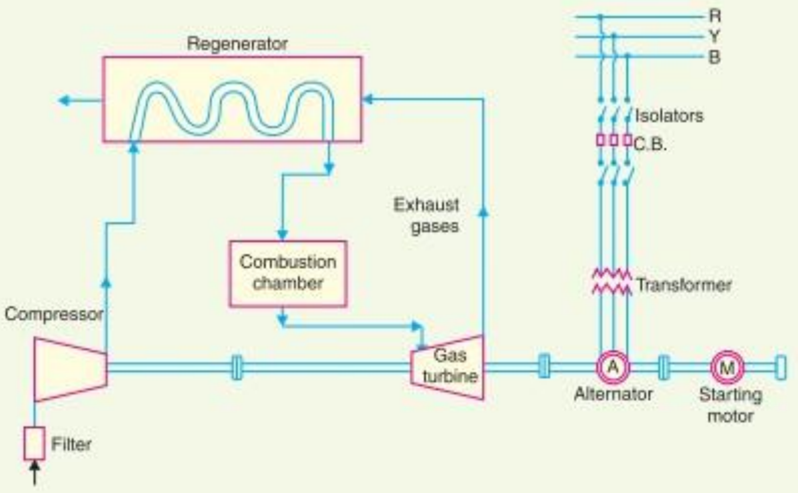
(vi) Starting motor

(i) Compressor. The compressor used in the plant is generally of rotatory type. The air at atmospheric pressure is drawn by the compressor *via* the filter which removes the dust from air. The rotatory blades of the compressor push the air between stationary blades to raise its pressure. Thus air at high pressure is available at the output of the compressor.

(ii) Regenerator. A regenerator is a device which recovers heat from the exhaust gases of the turbine. The exhaust is passed through the regenerator before wasting to atmosphere. A regenerator consists of a nest of tubes contained in a shell. The compressed air from the compressor passes through the tubes on its way to the combustion chamber. In this way, compressed air is heated by the hot exhaust gases.

(iii) Combustion chamber. The air at high pressure from the compressor is led to the combustion chamber *via* the regenerator. In the combustion chamber, heat* is added to the air by burning oil. The oil is injected through the burner into the chamber at high pressure to ensure atomisation of oil and its thorough mixing with air. The result is that the chamber attains a very high temperature (about 3000o F). The combustion gases are suitably cooled to 1300o F to 1500o F and then delivered to the gas turbine.

(iv) Gas turbine. The products of combustion consisting of a mixture of gases at high temperature and pressure are passed to the gas turbine. These gases in passing over the turbine blades expand and thus do the mechanical work. The temperature of the exhaust gases from the turbine is about 900o F.



Schematic arrangement of gas turbine power plant.
Fig. 2.9

(v) Alternator. The gas turbine is coupled to the alternator. The alternator converts mechanical energy of the turbine into electrical energy. The output from the alternator is given to the bus-bars through transformer, circuit breakers and isolators.

(vi) Starting motor. Before starting the turbine, compressor has to be started. For this purpose, an electric motor is mounted on the same shaft as that of the turbine. The motor is energised by the batteries. Once the unit starts, a part of mechanical power of the turbine drives the compressor and there is no need of motor now.

UNIT-2

Economic Aspects of Power Generation and Tariff Methods

Load Curves

The curve showing the variation of load on the power station with respect to (wrt) time is known as **load curve.**The load on a power station is never constant; it varies from time to time. These load variations during the whole day (ie, 24 hours) are recorded half-hourly or hourly and are plotted against time on the graph. The curve thus obtained is known as daily load curve as it shows the variations of load wrt time during the day. Fig. shows a typical daily load curve of a power station. It is clear that load on the power station is varying, being maximum at 6 PM in this case. It may be seen that load curve indicates at a glance the general character of the load that is being imposed on the plant. Such a clear representation cannot be obtained from tabulated figures. The monthly load curve can be obtained from the daily load curves of that month. For this purpose, average values of power over a month at different times of the day are calculated and then plotted on the graph. **The monthly load curve is generally used to fix the rates of energy.** The yearly load curve is obtained by considering the monthly load curves of that particular year. **The yearly load curve is generally used to determine the annual load factor.**

Importance The daily load curves have attained a great importance in generation as they sup-ply the following information readily:

(i) The daily load curve shows the variations of load on the power station during different hours of the day

(ii) The area under the daily load curve gives the number of units generated in the day

Units generated/day = Area (in kWh) under daily load curve

(iii) The highest point on the daily load curve represents the maximum demand on the station on that day

(iv) The area under the daily load curve divided by the total number of hours gives the average load on the station in the day

Average load=Area (in kWh) under daily load curve / 24 hours

(v) The ratio of the area under the load curve to the total area of rectangle in which it is contained gives the load factor

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}} = \frac{\text{Average load} \times 24}{\text{Max demand} \times 24}$$

$$= \frac{\text{Area (in kWh) under daily load curve}}{\text{Total area of rectangle in which the load curve is contained}}$$

(vi) The load curve helps in selecting the size and number of generating units

(vii) The load curve helps in preparing the operation schedule of the station

Important Terms and Factors

The variable load problem has introduced the following terms and factors in power plant engineering:

(i) Connected load It is the sum of continuous ratings of all the equipments connected to supply system.A power station supplies load to thousands of consumers Each consumer has certain equipment installed in his premises The sum of the continuous ratings of all the equipments in the consumer's premises is the "connected load" of the consumer For instance, if a consumer has connections of five 100-watt lamps and a power point of 500 watts, then connected load of the consumer is 5 × 100 + 500=1000 watts The sum of the connected loads of all the consumers is the connected load to the power station

(ii) Maximum demand: It is the greatest demand of load on the power station during a given period.The load on the power station varies from time to time. The maximum of all the demands that have occurred during a given period (say a day) is the maximum demand. Thus referring back to the load curve of Fig., the maximum demand on the power station during the day is 6 MW and it occurs at 6 PM Maximum demand is generally less than the connected load because all the consumers do not switch on their connected load to the system at a time The knowledge of maximum demand is very important as it helps in determining the installed capacity of the station The station must be capable of meeting the maximum demand

(iii) Demand factor It is the ratio of maximum demand on the power station to its connected load.

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

The value of demand factor is usually less than 1 It is expected because maximum demand on the power station is generally less than the connected load If the maximum demand on the power station is 80 MW and the connected load is 100 MW, then demand factor = 80/100 = 0·8 The knowledge of demand factor is vital in determining the capacity of the plant equipment

(iv) Average load The average of loads occurring on the power station in a given period (day or month or year) is known as **average load** or **average demand.**

$$\text{Daily average load} = \frac{\text{No of units (kWh) generated in a day}}{\text{24 hours}}$$

$$\text{Monthly average load} = \frac{\text{No of units (kWh) generated in a day}}{\text{Number of hours in a month}}$$

$$\text{Yearly average load} = \frac{\text{No of units (kWh) generated in a day}}{\text{8760 hours}}$$

(v) Load factor The ratio of average load to the maximum demand during a given period is known as **load factor**,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}}$$

The load factor may be daily load factor, monthly load factor or annual load factor if the time period considered is a day or month or year Load factor is always less than 1 because average load is smaller than the maximum demand The load factor plays key role in determining the overall cost per unit generated Higher the load factor of the power station, lesser* will be the cost per unit generated

(vi) Diversity factor The ratio of the sum of individual maximum demands to the maximum demand on power station is known as **diversity factor**

$$\text{Diversity factor} = \frac{\text{Sum of individual max demands}}{\text{Maximum demand on power station}}$$

A power station supplies load to various types of consumers whose maximum demands generally do not occur at the same time Therefore, the maximum demand on the power station is always less than the sum of individual maximum demands of the consumers Obviously,diversity† factor will always be greater than 1 The greater the diversity factor, the lesser‡ is the cost of generation of power.

(vii) Plant capacity factor It is the ratio of actual energy produced to the maximum possible energy that could have been produced during a given period

$$\text{Plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max energy that could have been produced}} = \frac{\text{Average demand*T}}{\text{Plant capacity*T}}$$

Thus if the considered period is one year,

$$\text{Annual plant capacity factor} = \frac{\text{Annual kWh output}}{\text{Plant capacity} \times 8760}$$

The plant capacity factor is an indication of the reserve capacity of the plant A power station is so designed that it has some reserve capacity for meeting the increased load demand in future Therefore, the installed capacity of the plant is always somewhat greater than the maximum demand on the plant.

Reserve capacity = Plant capacity − Max demand

It is interesting to note that difference between load factor and plant capacity factor is an indication of reserve capacity If the maximum demand on the plant is equal to the plant capacity, then load factor and plant capacity factor will have the same value In such a case, the plant will have no reserve capacity.

(viii) Plant use factor It is ratio of kWh generated to the product of plant capacity and the number of hours for which the plant was in operation ie

$$\text{Plant use factor} = \frac{\text{Station output in kWh}}{\text{Plant capacity} \times \text{Hours of use}}$$

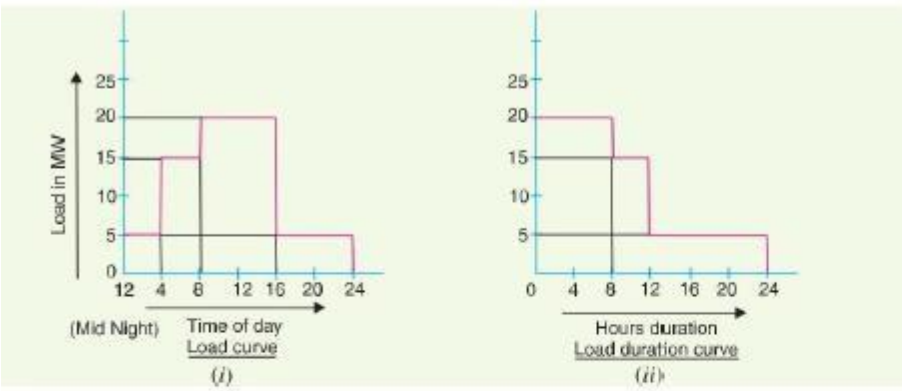
Units Generated per Annum

It is often required to find the kWh generated per annum from maximum demand and load factor. The procedure is as follows

$$\text{Load factor} = \frac{\text{Average load}}{\text{Max demand}}$$

Load Duration Curve

When the load elements of a load curve are arranged in the order of descending magnitudes, the curve thus obtained is called a **load duration curve.**



The load duration curve is obtained from the same data as the load curve but the ordinates are arranged in the order of descending magnitudes. In other words, the maximum load is represented to the left and decreasing loads are represented to the right in the descending order.Hence the area under the load duration curve and the area under the load curve are equal.Fig. shows the daily load curve. The daily load duration curve can be readily obtained from it.It is clear from daily load curve, that load elements in order of descending magnitude are: 20MW for 8 hours; 15 MW for 4 hours and 5 MW for 12 hours.

The following points may be noted about load duration curve:

(i) The load duration curve gives the data in a more presentable form. In other words, it readily shows the number of hours during which the given load has prevailed

(ii) The area under the load duration curve is equal to that of the corresponding load curve Obviously, area under daily load duration curve (in kWh) will give the units generated on that day

(iii) The load duration curve can be extended to include any period of time. By laying out the abscissa from 0 hour to 8760 hours, the variation and distribution of demand for an entire year can be summarised in one curve. The curve thus obtained is called the annual load duration curve

Types of Loads

A device which taps electrical energy from the electric power system is called a load on the system. The load may be resistive (eg, electric lamp), inductive (eg, induction motor), capacitive or some combination of them. The various types of loads on the power system are:**(i) Domestic load** Domestic load consists of lights, fans, refrigerators, heaters, television, small motors for pumping water etc. Most of the residential load occurs only for some hours during the day (ie, 24 hours) eg, lighting load occurs during night time and domestic appliance load occurs for only a few hours. For this reason, the load factor is low (10% to 12%)

(ii) Commercial load Commercial load consists of lighting for shops, fans and electric appliances used in restaurants etc. This class of load occurs for more hours during the day as compared to the domestic load. The commercial load has seasonal variations due to the extensive use of air-conditioners and space heaters.

(iii) Industrial load Industrial load consists of load demand by industries. The magnitude of industrial load depends upon the type of industry. Thus small scale industry requires load upto 25 kW, medium scale industry between 25kW and 100 kW and large-scale industry requires load above 500 kW Industrial loads are generally not weather dependent.

(iv) Municipal load Municipal load consists of street lighting, power required for water supply and drainage purposes. Street lighting load is practically constant throughout the hours of the night. For water supply, water is pumped to overhead tanks by pumps driven by electric motors. Pumping is carried out during the off-peak period, usually occurring during the night. This helps to improve the load factor of the power system.

(v) Irrigation load This type of load is the electric power needed for pumps driven by motors to supply water to fields. Generally this type of load is supplied for 12 hours during night.

(vi) Traction load This type of load includes tram cars, trolley buses, railways etc. This class of load has wide variation. During the morning hour, it reaches peak value because people have to go to their work place. After morning hours, the load starts decreasing and again rises during evening since the people start coming to their homes.

Load Curves and Selection of Generating Units

The load on a power station is seldom constant; it varies from time to time Obviously, a single generating unit (ie, alternator) will not be an economical proposition to meet this varying load.It is because a single unit will have very poor efficiency during the periods of light loads on the power station Therefore, in actual practice, a number of generating units of different sizes are installed in a power station The selection of the number and sizes of the units is decided from the annual load curve of the station. The number and size of the units are selected in such a way that they correctly fit the station load curve. Once this underlying principle is adhered to, it becomes possible to operate the generating units at or near the point of maximum efficiency.

Important Points in the Selection of Units

While making the selection of number and sizes of the generating units, the following points should be kept in view:

(i) The number and sizes of the units should be so selected that they approximately fit the annual load curve of the station.

(ii) The units should be preferably of different capacities to meet the load requirements. Although use of identical units (i.e., having same capacity) ensures saving* in cost, they often do not meet the load requirement.

(iii) The capacity of the plant should be made 15% to 20% more than the maximum demand to meet the future load requirements.

(iv) There should be a spare generating unit so that repairs and overhauling of the working Unitscan be carried out.

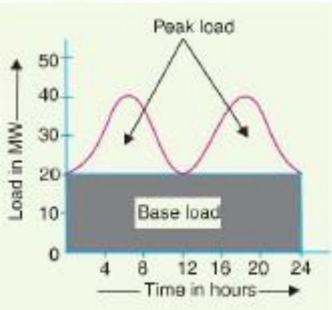
(v) The tendency to select a large number of units of smaller capacity in order to fit the load curve very accurately should be avoided. It is because the investment cost per kW of capacity increases as the size of the units decreases.

Base Load and Peak Load on Power Station

The changing load on the power station makes its load curve of variable nature Fig. shows the typical load curve of a power station. It is clear that load on the power station varies from time to time. However, a close look at the load curve reveals that load on the power station can be considered in two parts, namely;

(i) Base load

(ii) Peak load



(i) Base load. The unvarying load which occurs almost the whole day on the station is known as base load.Referring to the load curve of Fig., it is clear that 20 MW of load has to be supplied by the station at all times of day and night ie throughout 24 hours. Therefore, 20 MW is the base load of the station. As base load on the station is almost of constant nature, therefore, it can be suitably supplied (as discussed in the next Article) without facing the problems of variable load.

(ii) Peak load The various peak demands of load over and above the base load of the station is known as **peak load.** Referring to the load curve of Fig., it is clear that there are peak demands of load excluding base load. These peak demands of the station generally form a small part of the total load and may occur throughout the day.

Method of Meeting the Load

The total load on a power station consists of two parts viz, base load and peak load. In order to achieve overall economy, the best method to meet load is to interconnect two different power stations. The more efficient plant is used to supply the base load and is known as base load power station. The less efficient plant is used to supply the peak loads and is known as peak load power station. There is no hard and fast rule for selection of base load and peak load stations as it would depend upon the particular situation. For example, both hydro-electric and steam power stations are quite efficient and can be used as base load as well as peak load station to meet a particular load requirement.

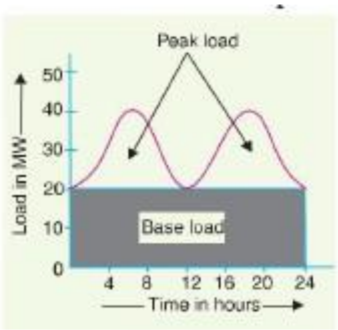
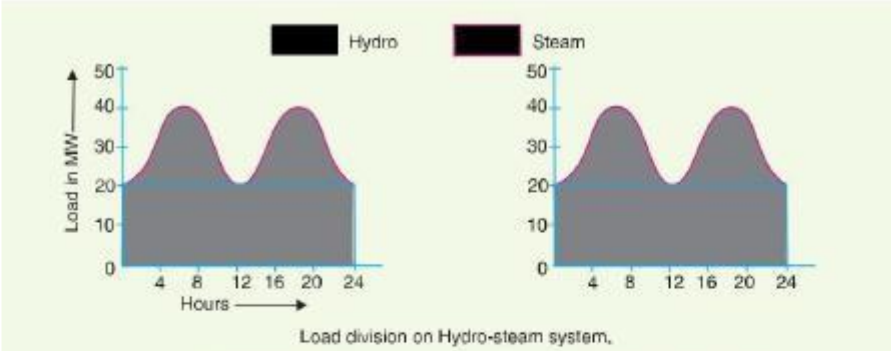


Illustration The interconnection of steam and hydro plants is a beautiful illustration to meet the load. When water is available in sufficient quantity as in summer and rainy season, the hydro-electric plant is used to carry the base load and the steam plant supplies the peak load as shown in Fig. (i).



Load division on Hydro-steam system.

(*i*) High Flow day (*ii*) Low Flow day

However, when the water is not available in sufficient quantity as in winter, the steam plant carries the base load, whereas the hydro-electric plant carries the peak load as shown in Fig. (ii).

Interconnected Grid System

The connection of several generating stations in parallel is known as **interconnected grid system.** The various problems facing the power engineers are considerably reduced by interconnecting different power stations in parallel. Although interconnection of station involves extra cost, yet considering the benefits derived from such an arrrangement, it is gaining much favour these days.

Some of the advantages of interconnected system are listed below:

(i) Exchange of peak loads: An important advantage of interconnected system is that the peak load of the power station can be exchanged. If the load curve of a power station shows a peak demand that is greater than the rated capacity of the plant, then the excess load can be shared by other stations interconnected with it.

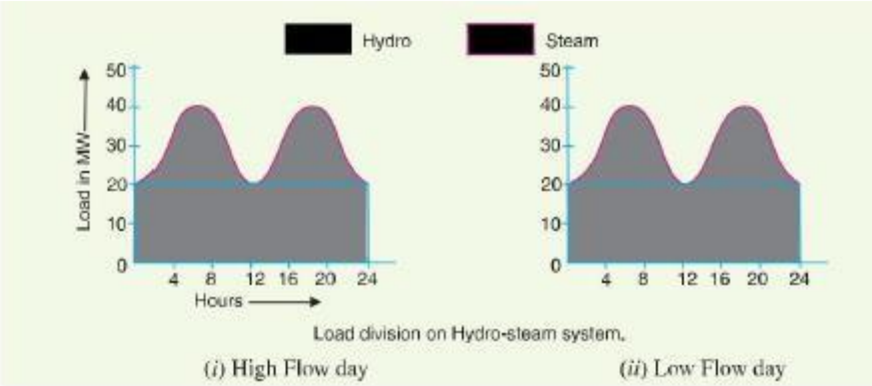
(ii) Use of older plants: The interconnected system makes it possible to use the older and less efficient plants to carry peak loads of short durations. Although such plants may be inadequate when used alone, yet they have sufficient capacity to carry short peaks of loads when interconnected with other modern plants. Therefore, interconnected system gives a direct key to the use of obsolete plants.

(iii) Ensures economical operation: The interconnected system makes the operation of concerned power stations quite economical. It is because sharing of load among the stations is arranged in such a way that more efficient stations work continuously throughout the year at a high load factor and the less efficient plants work for peak load hours only.

(iv) Increases diversity factor: The load curves of different interconnected stations are generally different. The result is that the maximum demand on the system is much reduced as compared to the sum of individual maximum demands on different stations. In other words, the diversity factor of the system is improved, thereby increasing the effective capacity of the system.

(v) Reduces plant reserve capacity: Every power station is required to have a standby unit for emergencies. However, when several power stations are connected in parallel, the reserve capacity of the system is much reduced. This increases the efficiency of the system.

(iv) Increases reliability of supply: The interconnected system increases the reliability of supply.If a major breakdown occurs in one station, continuity of supply can be maintained by other healthy stations.



Tariff

The rate at which electrical energy is supplied to a consumer is known as **tariff.**
Although tariff should include the total cost of producing and supplying electrical energy plus the profit, yet it cannot be the same for all types of consumers. It is because the cost of producing electrical energy depends to a considerable extent upon the magnitude of electrical energy consumed by the user and his load conditions. Therefore, in all fairness, due consideration has to be given to different types of consumers (eg, industrial, domestic and commercial) while fixing the tariff. This makes the problem of suitable rate making highly complicated.

Objectives of tariff Like other commodities, electrical energy is also sold at such a rate so that it not only returns the cost but also earns reasonable profit. Therefore, a tariff should include the following items:

(i) Recovery of cost of producing electrical energy at the power station

(ii) Recovery of cost on the capital investment in transmission and distribution systems

(iii) Recovery of cost of operation and maintenance of supply of electrical energy eg, metering equipment, billing etc

(iv) A suitable profit on the capital investment

Desirable Characteristics of a Tariff

A tariff must have the following desirable characteristics:

(i) Proper return: The tariff should be such that it ensures the proper return from each consumer. In other words, the total receipts from the consumers must be equal to the cost of producing and supplying electrical energy plus reasonable profit. This will enable the electric supply company to ensure continuous and reliable service to the consumers.

(ii) Fairness: The tariff must be fair so that different types of consumers are satisfied with the rate of charge of electrical energy. Thus a big consumer should be charged at a lower rate than a small consumer. It is because increased energy consumption spreads the fixed charges over a greater number of units, thus reducing the overall cost of producing electrical energy. Similarly, a consumer whose load conditions do not deviate much from the ideal (ie, non-variable) should be charged at a lower rate than the one whose load conditions change appreciably from the ideal.

(iii) Simplicity: The tariff should be simple so that an ordinary consumer can easily understand it. A complicated tariff may cause an opposition from the public which is generally distrustful of supply companies.

(iv) Reasonable profit: The profit element in the tariff should be reasonable. An electric supply company is a public utility company and generally enjoys the benefits of monopoly. There-fore, the investment is relatively safe due to non-competition in the market This calls for the profit to be restricted to 8% or so per annum.

