UNIT-I

Thermal power station – Selection of site, general layout of a thermal power plant showing paths of coal, steam, water, air, ash and flue gasses, ash handling system, brief description of major components.

Nuclear power stations – Selection of site, nuclear fission, nuclear fuels, nuclear chain reaction, general layout of a of nuclear power plant, brief description of major components, radiation hazards and shielding, nuclear waste disposal.

Factors to be consider for site selection for Thermal Power Stations

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

1) **Availability 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 place where coal is not available, then care should be taken that adequate facilities exist for the transportation of coal.

2) **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.

3) **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.

4) **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.

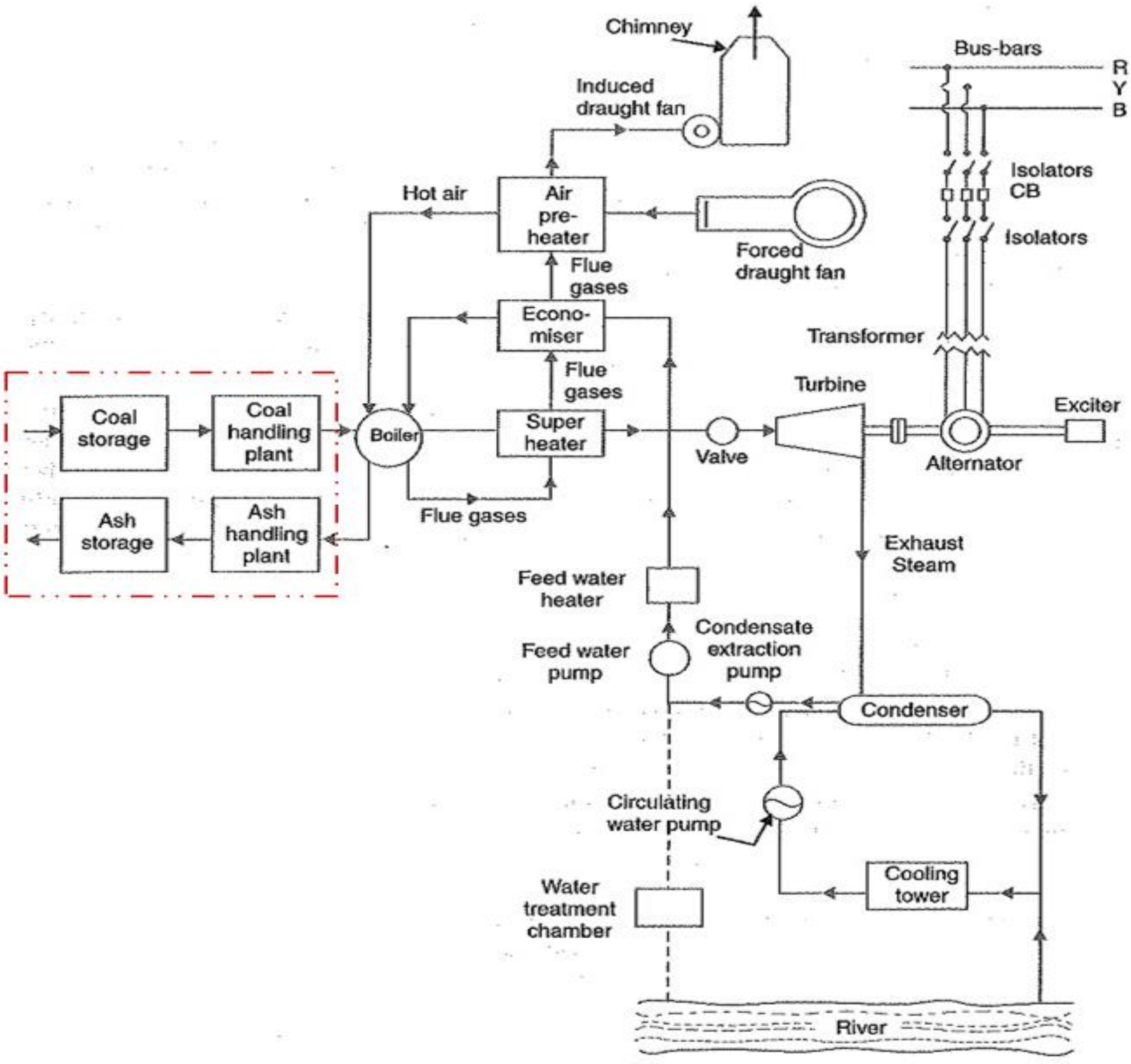
5) **Nearness to load centre's**: In order to reduce the transmission cost, the plant should be located near the centre of the load.

6) **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

7) **Ash disposal facility**: As thermal power plant produces huge amount of ash (Bottom ash and fly ash), therefore it requires an appropriate place to dispose it.

8) Geological Stability:

Ensure the site is geologically stable to prevent issues like landslides or ground subsidence that could impact plant structures.



Schematic arrangement of Steam Power Station

The whole arrangement can be divided into the following stages

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. From the coal storage plant, coal is delivered to the coal handling plant where it is pulverized (*i.e*., crushed into small pieces) in order to increase its surface exposure, thus send to combustion without using large quantity of excess air. The pulverized coal is send into 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.

2) Steam generating plant. The steam generating plant consists of a boiler for the production of steam and other auxiliary equipment for the utilization of heat in flue gases.

***i) Boiler*.** The heat of combustion of coal in the boiler is utilized to convert water into steam at high temperature and pressure. The flue gases from the boiler make their journey through superheater, economizer, 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 by the flue gases on their way to chimney. Superheating increases the overall efficiency. The superheated steam from the superheater is fed to steam turbine through the main valve.

iii) Economizer. An economizer is essentially a feed water heater and which takes heat from the flue gases for this purpose. The feed water is fed to the economizer before supplying to the boiler. The economizer 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 taking 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 main benefits of preheating the air are : increased thermal efficiency and increased steam capacity per square meter 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 economizer. This helps in raising the overall efficiency 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. The 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.

Coal handling

A large quantity of coal is required as a fuel in furnace of boiler for combustion to produce heat energy for production of steam for this purpose coal handling unit is used

Pulverization: The process of making coal into fine powder is known as pulverization

Advantages:

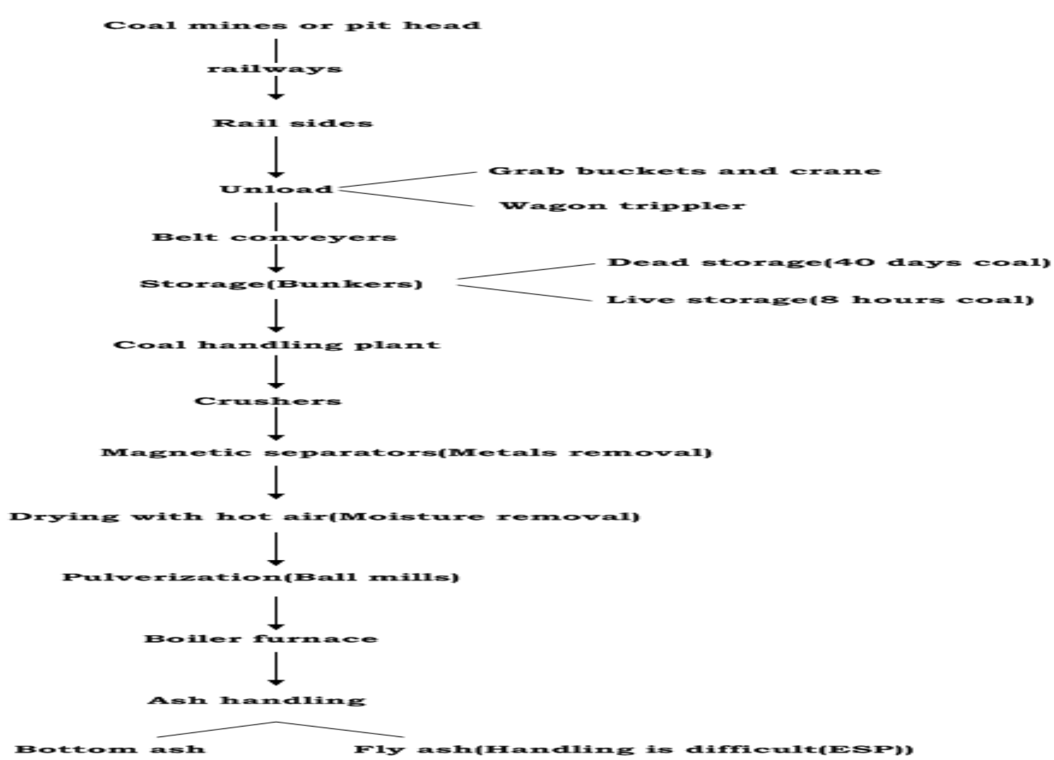
1) More heating effect

2) Less fuel consumption

Disadvantages:

1) Cost is high

2) More fly ash is produced (More pollution)



Steps/Activities for coal handling:

1. Coal delivery
2. Coal unloading
3. Coal storage:- a) outdoor storage (dead storage) b) Indoor storage (live storage)
4. In the plant coal is crushed into small pieces with the help of crusher and breaker. The coal is crushed to 2.5 cm. or less.
5. Than it is cleaned by passing forced air to remove the dust contain.
6. Than it is dewatered (remove of moisture) with the help of dryer. The moisture content must be less than 2% after drying operation.
7. Then it is passed through magnetic separator to separate the iron particles mixed in it.
8. Then coal is passed to pulverizing mill.
9. Pulverized Coal weighing
10. Pulverized coal is than transfer into the boiler furnace.

Ash handling plant

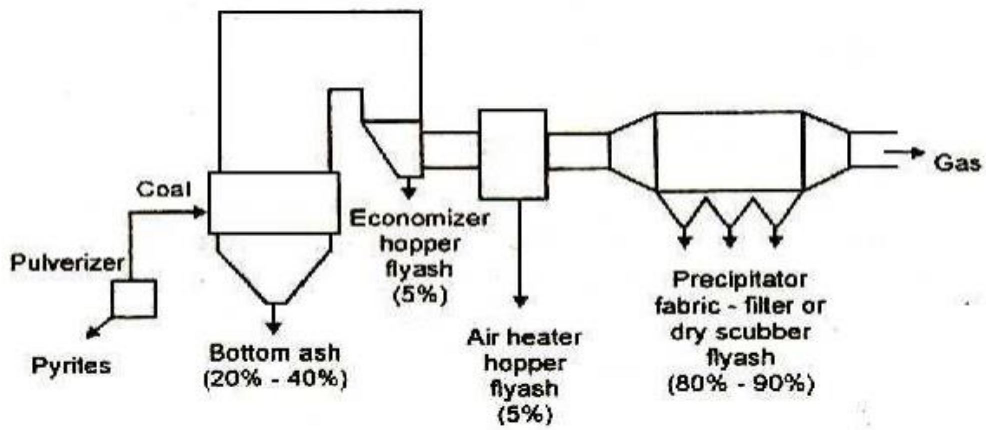


Figure: Layout of ash collection and transportation

In Thermal Power Plant's coal is generally used as fuel and hence the ash is produced as the byproduct of Combustion. Ash generated in power plant is about 30-40% of total coal consumption and hence the system is required to handle ash for its proper utilization or disposal.

Fly Ash (Around 80% is the value of fly ash generated)

Bottom ash (Bottom ash is 20% of the ash generated in coal based power stations)

Fly Ash

Ash generated in the Electrostatic Precipitator which got carried out with the flue gas is generally called Fly ash. It also consists of Air preheater ash & Economizer ash.

Bottom ash

Ash generated below furnace of the steam generator is called the bottom ash.

The operation of ash handling plants is

- Removal of ash from the furnace ash hoppers
- Transfer of the ash to a fill or storage
- Disposal of stored ash

The ash may be disposed in the following way…….

- Waste land site may be reserved for the disposal of ash.
- Building contractor may utilize it to fill the low lying area or manufacturing of bricks.
- Deep ponds may be made and ash can be dumped into these ponds to fill them completely

The modern ash handling system usually used in large steam power plants are …….