(v) Attractive: The tariff should be attractive so that a large number of consumers are encouraged to use electrical energy. Efforts should be made to fix the tariff in such a way so that consumers can pay easily.

Types of Tariff

There are several types of tariff. However, the following are the commonly used types of tariff:

Simple tariff When there is a fixed rate per unit of energy consumed, it is called a **simple tariff** or **uniform rate tariff.**

In this type of tariff, the price charged per unit is constant ie, it does not vary with increase or decrease in number of units consumed. The consumption of electrical energy at the consumer's terminals is recorded by means of an energy meter. This is the simplest of all tariffs and is readily understood by the consumers.

Disadvantages

(i) There is no discrimination between different types of consumers since every consumer has to pay equitably for the fixed charges.

(ii) The cost per unit delivered is high.

(iii) It does not encourage the use of electricity.

Flat rate tariff: When different types of consumers are charged at different uniform per unit rates, it is called a **flat rate tariff.**

In this type of tariff, the consumers are grouped into different classes and each class of consumers is charged at a different uniform rate. For instance, the flat rate per kWh for lighting load may be 60 paise, whereas it may be slightly less (say 55 paise per kWh) for power load. The different classes of consumers are made taking into account their diversity and load factors. The advantage of such a tariff is that it is more fair to different types of consumers and is quite simple in calculations.

Disadvantages

(i) Since the flat rate tariff varies according to the way the supply is used, separate meters are required for lighting load, power load etc. This makes the application of such a tariff expensive and complicated.

(ii) A particular class of consumers is charged at the same rate irrespective of the magnitude of energy consumed. However, a big consumer should be charged at a lower rate as in his case the fixed charges per unit are reduced.

Block rate tariff: When a given block of energy is charged at a specified rate and the succeeding blocks of energy are charged at progressively reduced rates, it is called a **block rate tariff.**In block rate tariff, the energy consumption is divided into blocks and the price per unit is fixed in each block. The price per unit in the first block is the highest and it is progressively reduced for the succeeding blocks of energy. For example, the first 30 units may be charged at the rate of 60 paise per unit; the next 25 units at the rate of 55 paise per unit and the remaining additional units may be charged at the rate of 30 paise per unit.

The advantage of such a tariff is that the consumer gets an incentive to consume more electrical energy. This increases the load factor of the system and hence the cost of generation is reduced. However, its principal defect is that it lacks a measure of the consumer's demand.This type of tariff is being used for majority of residential and small commercial consumers.

Two-part tariff: When the rate of electrical energy is charged on the basis of maximum demand of the consumer and the units consumed, it is called a **two-part tariff.**

In two-part tariff, the total charge to be made from the consumer is split into two components.viz, fixed charges and running charges. The fixed charges depend upon the maximum demand of the consumer while the running charges depend upon the number of units consumed by the consumer. Thus, the consumer is charged at a certain amount per kW of maximum demand plus a certain amount per kWh of energy consumed.

Total charges = Rs (b × kW + c × kWh)

where, b = charge per kW of maximum demand and c = charge per kWh of energy consumed.This type of tariff is mostly applicable to industrial consumers who have appreciable maximum Demand.

Advantages

- It is easily understood by the consumers.
- It recovers the fixed charges which depend upon the maximum demand of the consumer but are independent of the units consumed

Disadvantages

(i) The consumer has to pay the fixed charges irrespective of the fact whether he has consumed or not consumed the electrical energy

(ii) There is always error in assessing the maximum demand of the consumer

Maximum demand tariff: It is similar to two-part tariff with the only difference that the maximum demand is actually measured by installing maximum demand meter in the premises of the consumer. This removes the objection of two-part tariff where the maximum demand is assessed merely on the basis of the rateable value. This type of tariff is mostly applied to big consumers. However, it is not suitable for a small consumer (eg, residential consumer) as a separate maximum demand meter is required.

Power factor tariff: The tariff in which power factor of the consumer's load is taken into consideration is known as **power factor tariff.**

In an ac system, power factor plays an important role. A low power factor increases the rating of station equipment and line losses. Therefore, a consumer having low power factor must be penalized. The following are the important types of power factor tariff:

(i) k VA maximum demand tariff: It is a modified form of two-part tariff In this case, the fixed charges are made on the basis of maximum demand in kVA and not in kW. As kVA is inversely proportional to power factor, therefore, a consumer having low power factor has to contribute more towards the fixed charges. This type of tariff has the advantage that it encourages the consumers to operate their appliances and machinery at improved power factor.

(ii) Sliding scale tariff: This is also know as average power factor tariff. In this case, an average power factor, say 0·8 lagging, is taken as the reference. If the power factor of the consumer falls below this factor, suitable additional charges are made. On the other hand, if the power factor is above the reference, a discount is allowed to the consumer.

(iii) kW and kVAR tariff: In this type, both active power (kW) and reactive power (kVAR) supplied are charged separately. A consumer having low power factor will draw more reactive power and hence shall have to pay more charges.

Three-part tariff: When the total charge to be made from the consumer is split into three parts viz, fixed charge, semi-fixed charge and running charge, it is known as a **three-part tariff**.

Total charge = Rs (a + b × kW + c × kWh)

Where, a= fixed charge made during each billing period. It includes interest and depreciation on the cost of secondary distribution and labour cost of collecting revenues,

b= charge per kW of maximum demand,

c= charge per kWh of energy consumed.

It may be seen that by adding fixed charge or consumer's charge (ie, a) to two-part tariff, it becomes three-part tariff. The principal objection of this type of tariff is that the charges are split into three components. This type of tariff is generally applied to big consumers.

Unit-3

Underground Cables

An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.

Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfil the following necessary requirements :

(i) The conductor used in cables should be tinned stranded copper or aluminium of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without

overheating and causes voltage drop within permissible limits.

(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

11.2 Construction of Cables

Fig. 11.1 shows the general construction of a 3-conductor cable. The various parts are :

(i) Cores or Conductors. A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. 11.1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

(ii) Insulatian. Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

iii) Metallic sheath. In order to protect the cable from moisture,gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in figure.

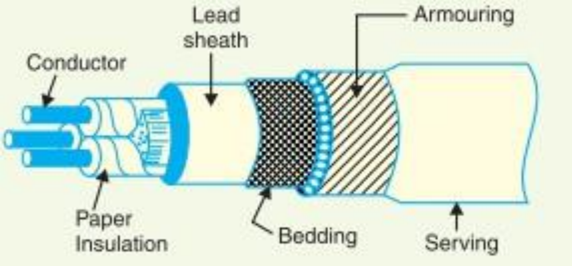


Fig. 11.1 Construction of a Cable

iv) Bedding. Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armouring.

(v) Armouring. Over the bedding, armouring is provided which consists of one or two layers of galvanised steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

(vi) Serving. In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving. It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from mechanical injury.

11.3 Insulating Materials for Cables

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following properties :

(i) High insulation resistance to avoid leakage current.

(ii) High dielectric strength to avoid electrical breakdown of the cable.

(iii) High mechanical strength to withstand the mechanical handling of cables.

(iv) Non-hygroscopic i.e., it should not absorb moisture from air or soil.

The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(v) Non-inflammable.

(vi) Low cost so as to make the underground system a viable proposition.

(vii) Unaffected by acids and alkalies to avoid any chemical action.

No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal insulating materials used in cables are rubber, vulcanised India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

1. Rubber. Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017Ω cm. Although pure rubber has reasonably high insulating properties, it suffers form some major drawbacks viz., readily absorbs moisture, maximum safe

temperature is low (about 38oC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2. Vulcanised India Rubber (V.I.R.). It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150oC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

3. Impregnated paper. It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar. Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a *few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lenghts are small and joints are required at a number of places, VIR cables will be cheaper and durable than paper insulated cables.

4. Varnished cambric. It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

5. Polyvinyl chloride (PVC). This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high

boiling point. The plasticizer forms a gell and renders the material plastic over the desired

range of temperature.Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme enviormental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

11.4 Classification of Cables

Cables for underground service may be classified in two ways according to (i) the type of insulating material used in their manufacture (ii) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into

the following groups :

(i) Low-tension (L.T.) cables — upto 1000 V

(ii) High-tension (H.T.) cables — upto 11,000 V

(iii) Super-tension (S.T.) cables — from 22 kV to 33 kV

(iv) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(v) Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc. For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple

construction and availability of larger copper section.

11.5 Cables for 3-Phase Service

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or *three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used. The following

types of cables are generally used for 3-phase service :

1. Belted cables — upto 11 kV

2. Screened cables — from 22 kV to 66 kV

3. Pressure cables — beyond 66 kV.

1. Belted cables. These cables are used for voltages upto 11kV but in extraordinary cases,

their use may be extended upto 22kV. Fig. 11.3 shows the constructional details of a 3-core belted

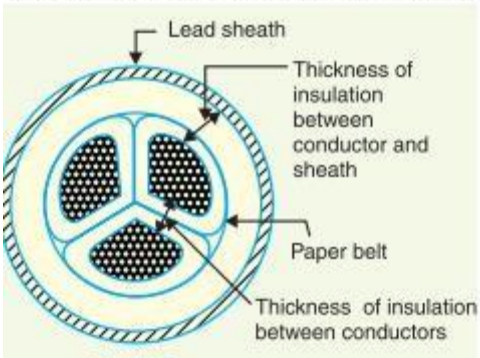


Fig. 11.3

cable. The cores are insulated from each other by layers of impregnated paper. Another layer of impreg nated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable.The cores are generally stranded and may be of non-circular shape to make better use of available space.The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure).The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial i.e., across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up **leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

2. Screened cables. These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are H-type cables and S.L. type cables.

(i) H-type cables. This type of cable was first designed by H. Hochstadter and hence the name. Fig. 11.4 shows the constructional details of a typical 3-core, H-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round

the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath.As all the four screens (3 core screens and one conducting belt) and the lead sheath are at †earth

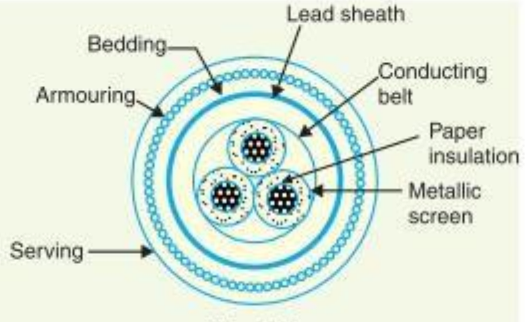


Fig. 11.4

potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

Two principal advantages are claimed for H-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

(ii) S.L. type cables. Fig. 11.5 shows the constructional details of a 3-core *S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over H-type cables. Firstly, the separate sheaths

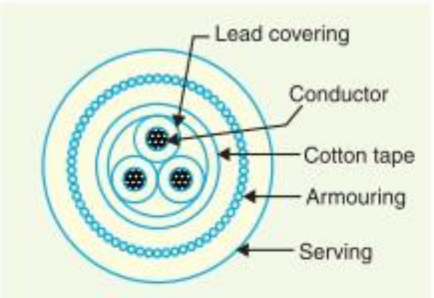


Fig. 11.5

minimise the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.

Limitations of solid type cables. All the cables of above construction are referred to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

(a) As a solid cable carries the load, its conductor temperature increases and the cable compound (i.e., insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(b) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable. The moisture reduces the dielectric strength of insulation and may eventually cause the break down of the cable.

(c) In practice, †voids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The breakdown strength of voids is considerably less than that of the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionisation causing permanent damage to the paper insulation.

3. Pressure cables For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used.

(i) Oil-filled cables. In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable. Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers. Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV. Oil-filled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels. Fig. 11.6 shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. How ever, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The **disadvantage** of this type of cable is that the channel is at the middle of the cable and is at full voltage w.r.t. earth, so that a very complicated system of joints is necessary.Fig. 11.7 shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable,the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown. In the 3-core oil-filler cable shown in Fig. 11.8, the oil ducts are located in the filler spaces. These channels are composed of perforated metal ribbon tubing and are at earth potential.

The oil-filled cables have three principal advantages. Firstly, formation of voids and ionization are avoided. Secondly, allowable temperature range and dielectric strength are increased. Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased. However, their major disadvantages are the high initial cost and complicated system of

laying.

(ii) Gas pressure cables. The voltage required to set up ionisation inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.Fig. 11.9 shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden.

The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high.

11.7 Insulation Resistance of a Single-Core Cable

The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The path for leakage current is radial through the insulation. The opposition offered by insulation to leakage current is known as insulation resistance of the cable. For satisfactory operation, the insulation resistance of the cable should be very high.

Consider a single-core cable of conductor radius r_1 and internal sheath radius r_2 as shown in Fig. 11.12. Let l be the length of the cable and ρ be the resistivity of the insulation.

Consider a very small layer of insulation of thickness dx at a radius x. The length through which leakage current tends to flow is dx and the area of X-section offered to this flow is $2\pi x\, l$.

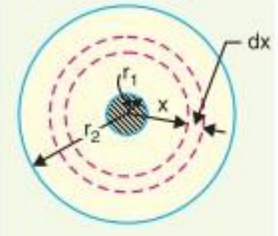


Fig. 11.12

∴ Insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x\, l}$$

Insulation resistance of the whole cable is

$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x\, l} = \frac{\rho}{2\pi l}\int_{r_1}^{r_2} \frac{1}{x}dx$$

$$\therefore \quad R = \frac{\rho}{2\pi l}\log_e \frac{r_2}{r_1}$$

This shows that insulation resistance of a cable is inversely proportional to its length. In other words, if the cable length increases, its insulation resistance decreases and *vice-versa*.

11.8 Capacitance of a Single-Core Cable

A single-core cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a single core cable with conductor diameter d and inner sheath diameter D (Fig. 11.13). Let the charge per metre axial length of the cable be Q coulombs and ε be the permittivity of the insulation material between core and lead sheath. Obviously *$\varepsilon = \varepsilon_0\, \varepsilon_r$ where ε_r is the relative permittivity of the insulation.

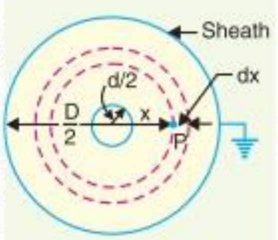


Fig. 11.13

Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is $= 2\,\pi\, x \times 1 = 2\,\pi\, x\ \text{m}^2$

∴ Electric flux density at any point P on the considered cylinder is

$$D_x = \frac{Q}{2\pi x}\ \text{C/m}^2$$

Electric intensity at point P, $E_x = \dfrac{D_x}{\varepsilon} = \dfrac{Q}{2\pi x \varepsilon} = \dfrac{Q}{2\pi x \varepsilon_0 \varepsilon_r}$ volts/m

The work done in moving a unit positive charge from point P through a distance dx in the direction of electric field is $E_x\, dx$. Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference V between conductor and sheath, is given by :

$$V = \int_{d/2}^{D/2} E_x\, dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r}\, dx = \frac{Q}{2\pi \varepsilon_0\, \varepsilon_r}\log_e \frac{D}{d}$$

Capacitance of the cable is

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\,\varepsilon_0\varepsilon_r}\log_e\frac{D}{d}} \text{ F/m}$$

$$= \frac{2\pi\,\varepsilon_o\varepsilon_r}{\log_e(D/d)} \text{ F/m}$$

$$= \frac{2\pi\times 8\cdot 854\times 10^{-12}\times\varepsilon_r}{2\cdot 303\,\log_{10}(D/d)} \text{ F/m}$$

$$= \frac{\varepsilon_r}{41\cdot 4\,\log_{10}(D/d)}\times 10^{-9} \text{ F/m}$$

If the cable has a length of l metres, then capacitance of the cable is

$$C = \frac{\varepsilon_r\ l}{41\cdot 4\,\log_{10}\frac{D}{d}}\times 10^{-9} \text{ F}$$

11.11 Grading of Cables

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables. It has already been shown that electrostatic stress in a single core cable has a maximum value (gmax) at the conductor surface and goes on decreasing as we move towards the sheath. The maxi-mum voltage that can be safely applied to a cable depends upon gmax i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of di- electric must be more than gmax . If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily overstrong. The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables. The following are the two main methods of grading of cables :

(i) Capacitance grading (ii) Intersheath grading

11.12 Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

In capacitance grading, the homogeneous dielectric is replaced

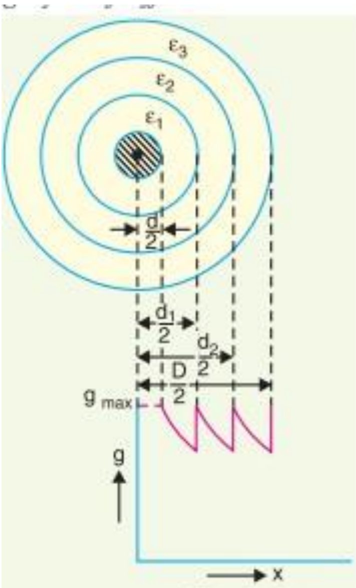


Fig. 11.15

by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity εr of any layer is inversely proportional to its distance from the centre. Under such conditions, the value of potential gra-

dient at any point in the dieletric is *constant and is independent of its distance from the centre. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. How ever, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielec trics are used in the decreasing order of permittivity ; the dielectric of highest permittivity being used near the core.The capacitance grading can be explained beautifully by referring to Fig. 11.15. There are three dielectrics of outer diameter d1, d2 and D and of relative permittivity ε1, ε2 and ε3 respectively. If the permittivities are such that ε1 > ε2 > ε3 and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1^{\dagger}}{\varepsilon_3 d_2}$$

or $$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi \varepsilon_0 \varepsilon_1 x} dx$$

$$= \frac{Q}{2\pi \varepsilon_0 \varepsilon_1} \log_e \frac{d_1}{d} = \frac{g_{max}}{2} d \log_e \frac{d_1}{d} \left[\because \frac{Q}{2\pi \varepsilon_0 \varepsilon_1} = \frac{g_{max}}{2} d \right]$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by ;

$$V_2 = \frac{g_{max}}{2} d_1 \log_e \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{max}}{2} d_2 \log_e \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= \frac{g_{max}}{2} \left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2} \right]$$

If the cable had homogeneous dielectric, then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

Obviously, V > V′ i.e., for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable. Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable. The following points may be noted :

(i) As the permissible values of gmax are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.

(ii) If the maximum stress in the three dielectrics is not the same, then,

$$V = \frac{g_{1max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3max}}{2} d_2 \log_e \frac{D}{d_2}$$

The principal disadvantage of this method is that there are a few high grade dielectrics of reasonable cost whose permittivities vary over the required range.

Insulators

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports i.e., line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of insulators.The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth. In general, the insulators should have the following desirable properties (i) High mechanical strength in order to withstand conductor load, wind load etc.

(ii) High electrical resistance of insulator material in order to avoid leakage currents to earth.

(iii) High relative permittivity of insulator material in order that dielectric strength is high.

(iv) The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.

(v) High ratio of puncture strength to flashover.

The most commonly used material for insulators of overhead line is porcelain but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass,

gives less trouble from leakage and is less effected by changes of temperature.

Types of Insulators

The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators. There are several types of insulators but the most commonly used are pin type, suspension type, strain insulator and shackle insulator.

1. Pin type insulators. The part sec-

tion of a pin type insulator is shown in Fig.

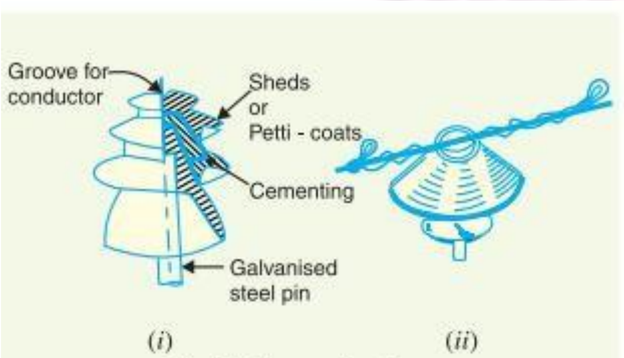


Fig. 8.5. Pin-type insulator

8.5 (i). As the name suggests, the pin type

insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor [See Fig. 8.5 (ii)].Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.Causes of insulator failure. Insulators are required to withstand both mechanical and electrical stresses. The latter type is pirmarily due to line voltage and may cause the breakdown of the insulator. The electrical break-down of the insulator can occur either by flash-over or puncture. In flash over, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the *air gaps, following shortest distance. Fig. 8.6 shows the arcing distance (i.e. a + b + c) for the insulator. In case of flash-over, the insulator will

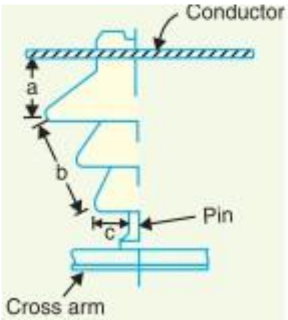


Fig. 8.6

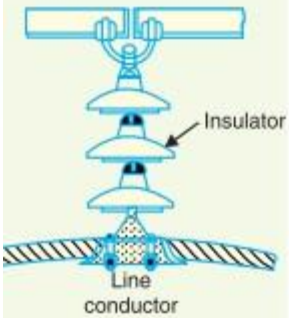


Fig. 8.7

continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator.In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved,the insulator is permanently destroyed due to excessive heat. In prac-

tice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flash over voltage is known as safety factor i.e.,

$$\text{Safety factor of insulator} = \frac{\text{Puncture strength}}{\text{Flash - over voltage}}$$

It is desirable that the value of safety factor is high so that flash-over takes place before the

insulator gets punctured. For pin type insulators, the value of safety factor is about 10.

2 Suspension type insulators.

The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Fig. 8.7. They consist of a number of porcelain discs connected in series by metal links in the form of a string. The

conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

Advantages

(i) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33

kV.

(ii) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV.

Depending upon the working voltage, the desired number of discs can be connected in se-ries.

(iii) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

(iv) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

(v) In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors.The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.

(vi) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain insulators. When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used. For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Fig. 8.8. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.