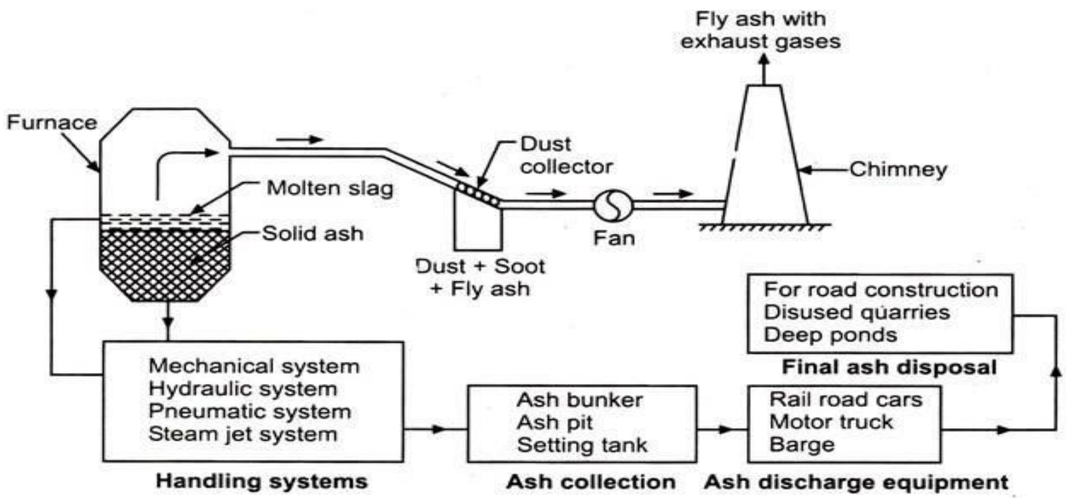


Fig. 12.21. General layout of ash handling and dust collection system.

1) Belt conveyor system

In this system the ash is made to flow through a water seal over the belt conveyor in order to cool it down and then carried out to a dumping site over the belt. The life of belt is 5 years. It is used in small power plants

2) Pneumatic system

In this system **air** is employed as a medium to driving the ash through a pipe over along distance. This system can handle 5-30 tonnes of ash per hour. This is used for disposal of fly ash

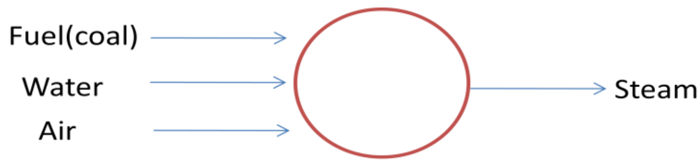
3) Hydraulic system

In this system a stream of **water** carries ash along with it in a closed channel and disposed it off to the proper site. It is of two types- high pressure system and low pressure system.

4) Steam jet system

This system employs jets of high pressure blowing in the direction of ash travel through a conveying pipe in which ash from the boiler ash hopper is fed. It is employed in small and medium size plant. Steam consumption is 110 kg per tonne of material conveyed.

BOILERS:



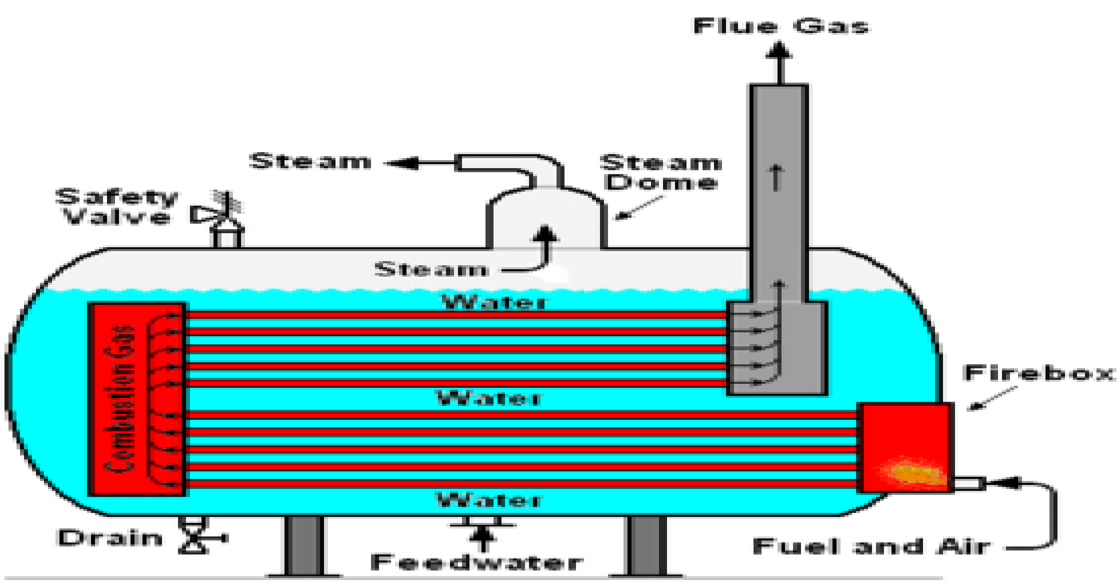
A boiler (or steam generator) is a closed vessel in which water, under pressure, is converted into steam. The heat is transferred from the boiler by all three modes of heat transfer i.e. conduction, convection and radiation. Major types of boilers are: (i) fire tube boiler and (ii) water tube boiler