4. Shackle insulators.

In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a

bolt or to the cross arm. Fig. 8.9 shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire

8.6 Potential Distribution over Suspension Insulator String

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. 8.10 (i) shows 3-disc string of suspension insulators. The porcelain portion of each disc is inbetween two metal links. Therefore, each disc forms a capacitor C as shown in Fig. 8.10 (ii). This is known as mutual capacitance or self-capacitance. If there were mutual capacitance alone, then charging current would have been

the same through all the discs and consequently voltage

across each unit would have been the same i.e., V/3 as shown in Fig. 8.10 (ii). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance C1. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. 8.10 (iii)]. Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum* voltage. Thus referring to Fig.8.10 (iii), V3 will be much more than V2 or V1

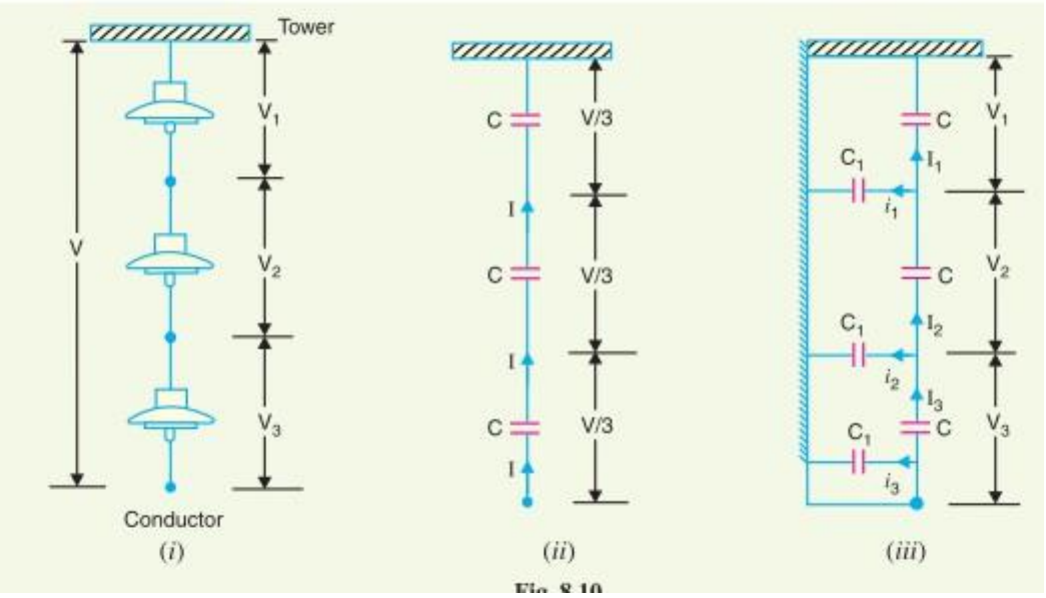


Fig. 8.10

The following points may be noted regarding the potential distribution over a string of suspension insulators :

(i) The voltage impressed on a string of suspension insulators does not distribute itself uni-

formly across the individual discs due to the presence of shunt capacitance.

(ii) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.

(iii) The unit nearest to the conductor is under maximum electrical stress and is likely to be

punctured. Therefore, means must be provided to equalise the potential across each unit.

This is fully discussed in Art. 8.8.

(iv) If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective for d.c.

8.7 String Ef ing Efficiency

As stated above, the voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs. This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency i.e.,

$$\text{String efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}}$$

where n = number of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100% string efficiency is an ideal case for which the volatge across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Mathematical expression. Fig. 8.11 shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C_1 is some fraction K of self-capacitance *i.e.*, $C_1 = KC$. Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.

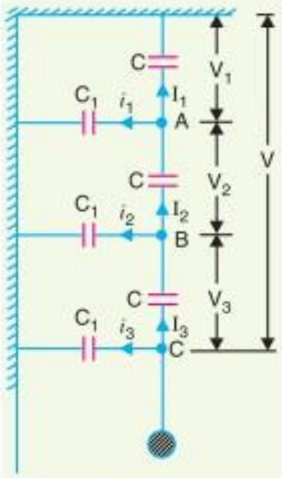


Fig. 8.11

Applying Kirchhoff's current law to node A, we get,

$$I_2 = I_1 + i_1$$

or $$V_2 \omega C^* = V_1 \omega C + V_1 \omega C_1$$

or $$V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

$\therefore$ $$V_2 = V_1 (1 + K) \quad ...(i)$$

Applying Kirchhoff's current law to node B, we get,

$$I_3 = I_2 + i_2$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega C_1 \dagger$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega K C$$

or
$$\begin{aligned} V_3 &= V_2 + (V_1 + V_2) K \\ &= K V_1 + V_2 (1 + K) \\ &= K V_1 + V_1 (1 + K)^2 \qquad [\because V_2 = V_1 (1 + K)] \\ &= V_1 [K + (1 + K)^2] \end{aligned}$$

$\therefore$ $$V_3 = V_1 [1 + 3K + K^2] \quad ...(ii)$$

Voltage between conductor and earth (*i.e.*, tower) is

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ &= V_1 + V_1 (1 + K) + V_1 (1 + 3K + K^2) \\ &= V_1 (3 + 4K + K^2) \end{aligned}$$

$\therefore$ $$V = V_1 (1 + K)(3 + K) \quad ...(iii)$$

From expressions (*i*), (*ii*) and (*iii*), we get,

$$\frac{V_1}{1} = \frac{V_2}{1 + K} = \frac{V_3}{1 + 3K + K^2} = \frac{V}{(1 + K)(3 + K)} \quad ...(iv)$$

$\therefore$ Voltage across top unit, $$V_1 = \frac{V}{(1 + K)(3 + K)}$$

Voltage across second unit from top, $V_2 = V_1 (1 + K)$

Voltage across third unit from top, $V_3 = V_1 (1 + 3K + K^2)$

$$\text{\%age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$

$$= \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis :

(i) If K = 0·2 (Say), then from exp. (iv), we get, V2 = 1·2 V1 and V3 = 1·64 V1. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(ii) The greater the value of K (= C1/C), the more non-uniform is the potential across the discs and lesser is the string efficiency.

(iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one**.**

8.8 Methods of Improving String Efficiency

It has been seen above that potential distribution in a string of suspension insulators is not uniform. The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross arm is approached. If the insulation of the highest stressed insulator (i.e. nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates to equalise the potential across the various units of the string i.e. to improve the string efficiency. The various methods for this purpose are :

(i) **By using longer cross-arms**. The value of string effi-ciency depends upon the value of K i.e.,

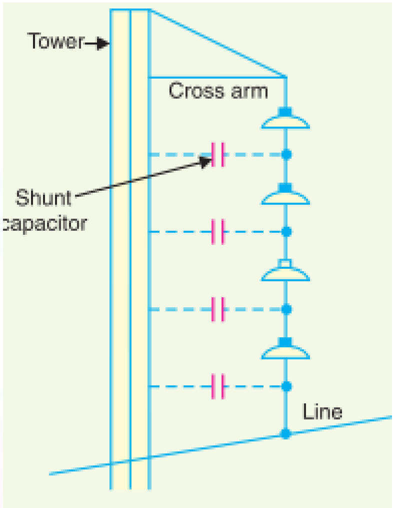


Fig. 8.12

ratio of shunt capacitance to mutual capacitance. The lesser the

value of K, the greater is the string efficiency and moreuniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased i.e., longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, K = 0·1 is the limit that can be achieved by this method.

(ii) **By grading the insulators**. In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded i.e. they are assembled in the string in such a way that the top unit has the minimum capacitance, in-

creasing progressively as the bottom unit (i.e., nearest to conductor) is reached. Since volt-

age is inversely proportional to capacitance, this method tends to equalise the potential

distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

(iii) **By using a guard ring**. The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. 8.13. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i_1, i_2 etc. are equal to metal fitting line capacitance currents i'_1, i'_2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

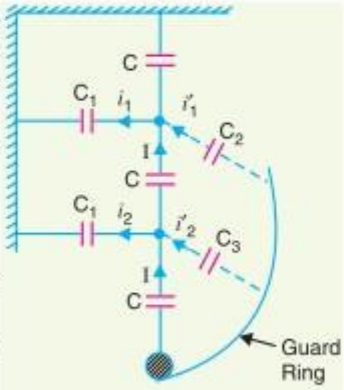


Fig. 8.13

8.9 Important Points

While solving problems relating to string efficiency, the following points must be kept in mind:

(i) The maximum voltage appears across the disc nearest to the conductor (*i.e.*, line conductor).

(ii) The voltage across the string is equal to phase voltage *i.e.*,

Voltage across string = Voltage between line and earth = Phase Voltage

(iii) Line Voltage = $\sqrt{3}$ × Voltage across string

Electric Potential

The electric potential at a point due to a charge is the work done in bringing a unit positive charge from infinity to that point. The concept of electric potential is extremely important for the determination of capacitance in a circuit since the latter is defined as the charge per unit potential. We shall now discuss in detail the electric potential due to some important conductor arrangements.

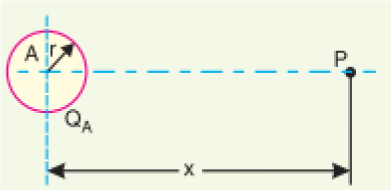


Fig. 9.19

(i) **Potential at a charged single conductor**. Consider a long straight cylindrical conductor A of radius r metres. Let the conductor operate at such a potential (VA) that charge QA coulombs per metre exists on the conductor. It is desired to find the expression for VA. The electric intensity E at a distance x from the centre of the conductor in air is given by:

$$E = \frac{Q_A}{2\pi x \varepsilon_0} \text{ volts/m}$$

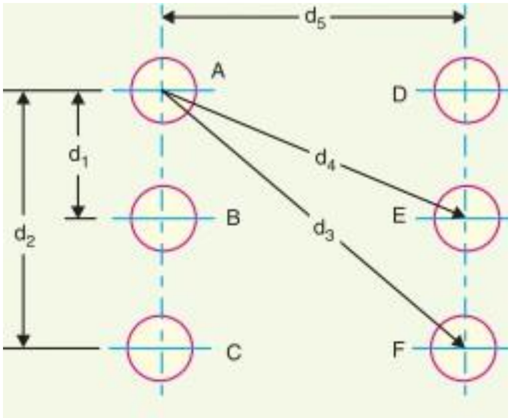
where Q_A = charge per metre length

ε_0 = permittivity of free space

As x approaches infinity, the value of E approaches zero. Therefore, the potential difference between conductor A and infinity distant * neutral plane is given by :

$$\dagger V_A = \int_r^\infty \frac{Q_A}{2\pi x \varepsilon_0} dx = \frac{Q_A}{2\pi\varepsilon_0} \int_r^\infty \frac{dx}{x}$$

(ii) **Potential at a conductor in a group of charged conductors.** Consider a group of long



straight conductors A, B, C etc. operating at potentials such that chargesQA, QB, QC etc.coulomb per metre length exist on the respective conductors (seeFig. 9.20). Let us find the potential at A (i.e. VA) in this arrangement. Potential at A due to its owncharge (i.e. QA)

$$= \int_r^{\infty} \frac{Q_A}{2\pi x \varepsilon_0} dx \quad ...(i)$$

Potential at conductor A due to charge Q_B

$$= \int_{d_1}^{\infty} \frac{Q_B}{2\pi x \varepsilon_0} dx \quad ...(ii)$$

Potential at conductor A due to charge Q_C

$$= \int_{d_2}^{\infty} \frac{Q_C}{2\pi x \varepsilon_0} dx$$

Overall potential difference between conductor A and infinite neutral plane is

$$V_A = (i) + (ii) + (iii) + ...$$

$$= \int_r^{\infty} \frac{Q_A}{2\pi x \varepsilon_0} dx + \int_{d_1}^{\infty} \frac{Q_B}{2\pi x \varepsilon_0} dx + \int_{d_2}^{\infty} \frac{Q_C}{2\pi x \varepsilon_0} dx + \ldots$$

$$= \frac{1}{2\pi \varepsilon_0} \Big[Q_A (\log_e \infty - \log_e r) + Q_B (\log_e \infty - \log_e d_1) + Q_C (\log_e \infty - \log_e d_2) + \ldots \Big]$$

$$= \frac{1}{2\pi \varepsilon_0} \left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_2} + \log_e \infty (Q_A + Q_B + Q_C) + \ldots \right]$$

Assuming balanced condtions *i.e.*, $Q_A + Q_B + Q_C = 0$, we have,

$$V_A = \frac{1}{2\pi \varepsilon_0} \left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_2} + \ldots \right]$$

Capacitance of a Single Phase pacitance of a Single Phase Two-wire Line

Consider a single phase overhead transmission line con sisting of two parallel conductors A and B spaced d metres apart in air. Suppose that radius of each conductor is r metres. Let their respective charge be + Q and − Q coulombs per metre length.

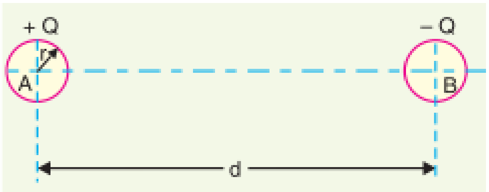


Fig. 9.21

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The total p.d. between conductor A and neutral "infinite" plane is

$$V_A = \int_r^{\infty} \frac{Q}{2\pi x \varepsilon_0} dx + \int_d^{\infty} \frac{-Q}{2\pi x \varepsilon_0} dx$$

$$= \frac{Q}{2\pi \varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] \text{volts} = \frac{Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

Similarly, p.d. between conductor *B* and neutral "infinite" plane is

$$V_B = \int_r^{\infty} \frac{-Q}{2\pi x \varepsilon_0} dx + \int_d^{\infty} \frac{Q}{2\pi x \varepsilon_0} dx$$

$$= \frac{-Q}{2\pi \varepsilon_0}\left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d}\right] = \frac{-Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

Both these potentials are *w.r.t.* the same neutral plane. Since the unlike charges attract each other, the potential difference between the conductors is

$$V_{AB} = 2V_A = \frac{2Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

∴ Capacitance, $$C_{AB} = Q/V_{AB} = \frac{Q}{\frac{2Q}{2\pi \varepsilon_0} \log_e \frac{d}{r}} \text{ F/m}$$

∴ $$C_{AB} = \frac{\pi \varepsilon_0}{\log_e \frac{d}{r}} \text{ F / m} \quad \text{...}(i)$$

Capacitance to neutral. Equation (i) gives the capacitance between the conductors of a two wire line [See Fig. 9.22]. Often it is desired to know the capacitance between one of the conductors and a neutral point between them. Since potential of the mid-point between the conductors is zero,the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the capacitance to ground or capacitance to neutral for the two-wire line is twice the line-to-line capacitance (capacitance between conductors as shown in Fig 9.23).

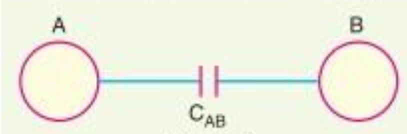


Fig. 9.22

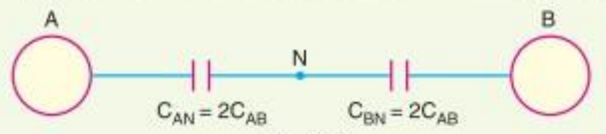


Fig. 9.23

∴ Capacitance to neutral, $C_N = C_{AN} = C_{BN} = 2C_{AB}$

$$\therefore \quad C_N = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m} \qquad ...(ii)$$

The reader may compare eq. (ii) to the one for inductance. One difference between the equations for capacitance and inductance should be noted carefully. The radius in the equation for capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula. Note that eq. (ii) applies only to a solid round conductor.

9.11 Capacitance of a 3-Phase Overhead Line

In a 3-phase transmission line, the capacitance of each conductor is considered instead of

capacitance from conductor to conductor.Here, again two cases arise viz., symmetrical spacing and unsymmetrical spacing.

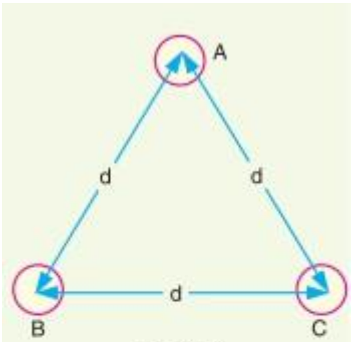


Fig. 9.24

(i) Symmetrical Spacing. Fig. 9.24 shows the three conductors A, B and C of the 3-phase overhead transmission line having charges QA, QB and QC per metre length respectively. Let the conductors be equidistant (d metres) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig. 9.24, overall potential difference between conductor A and infinite neutral plane is given by (Refer to Art. 9.9);

$$V_A = \int_r^\infty \frac{Q_A}{2\pi x \varepsilon_0} dx + \int_d^\infty \frac{Q_B}{2\pi x \varepsilon_0} dx + \int_d^\infty \frac{Q_C}{2\pi x \varepsilon_0} dx$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d} + Q_C \log_e \frac{1}{d}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + (Q_B + Q_C) \log_e \frac{1}{d}\right]$$

Assuming balanced supply, we have, $Q_A + Q_B + Q_C = 0$

$$\therefore \quad Q_B + Q_C = -Q_A$$

$$\therefore \quad V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} - Q_A \log_e \frac{1}{d}\right] = \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

$\therefore$ Capacitance of conductor A w.r.t neutral,

$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi\varepsilon_0}\log_e \frac{d}{r}} \text{ F/m} = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

$$\therefore \quad C_A = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

Note that this equation is identical to capacitance to neutral for two-wire line. Derived in a similar manner, the expressions for capacitance are the same for conductors B and C.

(ii) Unsymmetrical spacing. Fig. 9.25 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions i.e. QA + QB + QC = 0.

pacing. Let us assume balanced conditions i.e. $Q_A + Q_B + Q_C = 0$.

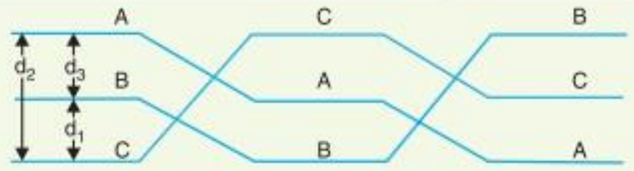


Fig. 9.25

Considering all the three sections of the transposed line for phase A, Potential of 1st position, $V_1 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right)$

Potential of 2nd position, $V_2 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_3}\right)$

Potential of 3rd position, $V_3 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_C \log_e \frac{1}{d_1}\right)$

Average voltage on condutor A is

$$V_A = \frac{1}{3}(V_1 + V_2 + V_3)$$

$$= \frac{1}{3 \times 2\pi\varepsilon_0} * \left[Q_A \log_e \frac{1}{r^3} + (Q_B + Q_C)\log_e \frac{1}{d_1 d_2 d_3}\right]$$

As $Q_A + Q_B + Q_C = 0$, therefore, $Q_B + Q_C = -Q_A$

$$\therefore \quad V_A = \frac{1}{6\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3}\right]$$

$$= \frac{Q_A}{6\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{1}{3} \times \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \left(\frac{d_1 d_2 d_3}{r^3}\right)^{1/3}$$

$$= \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{(d_1 d_2 d_3)^{1/3}}{r}$$

∴ Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2\pi\varepsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}} \ F/m$$

8.10 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, ultraviolet 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 is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cummulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

8.11 Factors Affecting Cor fecting 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 :

(i) Atmosphere. As corona is formed due to ionsiation 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.

(ii) **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 that a solid conductor.

(iii) **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 dis-

tance between conductors reduces the electro-static stresses at the conductor surface, thus

avoiding corona formation.

(iv) 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 go. If Vc is the phase-neutral potential required under these conditions, then,

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

where g_o = breakdown strength of air at 76 cm of mercury and 25°C

= 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

∴ 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°C becomes δg_o where

$$\delta = \text{air density factor} = \frac{3 \cdot 92b}{273 + t}$$

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

∴ 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.

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

where mo = 1 for polished conductors

= 0·98 to 0·92 for dirty conductors

= 0·87 to 0·8 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 Vc but at a higher voltage Vv called visual critical voltage. The phase-neutral effective value of visual critical voltage is given by the following empirical formula

$$V_v = m_v g_o \delta r \left(1 + \frac{0 \cdot 3}{\sqrt{\delta r}}\right) \log_e \frac{d}{r} \text{ kV/phase}$$

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 :

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

where f = supply frequency in Hz

V = phase-neutral voltage (*r.m.s.*)

V_c = disruptive voltage (*r.m.s.*) per phase

8.13 Advantages and Disadvantages of Cor antages 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

(i) 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 electrostatic stresses between the conductors.

(ii) Corona reduces the effects of transients produced by surges.

Disadvantages

(i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.

(ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.

(iii) The current drawn by the line due to corona is non-sinusoidal and hence non-sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighbouring communication lines.

8.14 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 :

(i) **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 transmis-

sion lines.

(ii) **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.

Skin Effect

When a conductor is carrying steady direct current (d.c.), this current is uniformly distributed over the whole X-section of the conductor. However, an alternating current flowing through the conductor does not distribute uniformly, rather it has the tendency to concentrate near the surface of the conductor as shown in Fig. 9.3. This is known as skin effect.The tendency of alternating current to concentrate near the surface of a conductor is known as skin effect.

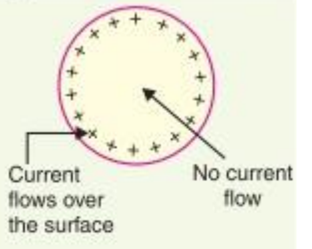


Fig. 9.3

Due to skin effect, the effective area of cross-section of the conductor through which current flows is reduced. Consequently, the resistance of the conductor is slightly increased when carrying an alter-

nating current. The cause of skin effect can be easily explained. A solid conductor may be thought to be consisting of a large number of strands, each carrying a small part of the current. The *inductance of each strand will vary according to its position. Thus, the strands near the centre are surrounded by a greater magnetic flux and hence have larger inductance than that near the surface. The high reactance of inner strands causes the alternating current to flow near the surface of conductor. This crowding of current near the conductor surface is the skin effect. The skin effect depends upon the following factors :

(i) Nature of material

(ii) Diameter of wire − increases with the diameter of wire.

(iii) Frequency − increases with the increase in frequency.

(iv) Shape of wire − less for stranded conductor than the solid conductor.

It may be noted that skin effect is negligible when the supply frequency is low (< 50 Hz) and conductor diameter is small (< 1cm).

Flux Linkages

As stated earlier, the inductance of a circuit is defined as the flux linkages per unit current. Therefore,in order to find the inductance of a circuit, the determination of flux linkages is of primary importance. We shall discuss two important cases of flux linkages.

1**. Flux linkages due to a single current carrying conductor**. Consider a long straight cylindrical conductor of radirus r metres and carrying a current I amperes (r.m.s.) as shown in Fig. 9.4 (i).This current will set up magnetic field. The magnetic lines of force will exist inside the conductor as well as outside the conductor. Both these fluxes will contribute to the inductance of the conductor.