i)Fire tube boiler:

In fire tube boiler, the fuel is burnt inside a furnace. The hot gases produced in the furnace then passes through the fire tubes. The fire tubes are immersed in water inside the main vessel of the boiler. As the hot gases are passed through these tubes, the heat energy of the gasses is transferred to the water surrounds them. As a result steam is generated in the water and naturally comes up and is stored upon the water in the same vessel of fire tube boiler.

As the steam and water is stored is the same vessel, it is quite difficult to produce very high pressure steam. General maximum capacity of this type of boiler is 17.5 kg/cm^2 and with a capacity of 9 Metric Ton of steam per hour. Depending on whether the tube is vertical or horizontal the fire tube boiler is divided into two types

i) Vertical tube boiler ii) Horizontal tube boiler



Advantages of Fire Tube Boiler

- Simple, compact and rugged in construction.
- Fluctuation of steam demand can be met easily.
- Cheaper than water tube boiler.

Disadvantages of Fire Tube Boiler

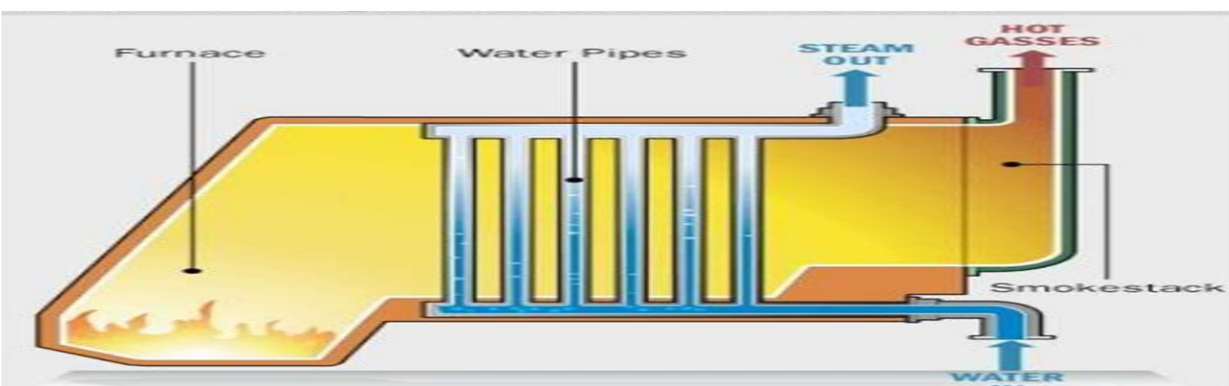
- Due to large water in the boiler, required steam pressure rising time is quite high.
- Output steam pressure cannot be very high since the water and steam are kept in same vessel.
- The steam received from fire tube boiler is not very dry.
- In a fire tube boiler, the steam drum is always under pressure, so there may be a chance of huge explosion which resulting to severe accident.

(ii) Water tube boiler:

In this boiler, the water flows inside the tubes and hot gases flow outside the tube. Water tube boiler are classified as

i) Vertical tube boiler ii) Horizontal tube boiler and iii) Inclined tube boiler

The circulation of water in the boiler is may be natural or forced. Temperature in boiler is $300\,^{0}$ for normal thermal power plants and 600^{0}-700^{0} for super critical thermal power plants



Advantages of Water Tube Boiler

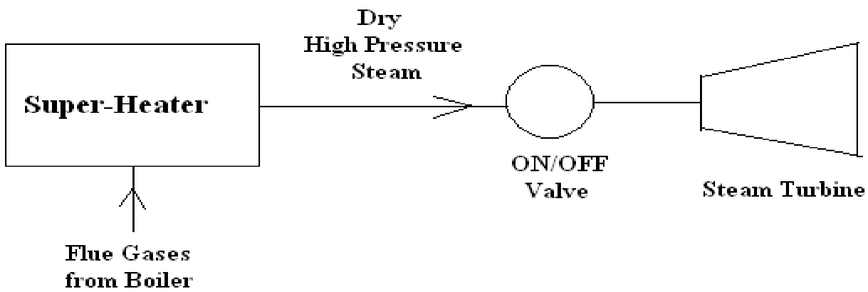
- Larger heating surface can be achieved by using more numbers of water tubes.
- Due to convectional flow, movement of water is much faster than that of fire tube boiler, hence rate of heat transfer is high which results into higher efficiency.
- Very high pressure in order of 140 kg/cm^2 can be obtained smoothly.

➤ Compact size

Disadvantages:

Costly

Super heaters



Without superheated: The steam which comes directly from boiler is having some traces of water. So weight is more and velocity is less. If this steam is directly pass through the turbine, gives less output and also metal blades gets corroded and life will be reduced.

The steam produced in the boiler is wet and is passed through a super heater where it is dried and superheated by the flue gases on their way to chimney. A Super heater consists of a group of tubes made of special alloy steels such as **chromium-molybdenum**. These tubes are heated by the heat of flue gases during their journey from the boiler furnace to the chimney. The steam produced in the boiler is passed through the super heater where it is superheated by the heat of flue gases from boiler.

Advantages:

1) The overall efficiency is increased.

2) Less steam consumption

3) Corrosion of blades is avoided

The super heater mainly classified into two types:

a. Radiant super heater: The Radiant super heater is placed in the boiler furnace between the water walls & receives heat from the fuel burning through radiation process.

b. Convection super heater: The convection super heater is placed in the boiler tube bank & receives heat from flue gases entirely through convection process.