(i) **Flux linkages due to internal flux**. Refer to Fig. 9.4 (ii) where the X-section of the conductor is shown magnified for clarity. The magnetic field intensity at a point x metres from the centre is given by;

$$^{*}H_x = \frac{I_x}{2\pi x}$$

Assuming a uniform current density,

$$I_x = \frac{\pi x^2}{\pi r^2} I = \frac{x^2}{r^2} I$$

$$\therefore \quad H_x = \frac{x^2}{r^2} \times I \times \frac{1}{2\pi x} = \frac{x}{2\pi r^2} I \text{ AT/m}$$

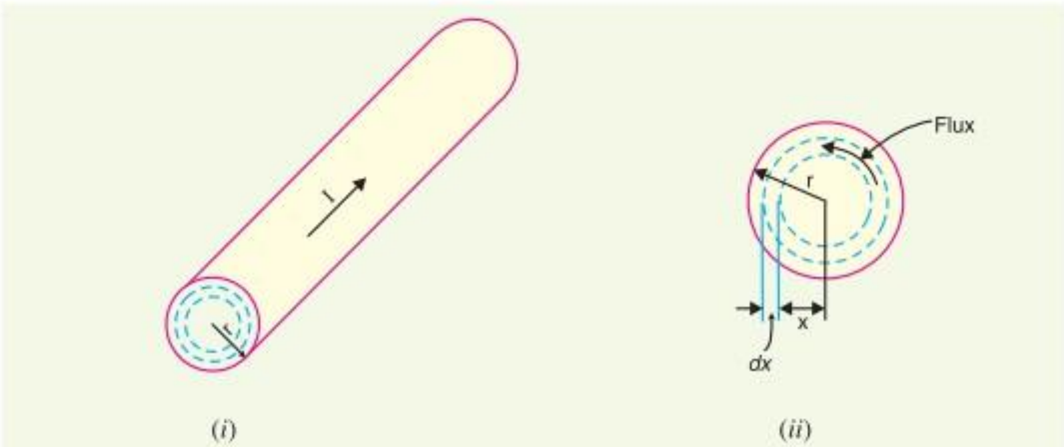


Fig. 9.4

If μ $(= \mu_0\mu_r)$ is the permeability of the conductor, then flux density at the considered point is given by;

$$B_x = \mu_0 \mu_r H_x \text{ wb/m}^2$$
$$= \frac{\mu_0 \mu_r x}{2\pi r^2} I = \frac{\mu_0 x I}{2\pi r^2} \text{ wb/m}^2 [\because \mu_r = 1 \text{ for non-magnetic material}]$$

Now, flux $d\phi$ through a cylindrical shell of radial thickness dx and axial length 1 m is given by;

$$d\phi = B_x \times 1 \times dx = \frac{\mu_0 x I}{2\pi r^2} dx \text{ weber}$$

This flux links with current $I_x \left(= \frac{I \pi x^2}{\pi r^2}\right)$ only. Therefore, flux linkages per metre length of the conductor is

$$d\psi = \frac{\pi x^2}{\pi r^2} d\phi = \frac{\mu_0 I x^3}{2\pi r^4} dx \text{ weber-turns}$$

Total flux linkages from centre upto the conductor surface is

$$\psi_{int} = \int_0^r \frac{\mu_0 I x^3}{2\pi r^4} dx$$
$$= \frac{\mu_0 I}{8\pi} \text{ weber-turns per metre length}$$

(ii) Flux linkages due to external flux. Now let us calculate the flux linkages of the conductor due to external flux. The external flux extends from the surface of the conductor to infinity. Referring to Fig. 9.5, the field intensity at a distance x metres (from centre) outside the conductor is given by ;

$$H_x = \frac{I}{2\pi x} \text{ AT/m}$$

Flux density, $$B_x = \mu_0 H_x = \frac{\mu_0 I}{2\pi x} \text{ wb/m}^2$$

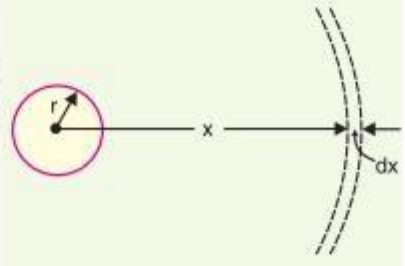


Fig. 9.5

Now, flux $d\phi$ through a cylindrical shell of thickness dx and axial length 1 metre is

$$d\phi = B_x dx = \frac{\mu_0 I}{2\pi x} dx \text{ webers}$$

The flux $d\phi$ links all the current in the conductor once and only once.

$\therefore$ Flux linkages, $$d\psi = d\phi = \frac{\mu_0 I}{2\pi x} dx \text{ weber-turns}$$

Total flux linkages of the conductor from surface to infinity,

$$\psi_{ext} = \int_r^\infty \frac{\mu_0 I}{2\pi x} dx \text{ weber-turns}$$

$\therefore$ Overall flux linkages, $$\psi = \psi_{int} + \psi_{ext} = \frac{\mu_0 I}{8\pi} + \int_r^\infty \frac{\mu_0 I}{2\pi x} dx$$

$$\therefore \quad \psi = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right] \text{ wb-turns/m length}$$

Inductance of a Single Phase Inductance of a Single Phase Two-wire Line

A single phase line consists of two parallel conductors which form a rectangular loop of one turn.When an alternating current flows through such a loop, a changing magnetic flux is set up. The changing flux links the loop and hence the loop (or single phase line) possesses inductance. It may appear that inductance of a single phase line is negligible because it consists of a loop of one turn and the flux path is through air of high reluctance. But as the X -sectional area of the loop is very **large, even for a small flux density, the total flux linking the loop is quite large and hence the line has appreciable inductance.

Consider a single phase overhead line consisting of two parallel conductors A and B spaced d metres apart as shown in Fig. 9.7. Conductors A and B carry the same amount of current (*i.e.* $I_A = I_B$), but in the opposite direction because one forms the return circuit of the other.

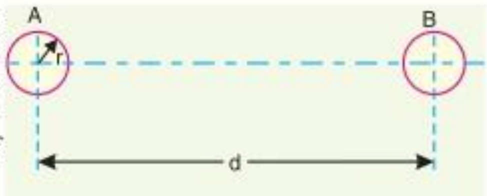


Fig. 9.7

$$\therefore \qquad I_A + I_B = 0$$

In order to find the inductance of conductor A (or conductor B), we shall have to consider the flux linkages with it. There will be flux linkages with conductor A due to its own current I_A and also due to the mutual inductance effect of current I_B in the conductor B.

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right) \quad ...(i) \quad \text{[See Art. 9.4]}$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_d^{\infty} \frac{dx}{x} \quad ...(ii)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x} \qquad ...(ii)$$

Total flux linkages with conductor A is

$$\psi_A = \text{exp. } (i) + \text{exp } (ii)$$

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4}+\int_r^\infty \frac{dx}{x}\right)+\frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}+\int_r^\infty \frac{dx}{x}\right)I_A + I_B\int_d^\infty \frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}+\log_e \infty - \log_e r\right)I_A + (\log_e \infty - \log_e d)I_B\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{I_A}{4}+\log_e \infty\,(I_A+I_B) - I_A \log_e r - I_B \log_e d\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \log_e r - I_B \log_e d\right] \quad (\because I_A + I_B = 0)$$

Now, $I_A + I_B = 0$ or $-I_B = I_A$

$\therefore$ $-I_B \log_e d = I_A \log_e d$

$\therefore$

$$\psi_A = \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e d - I_A \log_e r\right] \text{ wb-turns/m}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} + I_A \log_e \frac{d}{r}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ wb-turns/m}$$

Inductance of conductor $A, L_A = \frac{\psi_A}{I_A}$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}+\log_e \frac{d}{r}\right]\text{H / m} = \frac{4\pi\times 10^{-7}}{2\pi}\left[\frac{1}{4}+\log_e \frac{d}{r}\right]\text{H / m}$$

$$\therefore \quad L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{d}{r}\right] \text{H/m} \qquad \ldots(i)$$

$$\text{Loop inductance} = 2L_A \text{ H/m} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m}$$

$$\therefore \quad \text{Loop inductance} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m} \qquad \ldots(ii)$$

Note that eq. (*ii*) is the inductance of the two-wire line and is sometimes called loop inductance. However, inductance given by eq. (*i*) is the inductance per conductor and is equal to half the loop inductance.

Expression in alternate form. The expression for the inductance of a conductor can be put in a concise form.

$$L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{d}{r}\right] \text{H/m}$$

$$= 2\times 10^{-7}\left[\frac{1}{4} + \log_e \frac{d}{r}\right]$$

$$= 2\times 10^{-7}\left[\log_e e^{1/4} + \log_e \frac{d}{r}\right]$$

$$\therefore \quad L_A = 2\times 10^{-7} \log_e \frac{d}{r\,e^{-1/4}}$$

If we put $r\,e^{-1/4} = r'$, then,

$$L_A = 2\times 10^{-7} \log_e \frac{d}{r'} \text{ H/m} \qquad \ldots(iii)$$

The radius r' is that of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius r. The quantity $e^{-1/4} = 0{\cdot}7788$ so that

$$r' = r\,e^{-1/4} = 0{\cdot}7788\, r$$

The term r' $(= r\,e^{-1/4})$ is called *geometric mean radius* (GMR) of the wire. Note that eq. (*iii*) gives the same value of inductance L_A as eq. (*i*). The difference is that eq. (*iii*) omits the term to account for internal flux but compensates for it by using an adjusted value of the radius of the conductor.

$$\text{Loop inductance} = 2L_A = 2\times 2\times 10^{-7} \log_e \frac{d}{r'} \text{H/m}$$

Note that $r' = 0{\cdot}7788\, r$ is applicable to only solid round conductor.

Inductance of a 3-Phase Overhead Line

Fig. 9·8 shows the three conductors A, B and C of a 3-phase line carrying currents IA, IB and IC respectively. Let d1, d2 and d3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced i.e. IA + IB + IC = 0. Consider the flux linkages with conductor

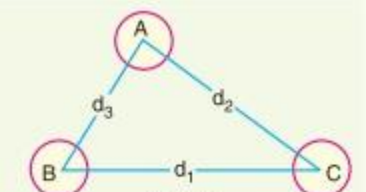


Fig. 9.8

A. There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of IB and IC.

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) \quad ...(i)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x} \quad ...(ii)$$

Flux linkages with conductor A due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x} \quad ...(iii)$$

Total flux linkages with conductor A is

$$\psi_A = (i) + (ii) + (iii)$$

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) + \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x} + \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x}\right) I_A + I_B\int_{d_3}^\infty \frac{dx}{x} + I_C\int_{d_2}^\infty \frac{dx}{x}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d_3 - I_C \log_e d_2 + \log_e \infty\,(I_A + I_B + I_C)\right]$$

As $I_A + I_B + I_C = 0,$

$$\therefore \quad \psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d_3 - I_C \log_e d_2\right]$$

(*i*) **Symmetrical spacing.** If the three conductors *A*, *B* and *C* are placed symmetrically at the corners of an equilateral triangle of side *d*, then, $d_1 = d_2 = d_3 = d$. Under such conditions, the flux linkages with conductor *A* become :

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d - I_C \log_e d\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - (I_B + I_C)\log_e d\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A + I_A \log_e d\right] \qquad (\because I_B + I_C = -I_A)$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ weber-turns/m}$$

Inductance of conductor *A*, $L_A = \frac{\psi_A}{I_A}\ \text{H/m} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right]$ H/m

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m}$$

$$\therefore \quad L_A = 10^{-7}\left[0\cdot 5 + 2\log_e \frac{d}{r}\right] \text{ H/m}$$

Derived in a similar way, the expressions for inductance are the same for conductors *B* and *C*.

(ii) Unsymmetrical spacing. When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, the flux linkages and inductance of each phase are not the same. A different inductance in each phase results in unequal voltage drops in the three phases even if the currents in the conductors are balanced. Therefore, the voltage at the receiving end will not be the same for all phases. In order that voltage drops are equal in all conductors, we generally interchange the positions of the conductors at regular intervals along the line so that each conductor occupies the original position of every other conductor over an equal distance. Such an exchange of positions is known as transposition. Fig. 9.9 shows the transposed line. The phase conductors are designated as A, B and C and the positions occupied are numbered 1, 2 and 3. The effect of transposition is that each conductor has the same average inductance.

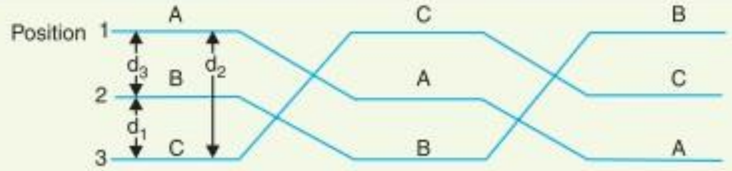


Fig. 9.9

Fig. 9.9 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume that each of the three sections is 1 m in length. Let us further assume balanced conditions i.e., IA + IB +

IC = 0. Let the line currents be :

IA = I (1+ j 0)

IB = I (− 0·5 − j 0·866)

IC = I (− 0·5 + j 0·866)

As proved above, the total flux linkages per metre length of conductor A is

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d_3 - I_C \log_e d_2\right]$$

Putting the values of I_A, I_B and I_C, we get,

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I - I(-0{\cdot}5 - j\,0{\cdot}866)\log_e d_3 - I(-0{\cdot}5 + j\,0{\cdot}866)\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I - I\log_e r + 0{\cdot}5\,I\log_e d_3 + j\,0{\cdot}866\log_e d_3 + 0{\cdot}5\,I\log_e d_2 - j\,0{\cdot}866\,I\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I - I\log_e r + 0{\cdot}5\,I(\log_e d_3 + \log_e d_2) + j\,0{\cdot}866\,I(\log_e d_3 - \log_e d_2)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I - I\log_e r + I\log_e \sqrt{d_2 d_3} + j\,0{\cdot}866\,I\log_e \frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I + I\log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0{\cdot}866\,I\log_e \frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0{\cdot}866\log_e \frac{d_3}{d_2}\right]$$

∴ Inductance of conductor A is

$$L_A = \frac{\psi_A}{I_A} = \frac{\psi_A}{I}$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j\,0{\cdot}866\log_e \frac{d_3}{d_2}\right]$$

$$= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2\, d_3}}{r} + j\, 0 \cdot 866 \log_e \frac{d_3}{d_2}\right] \text{H/m}$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_2\, d_3}}{r} + j\, 1 \cdot 732 \log_e \frac{d_3}{d_2}\right] \text{H/m}$$

Similarly inductance of conductors B and C will be :

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_3\, d_1}}{r} + j\, 1 \cdot 732 \log_e \frac{d_1}{d_3}\right] \text{H/m}$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_1\, d_2}}{r} + j\, 1 \cdot 732 \log_e \frac{d_2}{d_1}\right] \text{H/m}$$

Inducance of each line conductor

$$= \frac{1}{3}(L_A + L_B + L_C)$$

$$= ^{*}\left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1\, d_2\, d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

$$= \left[0 \cdot 5 + 2\log_e \frac{\sqrt[3]{d_1\, d_2\, d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

If we compare the formula of inductance of an unsymmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will be equal if d = ddd 1 2 3 3 . The distance d is known as equivalent equilateral spacing for unsymmetrically transposed line.

9.7 Concept of Self-GMD and Mutual-GMD

The use of *self geometrical mean distance* (abbreviated as self-GMD) and *mutual geometrical mean distance* (mutual-GMD) simplifies the inductance calculations, particularly relating to multiconductor arrangements. The symbols used for these are respectively D_s and D_m. We shall briefly discuss these terms.

***(i)* Self-GMD (D_s).** In order to have concept of self-GMD (also sometimes called Geometrical mean radius ; GMR), consider the expression for inductance per conductor per metre already derived in Art. 9.5

Inductance/conductor/m $= 2 \times 10^{-7}\left(\frac{1}{4} + \log_e \frac{d}{r}\right)$

$$= 2 \times 10^{-7} \times \frac{1}{4} + 2 \times 10^{-7} \log_e \frac{d}{r} \quad \ldots(i)$$

In this expression, the term $2 \times 10^{-7} \times (1/4)$ is the inductance due to flux within the solid conductor. For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR. If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero. Consequently, inductance due to internal flux would be zero and the term $2 \times 10^{-7} \times (1/4)$ shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage. It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = 0·7788 r. Using self-GMD, the eq. (i) becomes :

$$\text{Inductance/conductor/m} = 2 \times 10^{-7} \log_e d/D_s{*}$$

$$\text{where} \quad D_s = \text{GMR or self-GMD} = 0{\cdot}7788\, r$$

It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(*ii*) Mutual-GMD. The mutual-GMD is the geometrical mean of the distances form one conductor to the other and, therefore, must be between the largest and smallest such distance. In fact, mutual-GMD simply represents the equivalent geometrical spacing.

(*a*) The mutual-GMD between two conductors (assuming that spacing between conductors is large compared to the diameter of each conductor) is equal to the distance between their centres *i.e.*

$$D_m = \text{spacing between conductors} = d$$

(*b*) For a single circuit 3-ϕ line, the mutual-GMD is equal to the equivalent equilateral spacing *i.e.*, $(d_1\, d_2\, d_3)^{1/3}$.

$$D_m = (d_1\, d_2\, d_3)^{1/3}$$

25.1 Sub-Station

The assembly of apparatus used to change some characteristic (e.g. voltage, a.c. to d.c., frequency, p.f. etc.) of electric supply is called a **sub-station.**

Sub-stations are important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations. It is, therefore, essential to exercise utmost care while designing and building a sub-station. The following are the important points which must be kept in view while laying out a sub-station :

(*i*) It should be located at a proper site. As far as possible, it should be located at the centre of gravity of load.

(*ii*) It should provide safe and reliable arrangement. For safety, consideration must be given to the maintenance of regulation clearances, facilities for carrying out repairs and maintenance, abnormal occurrences such as possibility of explosion or fire etc. For reliability, consideration must be given for good design and construction, the provision of suitable protective gear *etc.*

(*iii*) It should be easily operated and maintained.

(*iv*) It should involve minimum capital cost.

25.2 Classification of Sub-Stations

There are several ways of classifying sub-stations. However, the two most important ways of classifying them are according to (1) service requirement and (2) constructional features.

1. According to service requirement. A sub-station may be called upon to change voltage level or improve power factor or convert a.c. power into d.c. power etc. According to the service requirement, sub-stations may be classified into :

(*i*) **Transformer sub-stations.** Those sub-stations which change the voltage level of electric supply are called transformer sub-stations. These sub-stations receive power at some voltage and deliver it at some other voltage. Obviously, transformer will be the main component in such sub-stations. Most of the sub-stations in the power system are of this type.

(*ii*) **Switching sub-stations.** These sub-stations do not change the voltage level *i.e.* incoming and outgoing lines have the same voltage. However, they simply perform the switching operations of power lines.

(*iii*) **Power factor correction sub-stations.** Those sub-stations which improve the power factor of the system are called power factor correction sub-stations. Such sub-stations are generally located at the receiving end of transmission lines. These sub-stations generally use synchronous condensers as the power factor improvement equipment.

(*iv*) **Frequency changer sub-stations.** Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilisation.

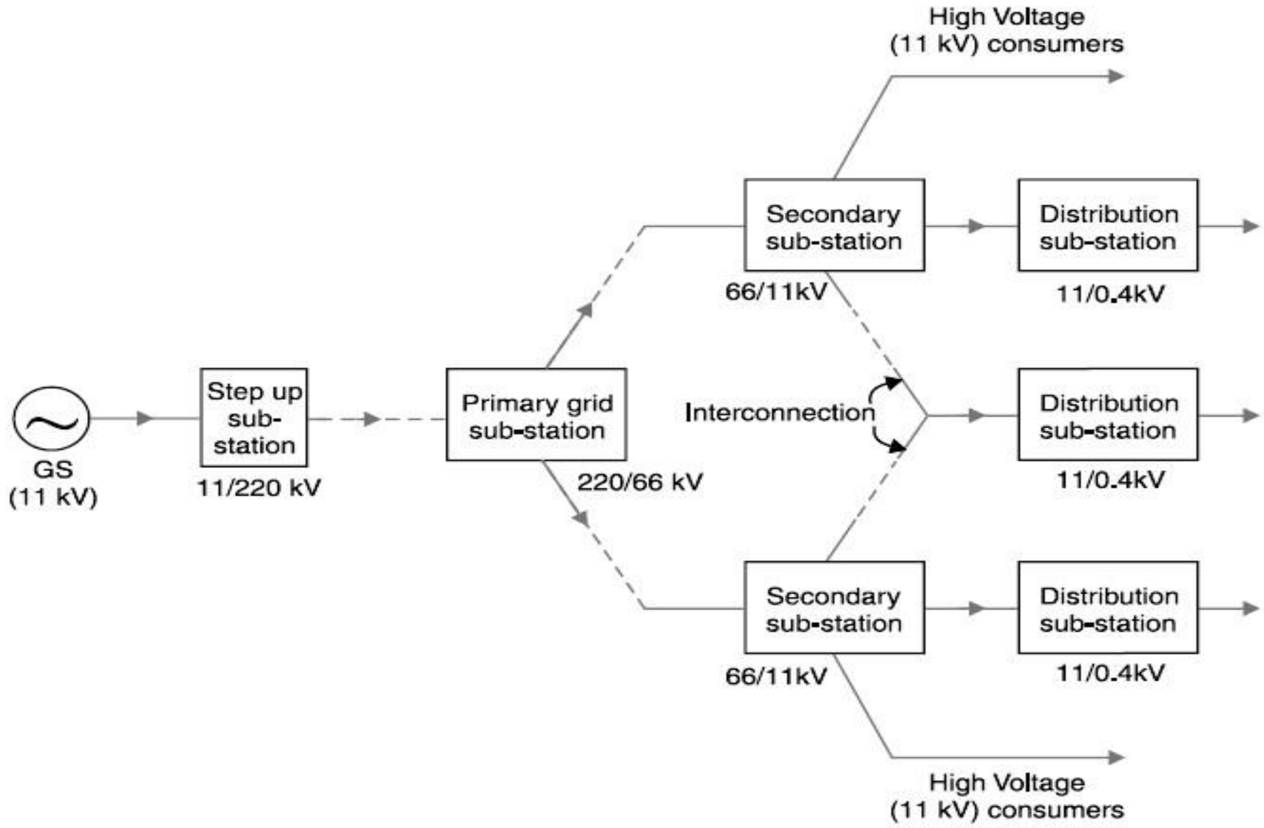
(*v*) **Converting sub-stations.** Those sub-stations which change a.c. power into d.c. power are called converting sub-stations. These sub-stations receive a.c. power and convert it into d.c. power with suitable apparatus (*e.g.* ignitron) to supply for such purposes as traction, electroplating, electric welding etc.

(*vi*) **Industrial sub-stations.** Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

Transformer Sub-Stations

(*i*) Step-up sub-station (*ii*) Primary grid sub-station

(*iii*) Secondary sub-station (*iv*) Distribution sub-station



(*i*) **Step-up sub-station.** The generation voltage (11 kV in this case) is stepped up to high voltage (220 kV) to affect economy in transmission of electric power. The sub-stations which accomplish this job are called step-up sub-stations. These are generally located in the power houses and are of outdoor type.

(*ii*) **Primary grid sub-station.** From the step-up sub-station, electric power at 220 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. Here, electric power is received by the primary grid sub-station which reduces the voltage level to 66 kV for secondary transmission. The primary grid sub-station is generally of outdoor type.

(*iii*) **Secondary sub-station.** From the primary grid sub-station, electric power is transmitted at 66 kV by 3-phase, 3-wire system to various secondary sub-stations located at the strategic points in

stations. The secondary sub-stations are also generally of outdoor type.

(*iv*) **Distribution sub-station.** The electric power from 11 kV lines is delivered to distribution sub-stations. These sub-stations are located near the consumers localities and step down the voltage to 400 V, 3-phase, 4-wire for supplying to the consumers. The voltage between any two phases is 400V and between any phase and neutral it is 230 V. The single phase residential lighting load is connected between any one phase and neutral whereas 3-phase, 400V motor load is connected across 3-phase lines directly. It may be worthwhile to mention here that majority of the distribution sub-stations are of pole-mounted type.

25.5 Pole-Mounted Sub-Station

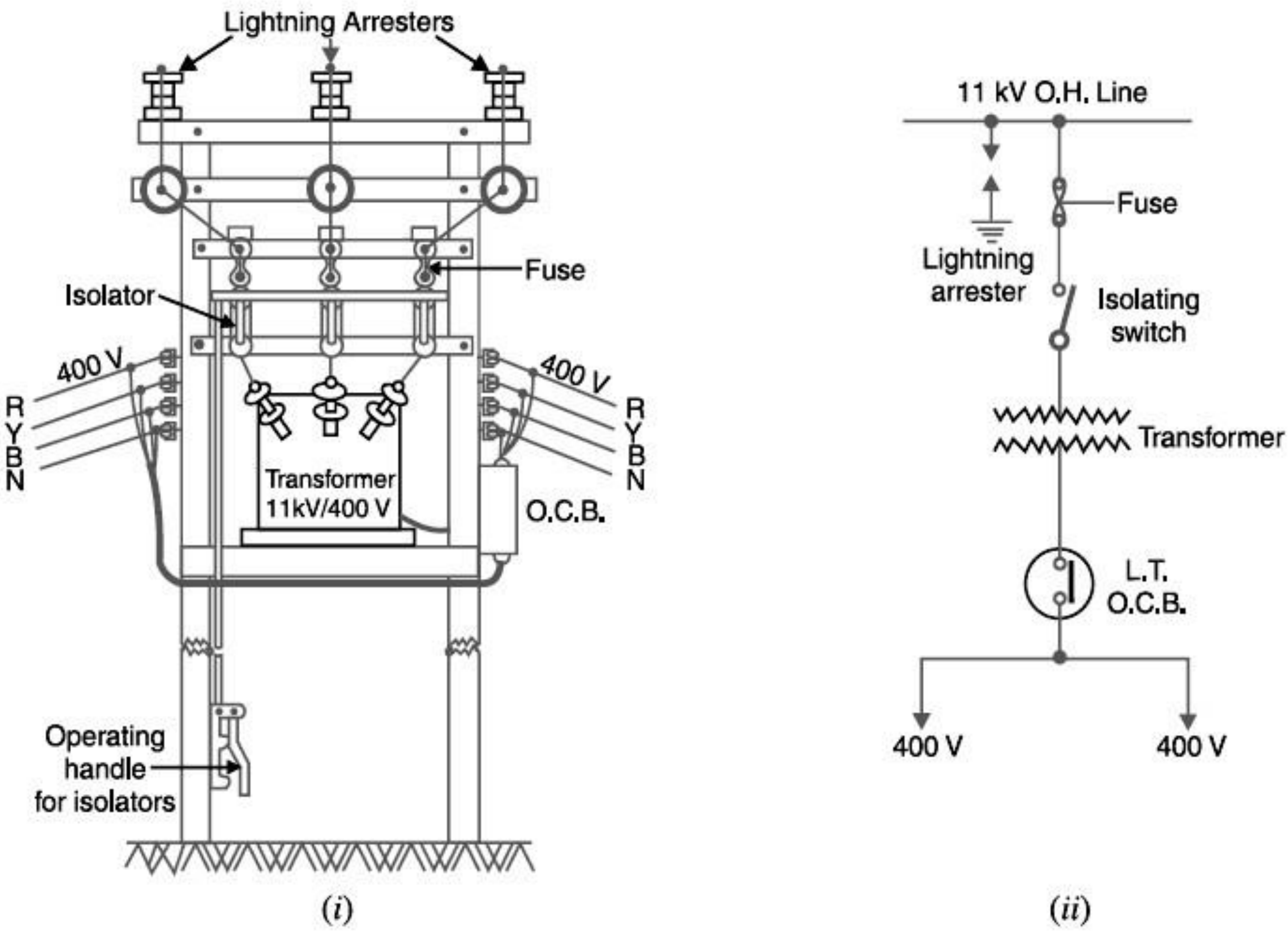
It is a distribution sub-station placed overhead on a pole. It is the cheapest form of sub-station as it does not involve any building work. Fig 25.2 (*i*) shows the layout of pole-mounted sub-station whereas Fig. 25.2 (*ii*) shows the schematic connections. The transformer and other equipment are mounted on H-type pole (or 4-pole structure).


Sub-Station

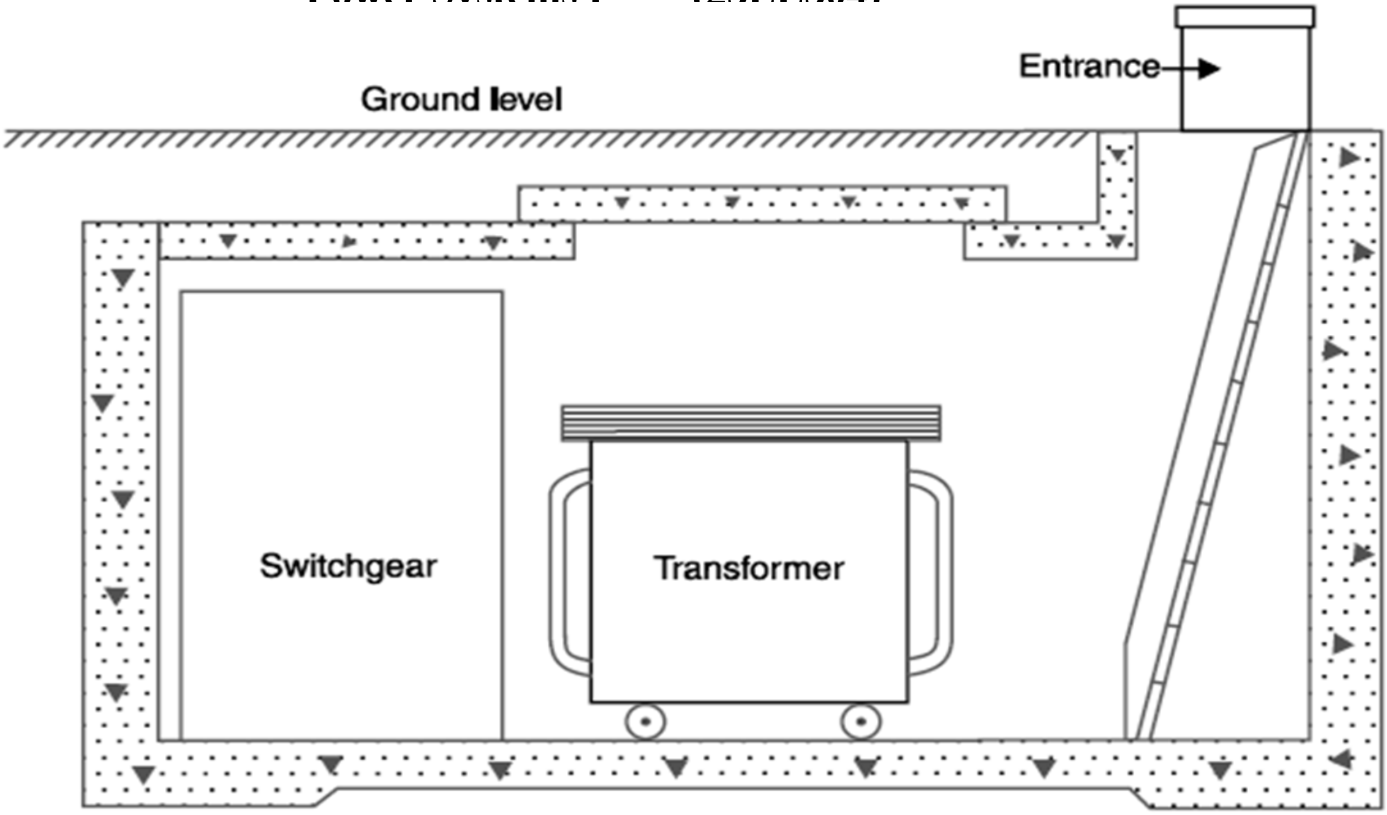
The 11 kV line is connected to the transformer (11kV / 400 V) through gang isolator and fuses. The lightning arresters are installed on the H.T. side to protect the sub-station from lightning strokes. The transformer steps down the voltage to 400V, 3-phase, 4-wire supply. The voltage between any two lines is 400V whereas the voltage between any line and neutral is 230 V. The oil circuit breaker (O.C.B.) installed on the L.T. side automatically isolates the transformer from the consumers in the event of any fault. The pole-mounted sub-stations are generally used for transformer capacity upto *200 kVA. The following points may be noted about pole-mounted sub-stations :

(*i*) There should be periodical check-up of the dielectric strength of oil in the transformer and O.C.B.

(*ii*) In case of repair of transformer or O.C.B., both gang isolator and O.C.B. should be shut off.



layout of pole-mounted sub-station



Underground Sub-Station

The design of underground sub-station requires more careful consideration than other types of sub-stations. While laying out an underground sub-station, the following points must be kept in view:

(*i*) The size of the station should be as minimum as possible.

(*ii*) There should be reasonable access for both equipment and personnel.

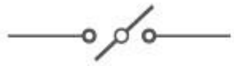
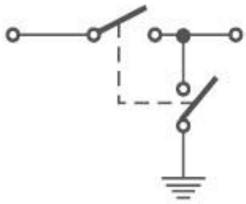
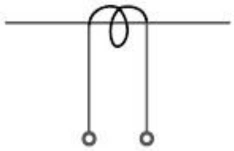
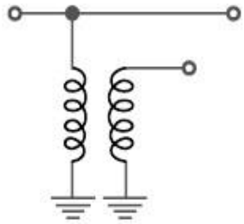
(*iii*) There should be provision for emergency lighting and protection against fire.

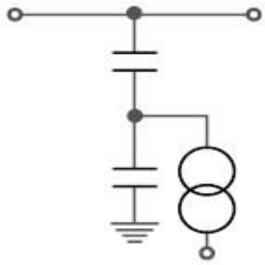
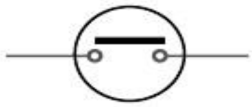
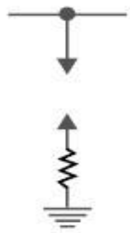
(*iv*) There should be good ventilation.

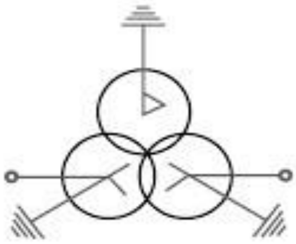
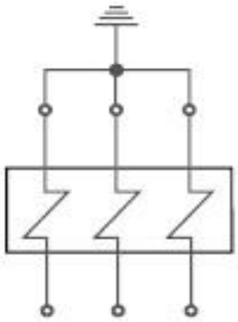
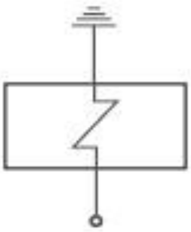
(*v*) There should be provision for remote indication of excessive rise in temperature so that H.V. supply can be disconnected.

(*vi*) The transformers, switches and fuses should be air cooled to avoid bringing oil into the premises.

Symbols for Equipment in Sub-Stations

S.No.	Circuit element	Symbol
1	Bus-bar	
2	Single-break isolating switch	
3	Double-break isolating switch	
4	On load isolating switch	
5	Isolating switch with earth Blade	
6	Current transformer	
7	Potential transformer	

8	Capacitive voltage transformer	
9	Oil circuit breaker	
10	Air circuit breaker with overcurrent tripping device	
11	Air blast circuit breaker	
12	Lightning arrester (active gap)	
13	Lightning arrester (valve type)	

S.No.	Circuit element	Symbol
14	Arcing horn	
15	3-ϕ Power transformer	
16	Overcurrent relay	
17	Earth fault relay	

25.8 Equipment in a Transformer Sub-Station

The equipment required for a transformer sub-station depends upon the type of sub-station, service requirement and the degree of protection desired. However, in general, a transformer sub-station has the following main equipment :

1. Bus-bars. When a number of lines operating at the same voltage have to be directly connected electrically, bus-bars are used as the common electrical component. Bus-bars are copper or aluminium bars (generally of rectangular *x*-section) and operate at constant voltage. The incoming and outgoing lines in a sub-station are connected to the bus-bars. The most commonly used bus-bar arrangements in sub-stations are :

(*i*) Single bus-bar arrangement

(*ii*) Single bus-bar system with sectionalisation

(*iii*) Double bus-bar arrangement

A detailed discussion on these bus-bar arrangements has already been made in Art. 16.3. However, their practical applications in sub-stations are discussed in Art. 25.9.

2. Insulators. The insulators serve two purposes. They support the conductors (or bus-bars) and confine the current to the conductors. The most commonly used material for the manufacture of insulators is porcelain. There are several types of insulators (*e.g.* pin type, suspension type, post insulator etc.) and their use in the sub-station will depend upon the service requirement. For example, post insulator is used for bus-bars. A post insulator consists of a porcelain body, cast iron cap and flanged cast iron base. The hole in the cap is threaded so that bus-bars can be directly bolted to the cap.

3. Isolating switches. In sub-stations, it is often desired to disconnect a part of the system for general maintenance and repairs. This is accomplished by an isolating switch or isolator. An isolator is essentially a knife switch and is designed to open a circuit under *no load*. In other words, isolator switches are operated only when the lines in which they are connected carry *no current.

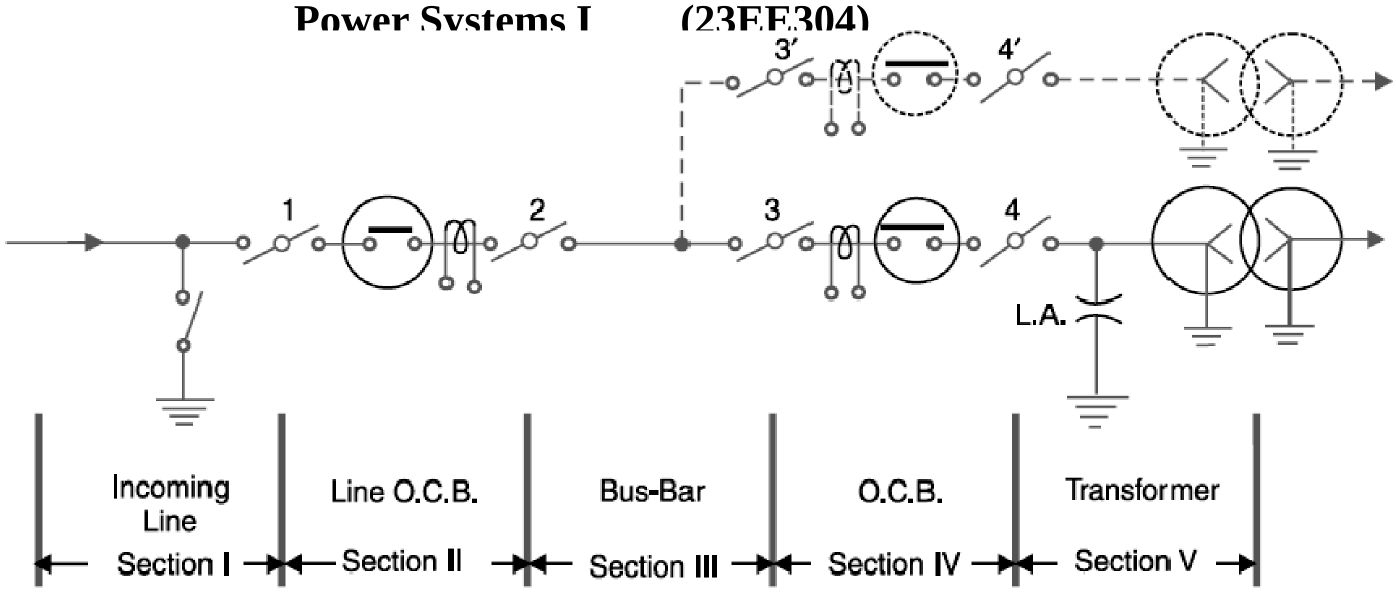


Fig. 25.4

Fig. 25.4 shows the use of isolators in a typical sub-station. The entire sub-station has been divided into V sections. Each section can be disconnected with the help of isolators for repair and maintenance. For instance, if it is desired to repair section No. II, the procedure of disconnecting this section will be as follows. First of all, open the circuit breaker in this section and then open the isolators 1 and 2. This procedure will disconnect section II for repairs. After the repair has been done, close the isolators 1 and 2 first and then the circuit breaker.

4. Circuit breaker. A circuit breaker is an equipment which can open or close a circuit under **normal as well as fault conditions. It is so designed that it can be operated manually (or by remote control) under normal conditions and automatically under fault conditions. For the latter operation, a relay circuit is used with a circuit breaker. Generally, bulk oil circuit breakers are used for voltages upto 66kV while for high (>66 kV) voltages, low oil circuit breakers are used. For still higher voltages, air-blast, vacuum or SF_6 circuit breakers are used. For detailed discussion of these breakers, the reader may refer to chapter 19.

5. Power Transformers. A power transformer is used in a sub-station to step-up or step-down the voltage. Except at the ***power station, all the subsequent sub-stations use step-down transformers to gradually reduce the voltage of electric supply and finally deliver it at utilisation voltage. The modern practice is to use 3-phase transformers in sub-stations ; although 3 single phase bank of

* For example, consider that the isolators are connected on both sides of a circuit breaker. If the isolators are to be opened, the C.B. must be opened first.

** An isolator cannot be used to open a circuit under normal conditions. It is because it has no provision to quench the arc that is produced during opening operation. Hence the use of circuit breaker is essential.

*** where a step-up transformer is used to step-up generation voltage to a high value (say 132 kV or 220 kV or more) for transmission of electric power.

transformers can also be used. The use of 3-phase transformer (instead of 3 single phase bank of transformers) permits two advantages. Firstly, only one 3-phase load-tap changing mechanism can be used. Secondly, its installation is much simpler than the three single phase transformers.

The power transformer is generally installed upon lengths of rails fixed on concrete slabs having foundations 1 to 1·5 m deep. For ratings upto 10 MVA, naturally cooled, oil immersed transformers are used. For higher ratings, the transformers are generally air blast cooled.

6. Instrument transformers. The lines in sub-stations operate at high voltages and carry current of thousands of amperes. The measuring instruments and protective devices are designed for low voltages (generally 110 V) and currents (about 5 A). Therefore, they will not work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing *instrument transformers* on the power lines. The function of these instrument transformers is to transfer voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays. There are two types of instrument transformers *viz*.

(*i*) Current transformer (C.T.) (*ii*) Potential transformer (P.T.)

(*i*) Current transformer (C.T.). A current transformer in essentially a step-up transformer which steps down the current to a known ratio. The primary of this transformer consists of one or more turns of thick wire connected in series with the line. The secondary consists of a large number of turns of fine wire and provides for the measuring instruments and relays a current which is a constant fraction of the current in the line. Suppose a current transformer rated at 100/5 A is connected in the line to measure current. If the current in the line is 100 A, then current in the secondary will be 5A. Similarly, if current in the line is 50A, then secondary of C.T. will have a current of 2·5 A. Thus the C.T. under consideration will step down the line current by a factor of 20.

(*ii*) Voltage transformer. It is essentially a step down transformer and steps down the voltage to a known ratio. The primary of this transformer consists of a large number of turns of fine wire connected across the line. The secondary winding consists of a few turns and provides for measuring instruments and relays a voltage which is a known fraction of the line voltage. Suppose a potential transformer rated at 66kV/110V is connected to a power line. If line voltage is 66kV, then voltage across the secondary will be 110 V.

7. Metering and Indicating Instruments. There are several metering and indicating instruments (*e.g.* ammeters, voltmeters, energy meters etc.) installed in a sub-station to maintain watch over the circuit quantities. The instrument transformers are invariably used with them for satisfactory operation.

8. Miscellaneous equipment. In addition to above, there may be following equipment in a sub-station :

(*i*) fuses
(*ii*) carrier-current equipment
(*iii*) sub-station auxiliary supplies

25.9 Bus-Bar Arrangements in Sub-Stations

Bus-bars are the important components in a sub-station. There are several bus-bar arrangements that can be used in a sub-station. The choice of a particular arrangement depends upon various factors such as system voltage, position of sub-station, degree of reliability, cost etc. The following are the important bus-bar arrangements used in sub-stations :

(*i*) Single bus-bar system. As the name suggests, it consists of a single bus-bar and all the incoming and outgoing lines are connected to it. The chief advantages of this type of arrangement are low initial cost, less maintenance and simple operation. However, the principal disadvantage of single bus-bar system is that if repair is to be done on the bus-bar or a fault occurs on the bus, there is a complete interruption of the supply. This arrangement is not used for voltages exceeding 33kV. The indoor 11kV sub-stations often use single bus-bar arrangement.

Fig. 25.5 shows single bus-bar arrangement in a sub-station. There are two 11 kV incoming lines connected to the bus-bar through circuit breakers and isolators. The two 400V outgoing lines are connected to the bus bars through transformers (11kV/400 V) and circuit breakers.