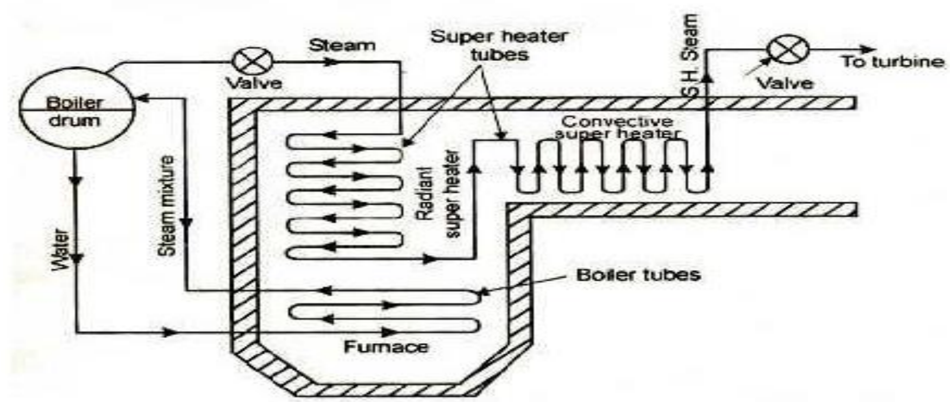
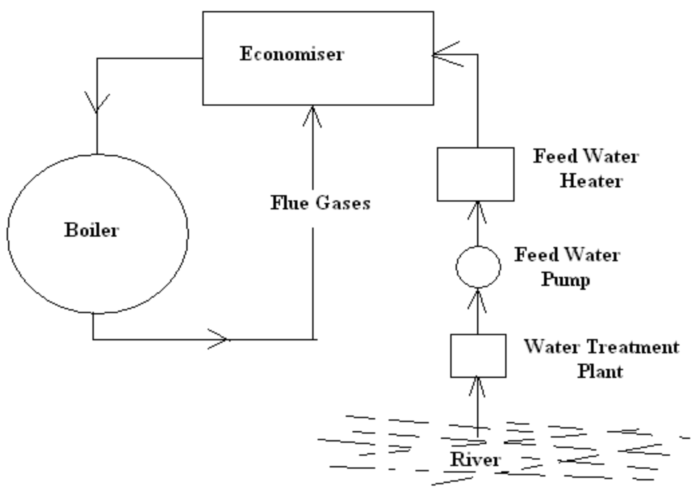
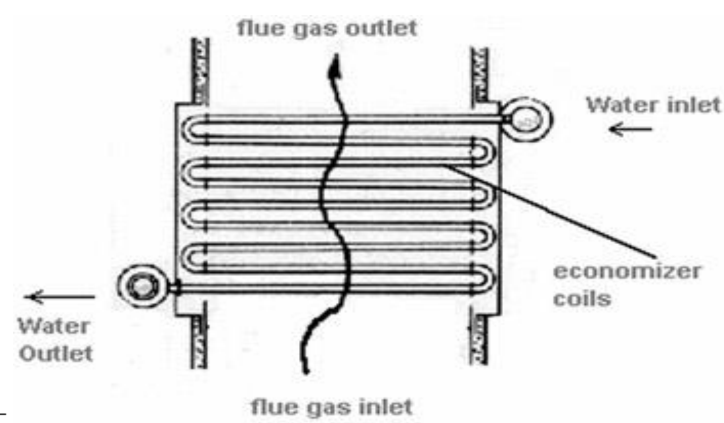


Fig Super heater (radiant and convective)

Economizer:





Boilers are provided with economizer and air pre-heaters to recover heat from the flue gases. An economizer is essentially a feed water heater and derives heat from the flue gases for this purpose. The feed water is fed to the economizer before supplying to the boiler. The economizer extracts a part of heat of flue gases to increase the feed water temperature by convection process. This results in increasing boiler efficiency and saving fuels. An **increase of about 20% in boiler efficiency** is achieved by providing **both economizer and air pre-heaters**. Economizer alone gives only 8% efficiency increase.

- It is costly
- It is used in power plants where steam pressure is greater than 70kg/cm^2

Draught System

- The combustion in the boiler requires supply of sufficient quality of air and removal of Exhaust gases
- The Circulation of air is caused by difference of pressure is known as draught. Thus draught is the differential in pressure between the two points.

A draught tube may be

1. Natural Draught
2. Mechanical Draught

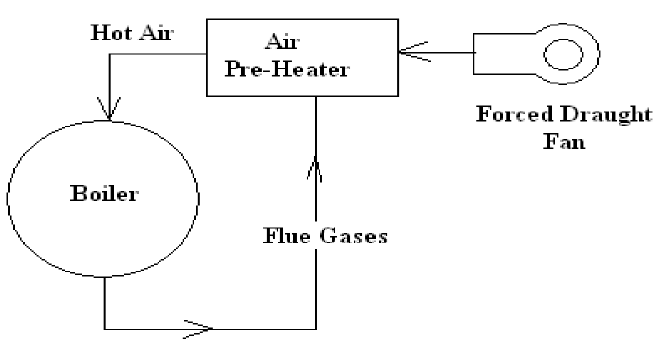
1. Natural Draught

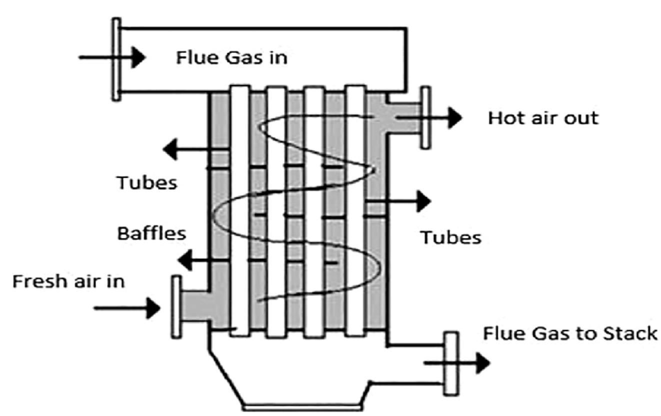
- A natural Draught is provided by the chimney or stack.
- Natural draught has its limitation. Modern plants has high rate of heat transfer and Draught losses are very high. In view of this Natural draught is used only for small boilers.