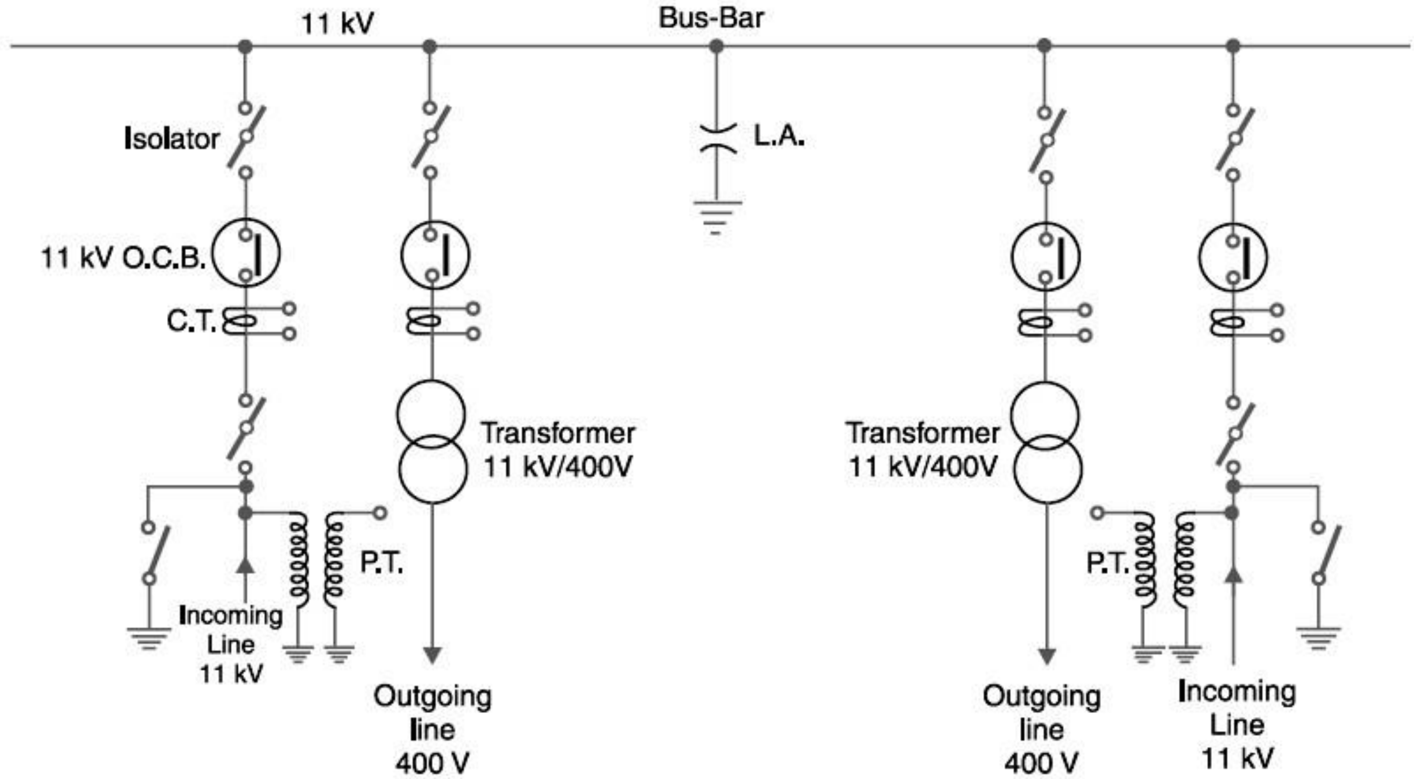


Fig. 25.5

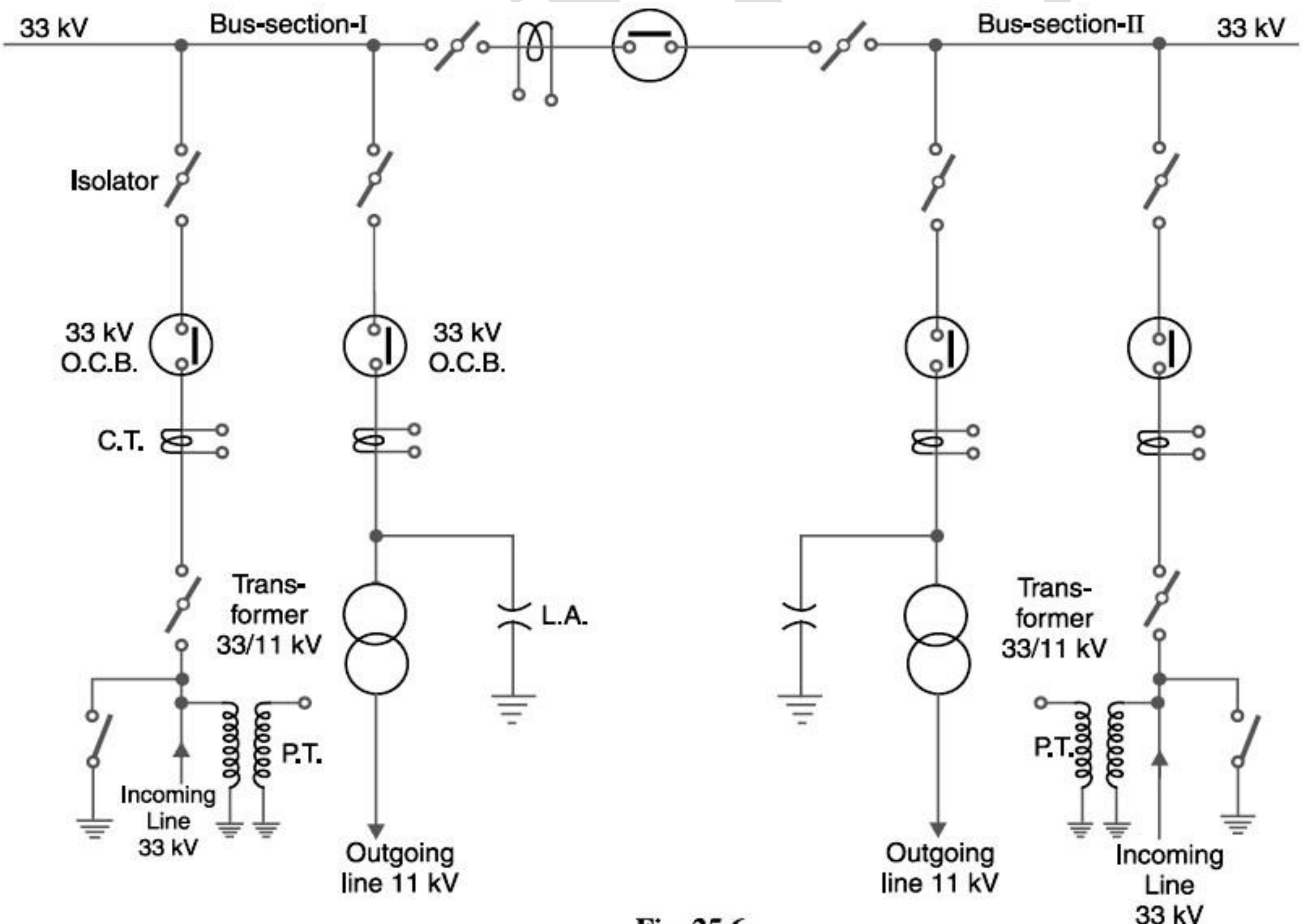


Fig. 25.6

(ii) **Single bus-bar system with sectionalisation.** In this arrangement, the single bus-bar is divided into sections and load is equally distributed on all the sections. Any two sections of the bus-bar are connected by a circuit breaker and isolators. Two principal advantages are claimed for this arrangement. Firstly, if a fault occurs on any section of the bus, that section can be isolated without affecting the supply from other sections. Secondly, repairs and maintenance of any section of the bus-bar can be carried out by de-energising that section only, eliminating the possibility of complete shut down. This arrangement is used for voltages upto 33 kV.

Fig. 25.6 shows bus-bar with sectionalisation where the bus has been divided into two sections. There are two 33 kV incoming lines connected to sections I and II as shown through circuit breaker and isolators. Each 11 kV outgoing line is connected to one section through transformer (33/11 kV) and circuit breaker. It is easy to see that each bus-section behaves as a separate bus-bar.

(iii) **Duplicate bus-bar system.** This system consists of two bus-bars, a "main" bus-bar and a "spare" bus-bar. Each bus-bar has the capacity to take up the entire sub-station load. The incoming and outgoing lines can be connected to either bus-bar with the help of a bus-bar coupler which consists of a circuit breaker and isolators. Ordinarily, the incoming and outgoing lines remain connected to the main bus-bar. However, in case of repair of main bus-bar or fault occuring on it, the continuity of supply to the circuit can be maintained by transferring it to the spare bus-bar. For voltages exceeding 33kV, duplicate bus-bar system is frequently used.

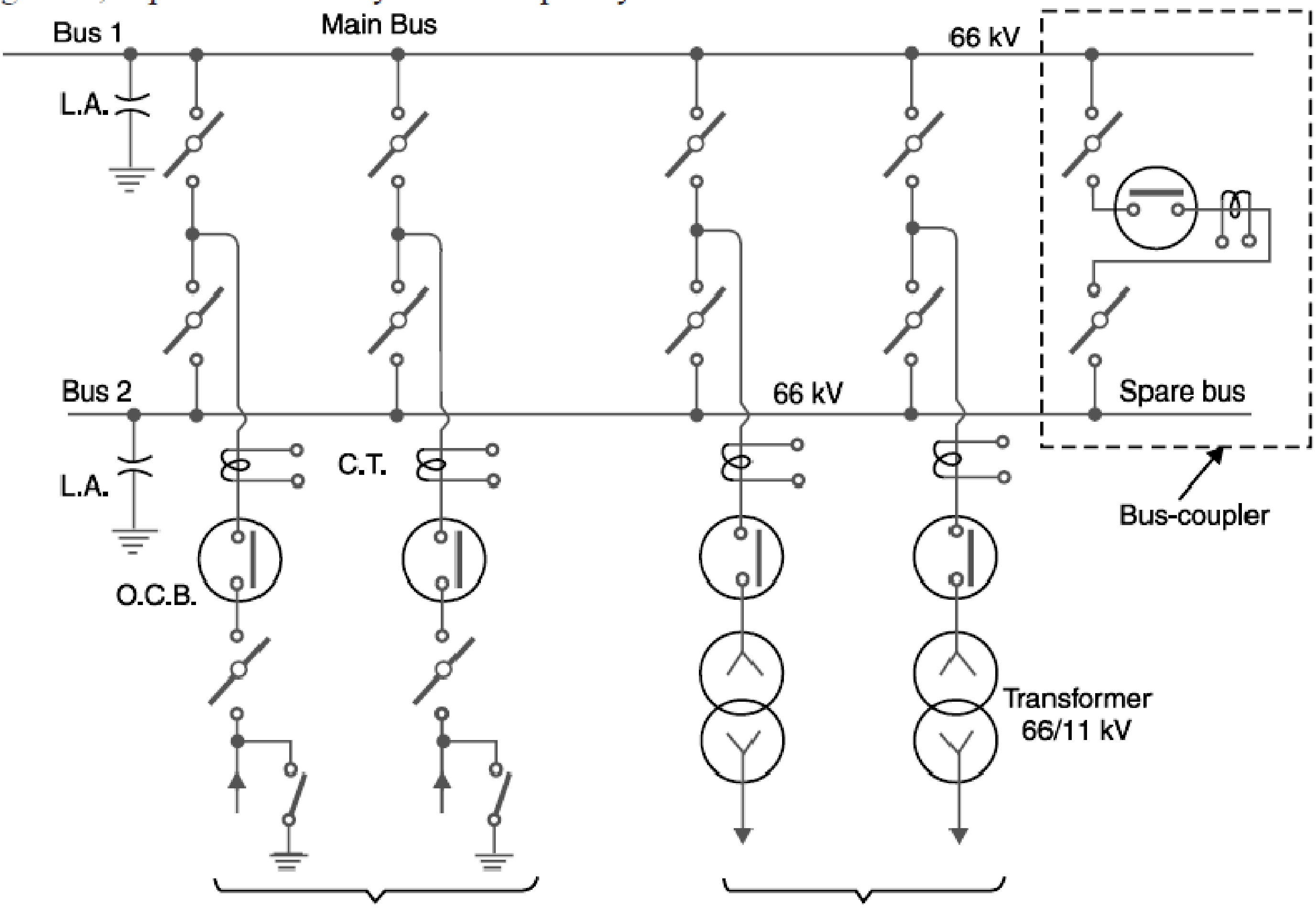


Fig. 25.7

Fig. 25.7 shows the arrangement of duplicate bus-bar system in a typical sub-station. The two 66kV incoming lines can be connected to either bus-bar by a bus-bar coupler. The two 11 kV outgoing lines are connected to the bus-bars through transformers (66/11 kV) and circuit breakers.

25.10 Terminal and Through Sub-Stations

All the transformer sub-stations in the line of power system handle incoming and outgoing lines. Depending upon the manner of incoming lines, the sub-stations are classified as :

(i) Terminal sub-station (ii) Through sub-station

(i) **Terminal sub-station.** A terminal sub-station is one in which the line supplying to the sub-station terminates or ends. It may be located at the end of the main line or it may be situated at a point away from main line route. In the latter case, a tapping is taken from the main line to supply to the sub-station. Fig. 25.8 shows the schematic connections of a terminal sub-station. It is clear that incoming 11 kV main line terminates at the sub-station. Most of the distribution sub-stations are of this type.

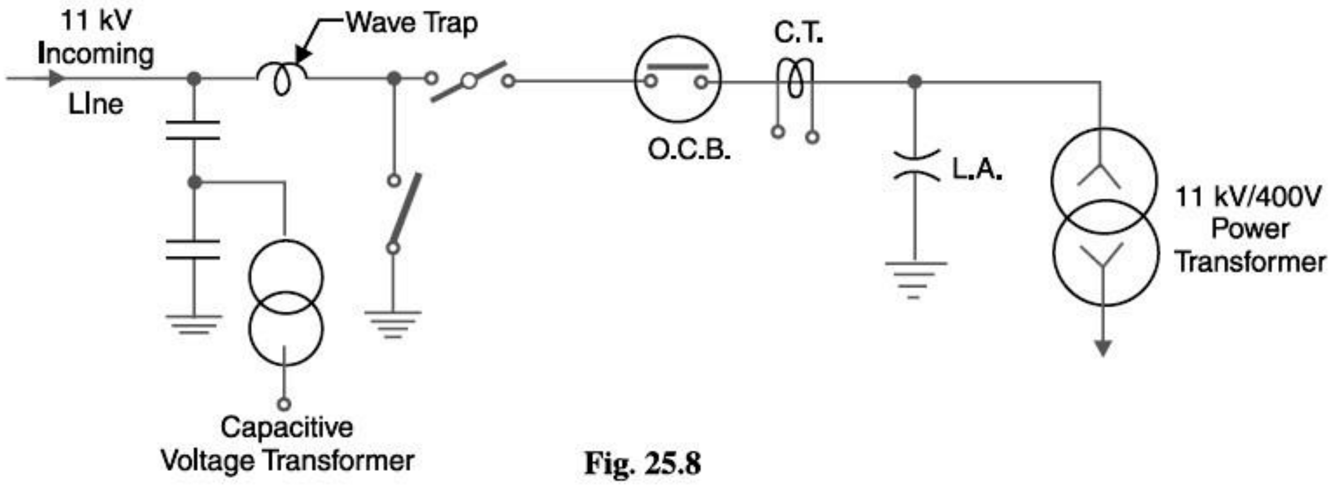


Fig. 25.8

(ii) **Through sub-station.** A through sub-station is one in which the incoming line passes 'through' at the same voltage. A tapping is generally taken from the line to feed to the transformer to reduce the voltage to the desired level. Fig. 25.9 shows the schematic connections of a through sub-station. The incoming 66 kV line passes through the sub-station as 66kV outgoing line. At the same time, the incoming line is tapped in the sub-station to reduce the voltage to 11 kV for secondary distribution.

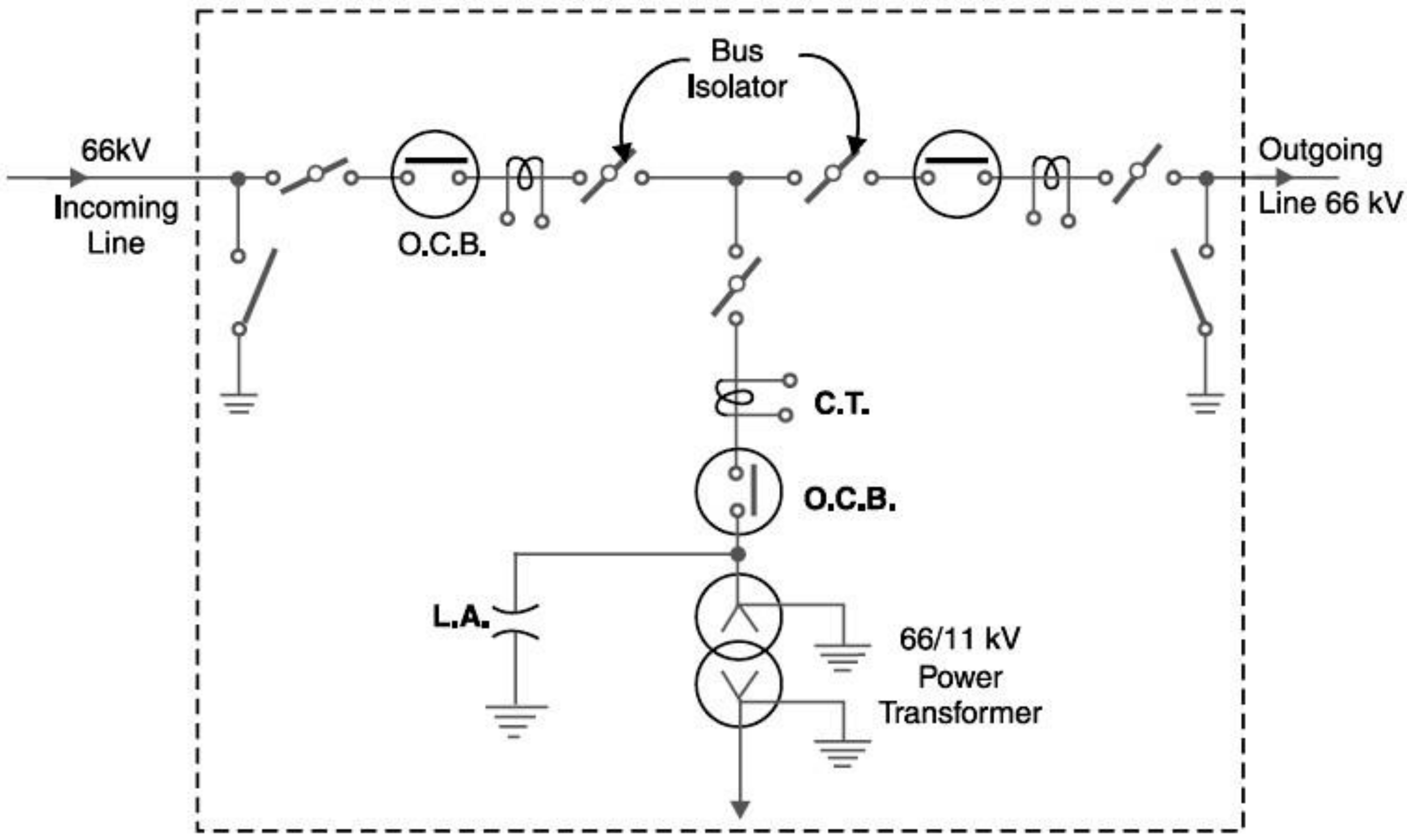

Bus
Isolator
66kV
Incoming
Line
O.C.B.
Outgoing
Line 66 kV
C.T.
O.C.B.
L.A.
66/11 kV
Power
Transformer

Fig. 25.9

25.11 Key Diagram of 66/11 kV Sub-Station

Fig. 25.10 shows the key diagram of a typical 66/11 kV sub-station. The key diagram of this sub-station can be explained as under :

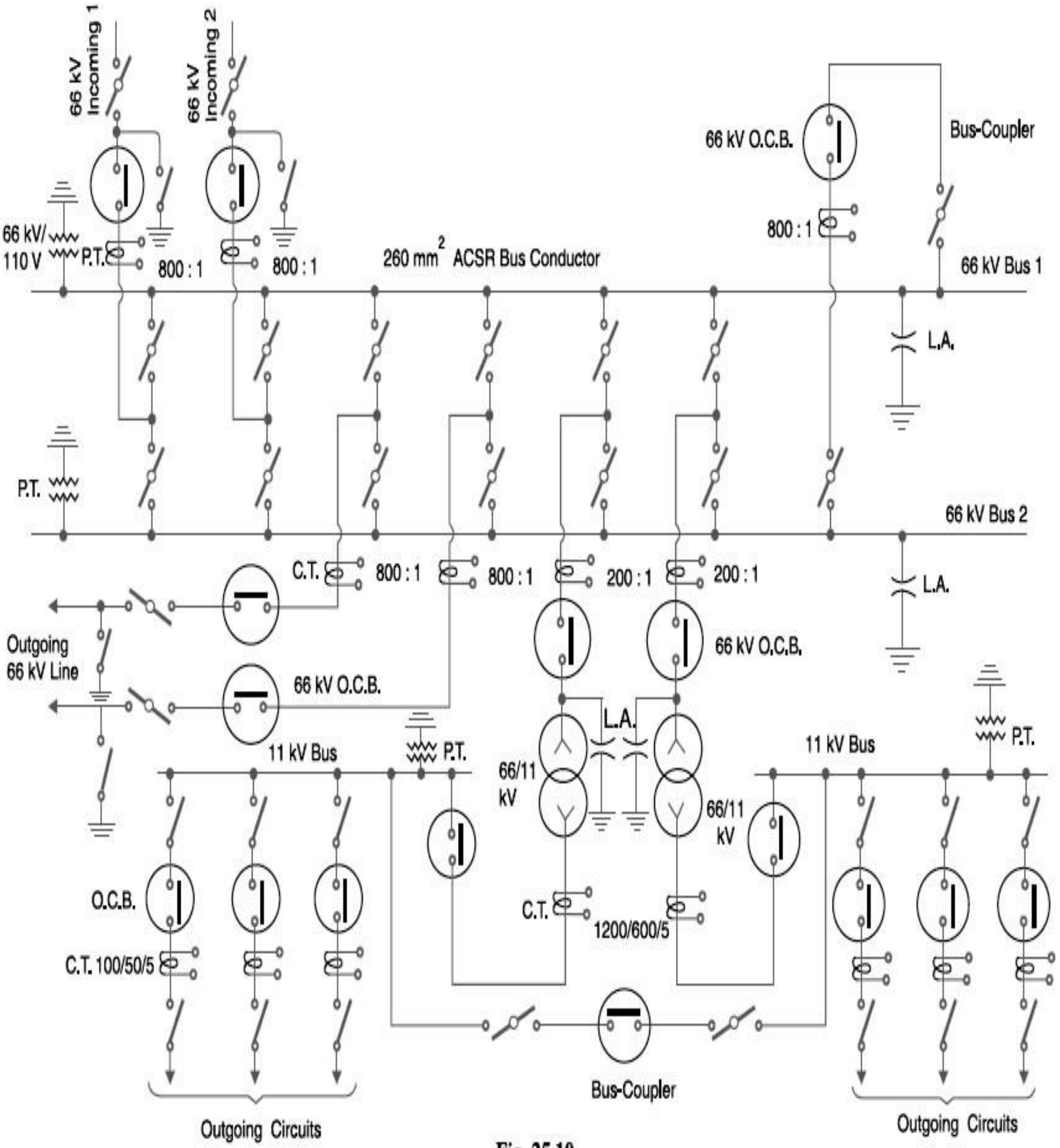


Fig. 25.10

(*i*) There are two 66 kV incoming lines marked 'incoming 1' and 'incoming 2' connected to the bus-bars. Such an arrangement of two incoming lines is called a double circuit. Each incoming line is capable of supplying the rated sub-station load. Both these lines can be loaded simultaneously to share the sub-station load or any one line can be called upon to meet the entire load. The double circuit arrangement increases the reliability of the system. In case there is a breakdown of one incoming line, the continuity of supply can be maintained by the other line.

(*ii*) The sub-station has duplicate bus-bar system; one 'main bus-bar' and the other spare bus-bar. The incoming lines can be connected to either bus-bar with the help of a bus-coupler which consists of a circuit breaker and isolators. The advantage of double bus-bar system is that if repair is to be carried on one bus-bar, the supply need not be interrupted as the entire load can be transferred to the other bus.

(*iii*) There is an arrangement in the sub-station by which the same 66 kV double circuit supply is going out *i.e.* 66 kV double circuit supply is passing through the sub-station. The outgoing 66 kV double circuit line can be made to act as incoming line.

(*iv*) There is also an arrangement to step down the incoming 66 kV supply to 11 kV by two units of 3-phase transformers; each transformer supplying to a separate bus-bar. Generally, one transformer supplies the entire sub-station load while the other transformer acts as a standby unit. If need arises, both the transformers can be called upon to share the sub-station load. The 11 kV outgoing lines feed to the distribution sub-stations located near consumers localities.

(*v*) Both incoming and outgoing lines are connected through circuit breakers having isolators on their either end. Whenever repair is to be carried over the line towers, the line is first switched off and then earthed.

(*vi*) The potential transformers (P.T.) and current transformers (C.T.) and suitably located for supply to metering and indicating instruments and relay circuits (not shown in the figure). The P.T. is connected right on the point where the line is terminated. The CTs are connected at the terminals of each circuit breaker.

(*vii*) The lightning arresters are connected near the transformer terminals (on H.T. side) to protect them from lightning strokes.

(*viii*) There are other auxiliary components in the sub-station such as capacitor bank for power factor improvement, earth connections, local supply connections, d.c. supply connections etc. However, these have been omitted in the key diagram for the sake of simplicity.

25.12 Key Diagram of 11 kV/400 V Indoor Sub-Station

Fig. 25.11 shows the key diagram of a typical 11 kV/400 V indoor sub-station. The key diagram of this sub-station can be explained as under :

(*i*) The 3-phase, 3-wire 11 kV line is tapped and brought to the gang operating switch installed near the sub-station. The G.O. switch consists of isolators connected in each phase of the 3-phase line.

(*ii*) From the G.O. switch, the 11 kV line is brought to the indoor sub-station as underground cable. It is fed to the H.T. side of the transformer (11 kV/400 V) *via* the 11 kV O.C.B. The transformer steps down the voltage to 400 V, 3-phase, 4-wire.

(*iii*) The secondary of transformer supplies to the bus-bars *via* the main O.C.B. From the bus-bars, 400 V, 3-phase, 4-wire supply is given to the various consumers *via* 400 V O.C.B. The voltage between any two phases is 400 V and between any phase and neutral it is 230 V. The single phase residential load is connected between any one phase and neutral whereas 3-phase, 400 V motor load is connected across 3-phase lines directly.

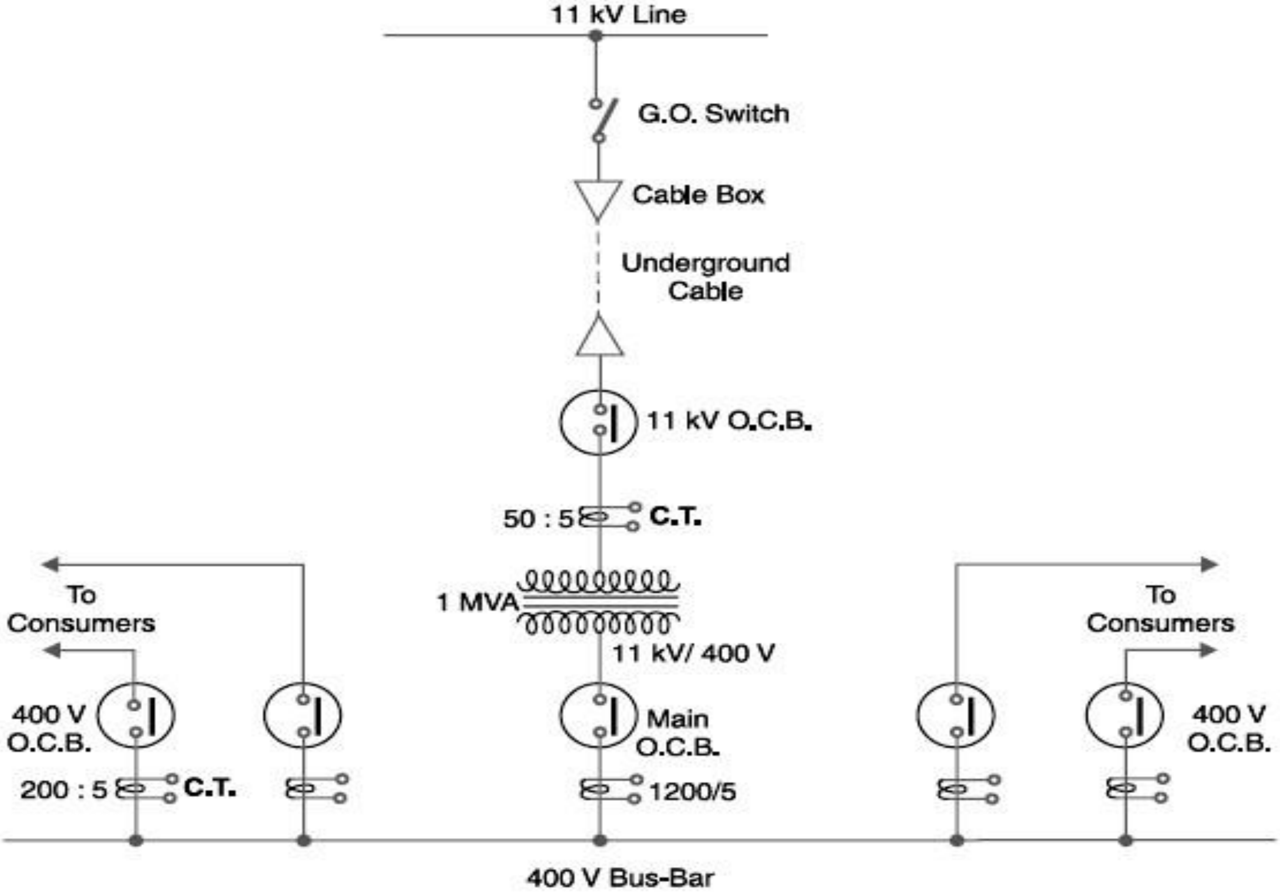


Fig. 25.11

(*iv*) The CTs are located at suitable places in the sub-station circuit and supply for the metering and indicating instruments and relay circuits.

Unit-5

A.C. Distribution Calculations

A.C. distribution calculations differ from those of d.c. distribution in the following respects :

(i) In case of d.c. system, the voltage drop is due to resistance alone. However, in a.c. system,the voltage drops are due to the combined effects of resistance, inductance and capacitance.

(ii) In a d.c. system, additions and subtractions of currents or voltages are done arithmetically but in case of a.c. system, these operations are done vectorially.

(iii) In an a.c. system, power factor (p.f.) has to be taken into account. Loads tapped off form the distributor are generally at different power factors. There are two ways of referring power factor viz

(a) It may be referred to supply or receiving end voltage which is regarded as the reference

vector.

(b) It may be referred to the voltage at the load point itself.There are several ways of solving a.c. distribution problems. However, symbolic notation method has been found to be most convenient for this purpose. In this method, voltages, currents and impedances are expressed in complex notation and the calculations are made exactly as in d.c. distribution.

Methods of Solving A.C. Distribution Pr Methods of Solving A.C. Distribution Problems

In a.c. distribution calculations, power factors of various load currents have to be considered since currents in different sections of the distributor will be the vector sum of load currents and not the arithmetic sum. The power factors of load currents may be given (i) w.r.t. receiving or sending end voltage or (ii) w.r.t. to load voltage itself. Each case shall be discussed separately.

(i) Power factors referred to receiving end voltage. Consider an a.c. distributor A B with concentrated loads of I1 and I2 tapped off at points C and B as shown in Fig. 14.1. Taking the receiving end

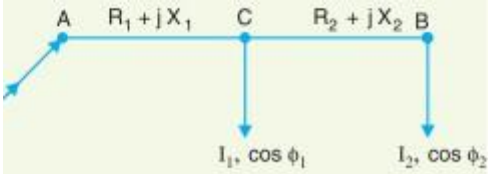


Fig. 14.1

voltage VB as the reference vector, let lagging power factors at C and B be cos φ1 and cos φ2 w.r.t. VB. Let R1, X1 and R2, X2 be the resistance and reactance of sections AC and CB of the distributor.

Impedance of section AC, $\overline{Z_{AC}} = R_1 + j X_1$

Impedance of section CB, $\overline{Z_{CB}} = R_2 + j X_2$

Load current at point C, $\overrightarrow{I_1} = I_1 (\cos \phi_1 - j \sin \phi_1)$

Load current at point B, $\overrightarrow{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

Current in section CB, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

Current in section AC, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2}$

$= I_1 (\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)$

Voltage drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\,\overrightarrow{Z_{CB}} = I_2 (\cos \phi_2 - j \sin \phi_2)(R_2 + j X_2)$

Voltage drop in section AC, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}} = \left(\overrightarrow{I_1} + \overrightarrow{I_2}\right) Z_{AC}$

$= [I_1(\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)]\,[R_1 + j X_1]$

Sending end voltage, $\overrightarrow{V_A} = \overrightarrow{V_B} + \overrightarrow{V_{CB}} + \overrightarrow{V_{AC}}$

Sending end current, $\overrightarrow{I_A} = \overrightarrow{I_1} + \overrightarrow{I_2}$

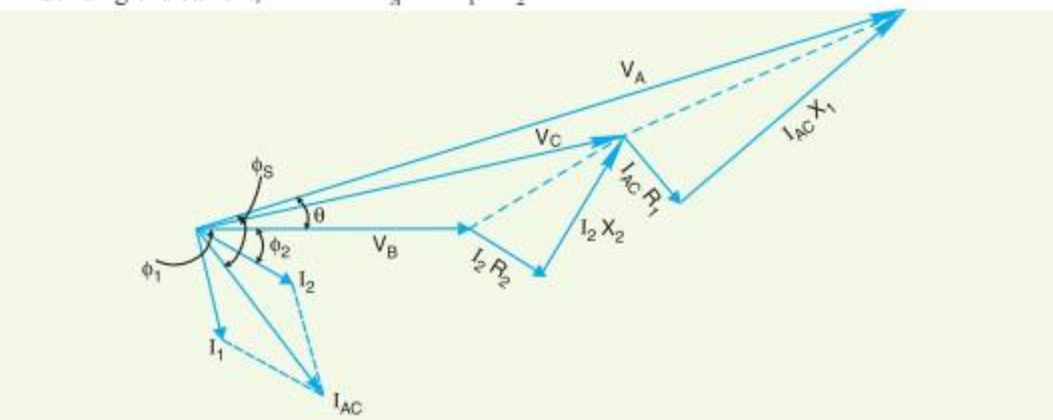


Fig. 14.2

The vector diagram of the a.c. distributor under these conditions is shown in Fig. 14.2. Here, the receiving end voltage VB is taken as the reference vector. As power factors of loads are given w.r.t. VB, therefore, I1 and I2 lag behind VB by φ1 and φ2 respectively.

(ii) Power factors referred to respective load voltages. Suppose the power factors of loads in

the previous Fig. 14.1 are referred to their respective load voltages. Then φ1 is the phase angle between VC and I1 and φ2 is the phase angle between VB and I2. The vector diagram under these conditions is shown in Fig. 14.3.

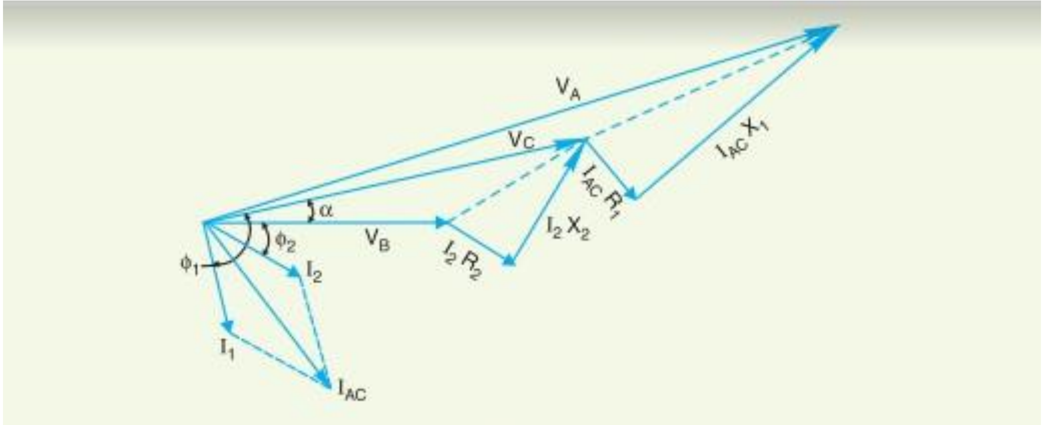


Fig. 14.3

$$\text{Voltage drop in section } CB = \overrightarrow{I_2}\,\overrightarrow{Z_{CB}} = I_2(\cos\phi_2 - j\sin\phi_2)(R_2 + jX_2)$$

$$\text{Voltage at point } C = \overrightarrow{V_B} + \text{Drop in section } CB = V_C \angle \alpha \text{ (say)}$$

Now $\overrightarrow{I_1} = I_1 \angle -\phi_1$ *w.r.t.* voltage V_C

∴ $\overrightarrow{I_1} = I_1 \angle -(\phi_1 - \alpha)$ *w.r.t.* voltage V_B

i.e. $\overrightarrow{I_1} = I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)]$

Now $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2}$

$$= I_1[\cos(\phi_1 - \alpha) - j\sin(\phi_1 - \alpha)] + I_2(\cos\phi_2 - j\sin\phi_2)$$

$$\text{Voltage drop in section } AC = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}}$$

∴ $\text{Voltage at point } A = V_B + \text{Drop in } CB + \text{Drop in } AC$

Example 14.1. *A single phase a.c. distributor AB 300 metres long is fed from end A and is loaded as under :*

(i) 100 A at 0·707 p.f. lagging 200 m from point A

(ii) 200 A at 0·8 p.f. lagging 300 m from point A

The load resistance and reactance of the distributor is 0·2 Ω and 0·1 Ω per kilometre. Calculate the total voltage drop in the distributor. The load power factors refer to the voltage at the far end.

Solution. Fig. 14.4 shows the single line diagram of the distributor.

Impedance of distributor/km = (0·2 + j 0·1) Ω

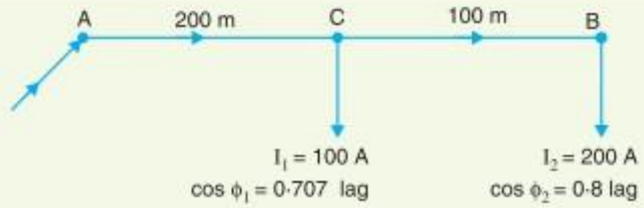


Fig. 14.4

Impedance of section *AC*, $\overrightarrow{Z_{AC}} = (0{\cdot}2 + j\,0{\cdot}1) \times 200/1000 = (0{\cdot}04 + j\,0{\cdot}02)\ \Omega$

Impedance of section *CB*, $\overrightarrow{Z_{CB}} = (0{\cdot}2 + j\,0{\cdot}1) \times 100/1000 = (0{\cdot}02 + j\,0{\cdot}01)\ \Omega$

Taking voltage at the far end *B* as the reference vector, we have,

Load current at point *B*, $\overrightarrow{I_2} = I_2(\cos\phi_2 - j\sin\phi_2) = 200\,(0{\cdot}8 - j\,0{\cdot}6)$
$= (160 - j\,120)$ A

Load current at point *C*, $\overrightarrow{I_1} = I_1(\cos\phi_1 - j\sin\phi_1) = 100\,(0{\cdot}707 - j\,0{\cdot}707)$
$= (70{\cdot}7 - j\,70{\cdot}7)$ A

Current in section *CB*, $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = (160 - j\,120)$ A

Current in section *AC*, $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2} = (70{\cdot}7 - j\,70{\cdot}7) + (160 - j\,120)$
$= (230{\cdot}7 - j\,190{\cdot}7)$ A

Voltage drop in section *CB*, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\,\overrightarrow{Z_{CB}} = (160 - j\,120)\,(0{\cdot}02 + j\,0{\cdot}01)$
$= (4{\cdot}4 - j\,0{\cdot}8)$ volts

Voltage drop in section *AC*, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}} = (230{\cdot}7 - j\,190{\cdot}7)\,(0{\cdot}04 + j\,0{\cdot}02)$
$= (13{\cdot}04 - j\,3{\cdot}01)$ volts

Voltage drop in the distributor $= \overrightarrow{V_{AC}} + \overrightarrow{V_{CB}} = (13{\cdot}04 - j\,3{\cdot}01) + (4{\cdot}4 - j\,0{\cdot}8)$
$= (17{\cdot}44 - j\,3{\cdot}81)$ volts

Magnitude of drop $= \sqrt{(17{\cdot}44)^2 + (3{\cdot}81)^2} = \mathbf{17{\cdot}85\ V}$

Example 14.2. A single phase distributor 2 kilometres long supplies a load of 120 A at 0·8 p.f. lagging at its far end and a load of 80 A at 0·9 p.f. lagging at its mid-point. Both power factors are referred to the voltage at the far end. The resistance and reactance per km (go and return) are 0·05 Ω and 0·1 Ω respectively. If the voltage at the far end is maintained at 230 V, calculate :

(i) voltage at the sending end

(ii) phase angle between voltages at the two ends.

Solution. Fig. 14.5 shows the distributor AB with C as the mid-point

Impedance of distributor/km = (0·05 + j 0·1) Ω

Impedance of section AC, ZAC = (0·05 + j 0·1) × 1000/1000 = (0·05 + j 0·1) Ω

Impedance of section CB, ZCB = (0·05 + j 0·1) × 1000/1000 = (0·05 + j 0·1) Ω

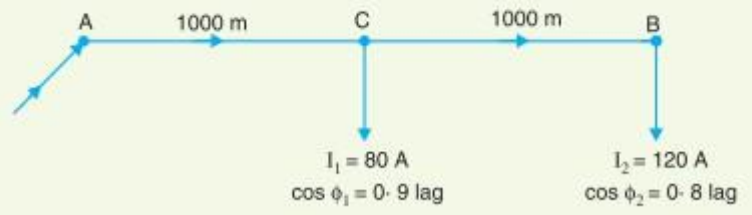


Fig. 14.5

Let the voltage V_B at point B be taken as the reference vector.

Then, $\vec{V_B} = 230 + j\,0$

(i) Load current at point B, $\vec{I_2} = 120\,(0{\cdot}8 - j\,0{\cdot}6) = 96 - j\,72$

Load current at point C, $\vec{I_1} = 80\,(0{\cdot}9 - j\,0{\cdot}436) = 72 - j\,34{\cdot}88$

Current in section CB, $\overrightarrow{I_{CB}} = \vec{I_2} = 96 - j\,72$

Current in section AC, $\overrightarrow{I_{AC}} = \vec{I_1} + \vec{I_2} = (72 - j\,34{\cdot}88) + (96 - j\,72)$

$= 168 - j\,106{\cdot}88$

Drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\,\overrightarrow{Z_{CB}} = (96 - j\,72)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 12 + j\,6$

Drop in section AC, $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}}\,\overrightarrow{Z_{AC}} = (168 - j\,106{\cdot}88)\,(0{\cdot}05 + j\,0{\cdot}1)$

$= 19{\cdot}08 + j\,11{\cdot}45$

∴ Sending end voltage, $\vec{V_A} = \vec{V_B} + \overrightarrow{V_{CB}} + \overrightarrow{V_{AC}}$

$= (230 + j\,0) + (12 + j\,6) + (19.08 + j\,11.45)$

$= 261.08 + j\,17.45$

Its magnitude is $= \sqrt{(261{\cdot}08)^2 + (17{\cdot}45)^2} = \mathbf{261{\cdot}67\ V}$

(ii) The phase difference θ between V_A and V_B is given by :

$$\tan\theta = \frac{17{\cdot}45}{261{\cdot}08} = 0{\cdot}0668$$

$$\therefore\quad \theta = \tan^{-1} 0{\cdot}0668 = \mathbf{3{\cdot}82^\circ}$$

Distribution System

That part of power system which distributes elec-tric power for local use is known as distribution system**.** In general, the distribution system is the electrical system between the sub-station fed by the transmission system and the consumers meters. It generally consists of feeders, distributors and the service mains. Fig. 12.1 shows the single line diagram of a typical low tension distribution system.

(i) **Feeders.** A feeder is a conductor which connects the sub-station (or localised generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(ii) **Distributor.** A distributor is a conductor from which tappings are taken for supply to the consumers. In Fig. 12.1, A B, BC, CD and DA are the distributors. The current through a distributor is not constant because tappings are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of rated value at the consumers' terminals.

(iii) **Service mains**. A service mains is generally a small cable which connects the distributor to the consumers' terminals.

12.2 Classification of Distribution Systems

A distribution system may be classified according to ;

(i) **Nature of current**. According to nature of current, distribution system may be classified as (a) d.c. distribution system (b) a.c. distribution system.

Now-a-days, a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method.

(ii) **Type of construction**. According to type of construction, distribution system may be classified as (a) overhead system (b) underground system. The overhead system is gen- erally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the

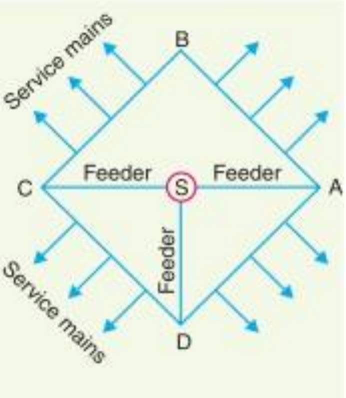


Fig. 12.1

underground system is used at places where overhead construction is impracticable or prohibited by the local laws.

(iii) **Scheme of connection**. According to scheme of connection, the distribution system may be classified as (a) radial system (b) ring main system (c) inter-connected system.

Each scheme has its own advantages and disadvantages and those are discussed in Art.12.7.

12.3 A.C. Distribution

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit a.c. power at high voltage and utilise it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting line losses.

There is no definite line between transmission and distribution according to voltage or bulk

capacity. However, in general, the a.c. distribution system is the electrical system between the step-down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into (i) primary distribution system and (ii) secondary distribution system.

(i) **Primary distribution system**. It is that part of a.c. distribution system which operates at

voltages somewhat higher than general utilisation and handles large blocks of electrical energy than the average low-voltage consumer uses. The voltage used for primary distribu- tion depends upon the amount of power to be conveyed and the distance of the substation

required to be fed. The most commonly used primary distribution voltages are 11 kV, 6·6

kV and 3·3 kV. Due to economic considerations, primary distribution is carried out by 3-

phase, 3-wire system.

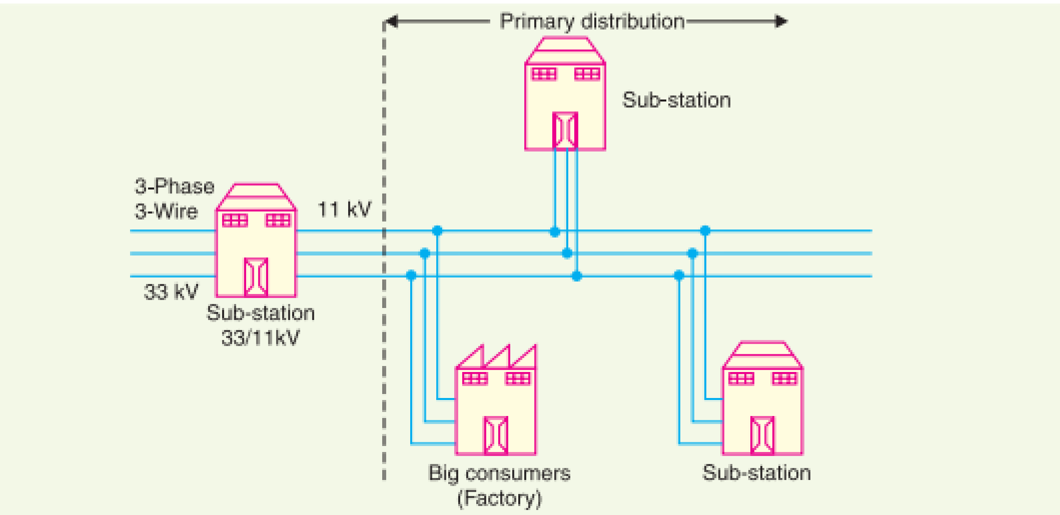


Fig. 12.2

Fig. 12.2 shows a typical primary distribution system. Electric power from the generating station is transmitted at high voltage to the substation located in or near the city. At this substation, voltage is stepped down to 11 kV with the help of step-down transformer. Power is supplied to various substations for distribution or to big consumers at this voltage. This forms the high voltage distribution or primary distribution.

(ii) **Secondary distribution system**. It is that part of a.c. distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

Fig. 12.3 shows a typical secondary distribution system. The primary distribution circuit delivers power to various substa-tions, called distribution sub-stations. The substations are situated near the consumers' localities and contain step-down transformers. At each distribution substation, thevoltage is stepped down to 400V and power is delivered by 3-phase,4-wire a.c. system.The voltage between any twophases is 400 V and between any phase and neutral is 230V. The single phase domesticloads are connected between any one phase and the neutral, whereas 3-phase 400 V motor loads are connected across 3-

phase lines directly.

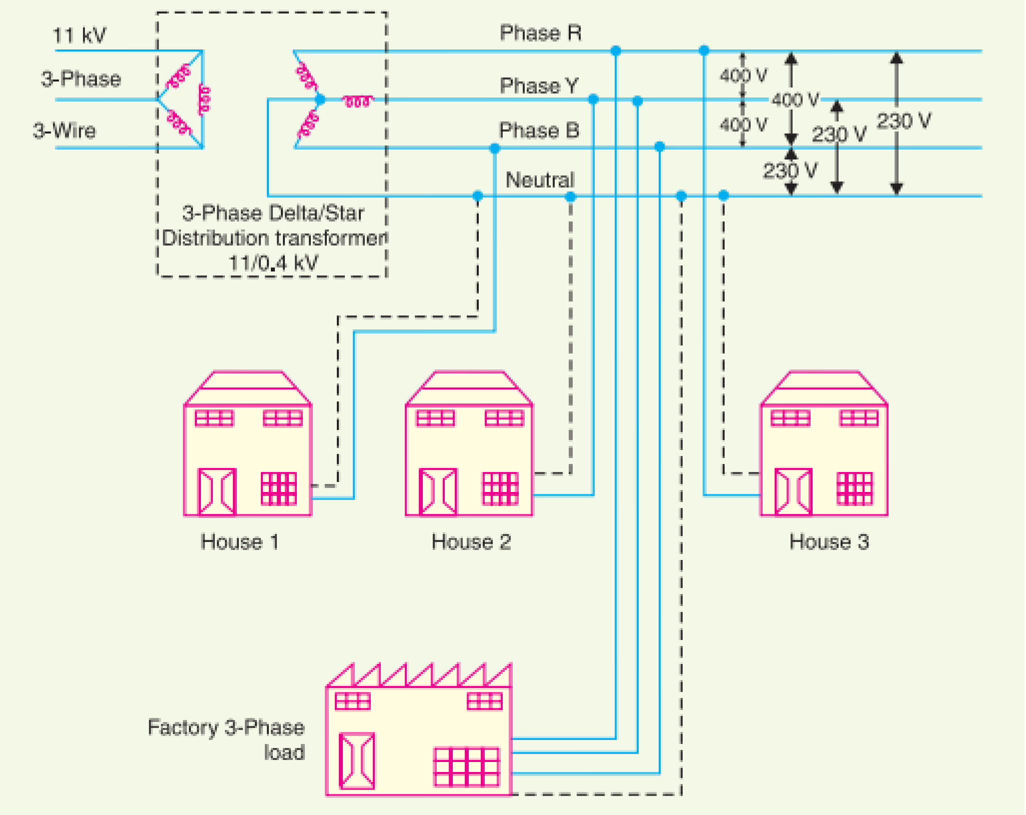


Fig. 12.3

12.4 D.C. Distribution

It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery (i.e., d.c. motors), for electrochemical work and for congested areas where storage battery reserves are necessary.

For this purpose, a.c. power is converted into d.c. power at the substation by using converting machinery e.g.,mercury arc rectifiers, rotary converters and motor generator sets. The d.c. supply from the substation may be obtained in the form of (i) 2-wire or (ii) 3-wire for distribution.(i) 2-wire d.c. system. As the name implies, this system of distribution consists of two wires.One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires as shown in Fig. 12.4. This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.

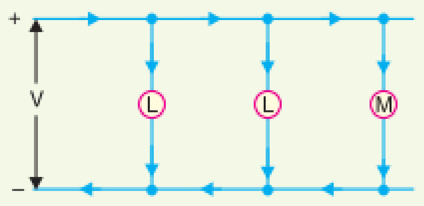


Fig. 12.4

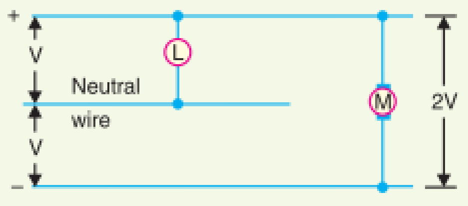


Fig. 12.5

(ii**) 3-wire d.c. system.** It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer and neutral wire as shown in Fig. 12.5. The principal advantage of this system is that it makes available two voltages at the consumer terminals viz., V between any outer and the neutral and 2V between the outers. Loads requiring high voltage (e.g., motors) are connected across the outers, whereas lamps and heating circuits requiring less voltage are connected between either outer and the neutral. The methods of obtaining 3-wire system are discussed in the following article.

12.5 Methods of Obtaining 3-wir Methods of Obtaining 3-wire D.C. System

There are several methods of obtaining 3-wire d.c. system. However, the most important ones are:

(i) **Two generator method**. In this method, two shunt wound d.c. generators G1 and G2 are connected in series and the neutral is obtained from the common point between generators as shown in Fig. 12.6 (i). Each generator supplies the load on its own side. Thus generator G1 supplies a load current of I1, whereas generator G2 supplies a load current of I2. The difference of load currents on the two sides, known as out of balance current (I1 − I2) flows through the neutral wire. The principal disadvantage of this method is that two separate generators are required.

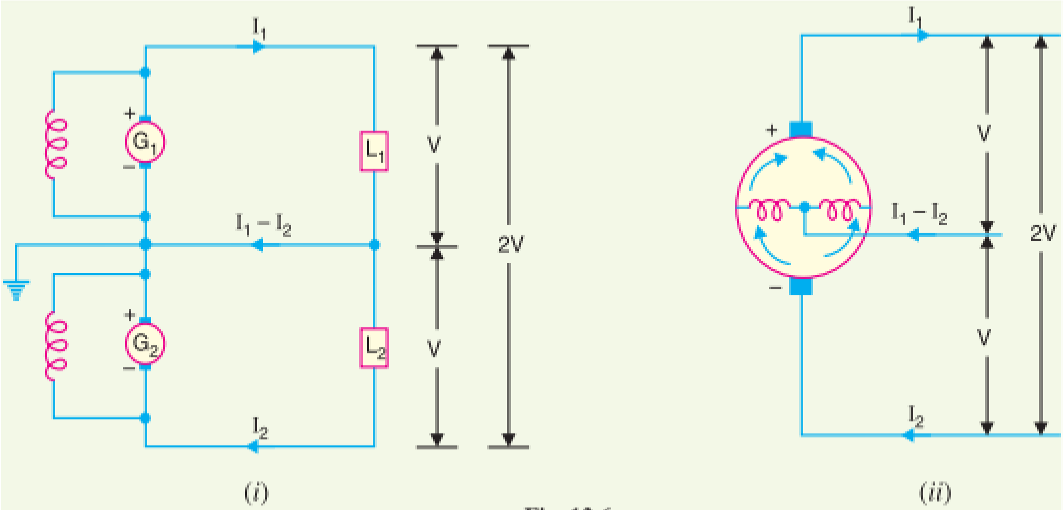


Fig. 12.6

(ii) **3-wire d.c. generator**. The above method is costly on account of the necessity of two generators. For this reason, 3-wire d.c. generator was developed as shown in Fig. 12.6 (ii). It consists of a standard 2-wire machine with one or two coils of high reactance and low resistance,

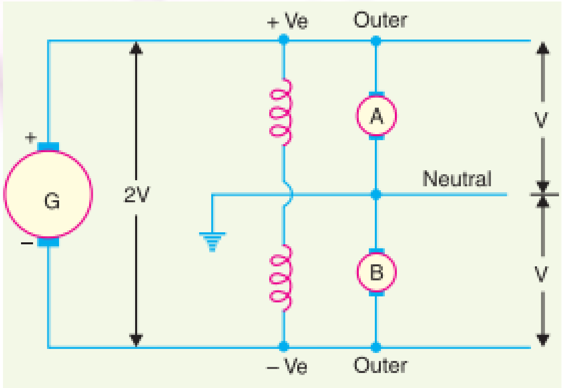


Fig. 12.7

connected permanently to diametrically opposite points of the armature winding. The neutral wire is obtained from the common point as shown.

(iii) **Balancer set**. The 3-wire system can be obtained from 2-wire d.c. system by the use of balancer set as shown in Fig. 12.7. G is the main 2-wire d.c. gen-erator and supplies power to the whole system. The balancer set consists of two identical d.c shunt machines A and B coupled mechanically with their armatures and field windings joined in series across the outers. The junction of their armatures is earthed and neutral wire is taken out from here. The balancer set has the additional advantage that it maintains the potential difference on two sides of neutral equal to each other.

12.6 Overhead Versus Under ersus Underground System

The distribution system can be overhead or underground. Overhead lines are generally mounted on wooden, concrete or steel poles which are arranged to carry distribution transformers in addition to the conductors. The underground system uses conduits, cables and manholes under the surface of streets and sidewalks. The choice between overhead and underground system depends upon a number of widely differing factors. Therefore, it is desirable to make a comparison between the two.

(i) **Public safety.** The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.

(ii) **Initial cost**. The underground system is more expensive due to the high cost of trenching,conduits, cables, manholes and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.

(iii) **Flexibility.** The overhead system is much more flexible than the underground system. In the latter case, manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers etc., can be easily shifted to meet the changes in load conditions.

(iv) **Faults**. The chances of faults in underground system are very rare as the cables are laid

underground and are generally provided with better insulation.

(v) **Appearance.** The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.

(vi) **Fault location and repairs**. In general, there are little chances of faults in an underground system. However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made.

(vii) Current carrying capacity and voltage drop. An overhead distribution conductor has a considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. On the other hand, underground cable conductor has much lower inductive reactance than that of an overhead conductor because of closer spacing of conductors.

(viii) **Useful life**. The useful life of underground system is much longer than that of an overhead system. An overhead system may have a useful life of 25 years, whereas an underground system may have a useful life of more than 50 years.

(ix) **Maintenance cost**. The maintenance cost of underground system is very low as compared with that of overhead system because of less chances of faults and service interruptions from wind, ice, lightning as well as from traffic hazards.

(x) **Interference with communication circuits**. An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable level. However, there is no such interference with the underground system.

13.1 Types of D.C. Distributors

The most general method of classifying d.c. distributors is the way they are fed by the feeders. On this basis, d.c. distributors are classified as:

(i) Distributor fed at one end

(ii) Distributor fed at both ends

(iii) Distributor fed at the centre

(iv) Ring distributor.

(i) **Distributor fed at one end**. In this

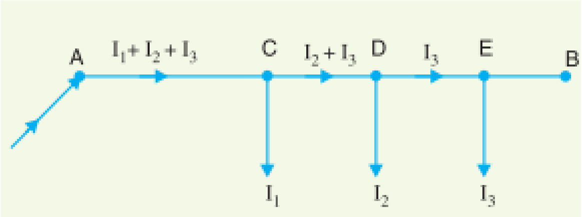


Fig. 13.1

type of feeding, the distributor is con-
nected to the supply at one end and

loads are taken at different points along the length of the distributor.

Fig. 13.1 shows the single line dia-gram of a d.c. distributor A B fed at the end A (also known as singly fed distributor) and loads I1, I2 and I3 tapped off at points C, D and E respectively.

The following points are worth noting in a singly fed distributor :

(a) The current in the various sections of the distributor away from feeding point goes on

decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.

(b) The voltage across the loads away from the feeding point goes on decreasing. Thus in Fig. 13.1, the minimum voltage occurs at the load point E.

(c) In case a fault occurs on any section of the distributor, the whole distributor will have to be disconnected from the supply mains. Therefore, continuity of supply is interrupted.

(ii) **Distributor fed at both ends**. In this type of feeding, the distributor is connected to the

supply mains at both ends and loads are tapped off at different points along the length of the distributor. The voltage at the feeding points may or may not be

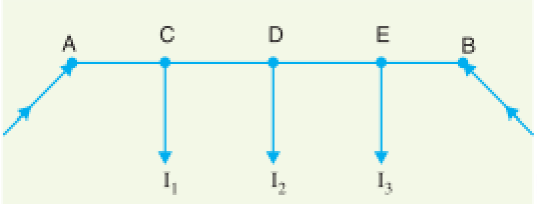


Fig. 13.2

equal. Fig. 13.2 shows a distributor A B fed at the ends A and B and loads of I1, I2 and I3 tapped off at points C, D and E respectively. Here, the load voltage goes on decreasing as we move away from one feeding point say A, reaches minimum value and then again starts rising and reaches maximum value when we reach the other feeding point

B. The minimum voltage occurs at some load point and is never fixed. It is shifted with the

variation of load on different sections of the distributor.

Advantages

(a) If a fault occurs on any feeding point of the distributor, the continuity of supply is main-

tained from the other feeding point.

(b) In case of fault on any section of the distributor, the continuity of supply is maintained from the other feeding point.

(c) The area of X-section required for a doubly fed distributor is much less than that of a singly fed distributor.

(iii) Distributor fed at the centre. In this type of feeding, the centre of the distributor is connected to the supply mains as shown in Fig. 13.3. It is equivalent to two singly fed distributors, each distributor having a common feeding point and length equal to half of the total length.

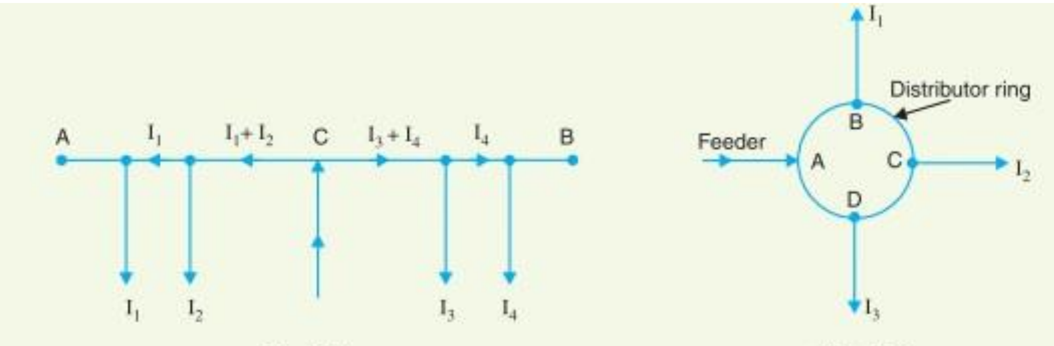


Fig. 13.3 Fig. 13.4

(iv) Ring mains. In this type, the distributor is in the form of a closed ring as shown in Fig.13.4. It is equivalent to a straight distributor fed at both ends with equal voltages, the two ends being brought together to form a closed ring. The distributor ring may be fed at one or more than one point.

13.3 D.C. Distributor Fed at one End —Concentrated Loading

Fig. 13.5 shows the single line diagram of a 2-wire d.c. distributor A B fed at one end A and having concentrated loads I1, I2, I3 and I4 tapped off at points C, D, E and F respectively.

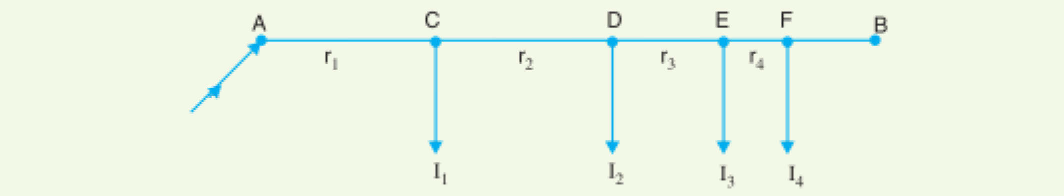


Fig. 13.5

Let r_1, r_2, r_3 and r_4 be the resistances of both wires (go and return) of the sections AC, CD, DE and EF of the distributor respectively.

Current fed from point $A = I_1 + I_2 + I_3 + I_4$

Current in section $AC = I_1 + I_2 + I_3 + I_4$

Current in section $CD = I_2 + I_3 + I_4$

Current in section $DE = I_3 + I_4$

Current in section $EF = I_4$

Voltage drop in section $AC = r_1 (I_1 + I_2 + I_3 + I_4)$

Voltage drop in section $CD = r_2 (I_2 + I_3 + I_4)$

Voltage drop in section $DE = r_3 (I_3 + I_4)$

Voltage drop in section $EF = r_4 I_4$

$\therefore$ Total voltage drop in the distributor

$$= r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$$

It is easy to see that the minimum potential will occur at point F which is farthest from the feeding point A.

13.4 Unifor Uniformly Loaded Distributor Fed at One End

Fig 13.11 shows the single line diagram of a 2-wire d.c. distributor A B fed at one end A and loaded uniformly with i amperes per metre length. It means that at every 1 m length of the distributor, the load tapped is i amperes. Let l metres be the length of the distributor and r ohm be the resistance per metre run.

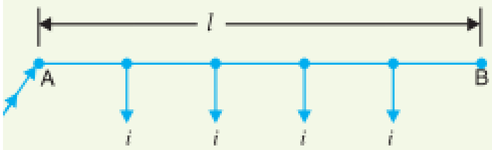


Fig. 13.11

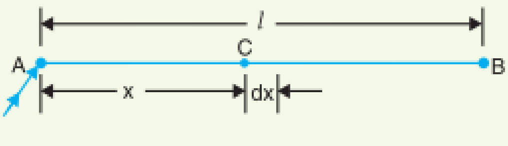


Fig. 13.12

Consider a point C on the distributor at a distance x metres from the feeding point A as shown in Fig. 13.12. Then current at point C is

= i l − i x amperes = i (l − x) amperes

Now, consider a small length dx near point C. Its resistance is $r\,dx$ and the voltage drop over length dx is

$$dv = i\,(l - x)\,r\,dx = i\,r\,(l - x)\,dx$$

Total voltage drop in the distributor upto point C is

$$v = \int_0^x i\,r\,(l - x)\,dx = i\,r\left(l\,x - \frac{x^2}{2}\right)$$

The voltage drop upto point B (*i.e.* over the whole distributor) can be obtained by putting $x = l$ in the above expression.

$\therefore$ Voltage drop over the distributor AB

$$= i\,r\left(l \times l - \frac{l^2}{2}\right)$$

$$= \frac{1}{2}\,i\,r\,l^2 = \frac{1}{2}\,(i\,l)\,(r\,l)$$

$$= \frac{1}{2}\,I\,R$$

where $i\,l = I$, the total current entering at point A

$r\,l = R$, the total resistance of the distributor

Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.