2. Mechanical Draught

- Modern large size plants use very large size of boilers of capacity above 1000,000 kg per Hour. Such boiler needs tremendous volume of air (around 200000 m3) per minute. A chimney provides this. Therefore mechanical draught is used.
- In a mechanical draught the system the movement air is due to the action of fan. A mechanical Draught consists of forced Draught or induced draught or both.
- In **Forced draught**(Positive draught) system the fan is installed near the boiler .the fan force the air through the furnace , economizer, air preheater and chimney. The pressure of air, throughout the system, is above atmospheric and air is forced to flow through the system(F.D fan)
- In an **Induced draught** (Negative draught) system fan is installed near the base of the chimney .The burnt gases are sucked out from the boiler , thus reducing the pressure inside the boiler to less than atmosphere. This induces fresh air to enter the furnace.(I.D fan)
- A mechanical Draught need additional capital investment and maintenance .But it required for proper operation of modern power plant. In super thermal power plant, each boiler may used two forced fans and two induced fan.

Air preheater





An air pre-heater 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 pre-heater before supplying to the boiler furnace. The air pre-heater extracts heat from flue gases and increases the temperature of air used for coal combustion.

The main benefits of preheating the air are:

- Increased thermal efficiency of the boiler (increases 12%) and
- Increased steam capacity per square meter of boiler surface

<u>Electrostatic Precipitator</u> (Flue gas = Fly ash + CO_2 + CO + Sulpher content (SO_x))

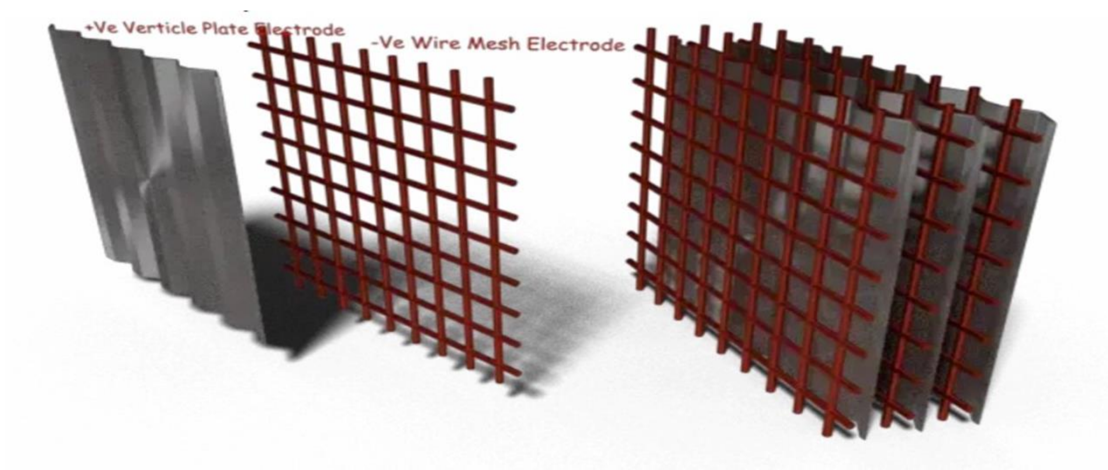
The flue gases produced due to combustion of solid pulverized fuel in the furnace contain plenty of dust particles. When a chimney releases these flue gases in the atmosphere without filtering these dust particles, the atmosphere may get polluted. Hence, these dust particles need to be removed from the flue gases as much as possible before these flue gases get discharged to the atmosphere. By removing the dust particles from flue gases, we can control the air pollution. Electrostatic precipitator does this work for a furnace system. We install this device in the way of flue gases from the furnace to the chimney so that the device can filter the flue gases before they enter the chimney.

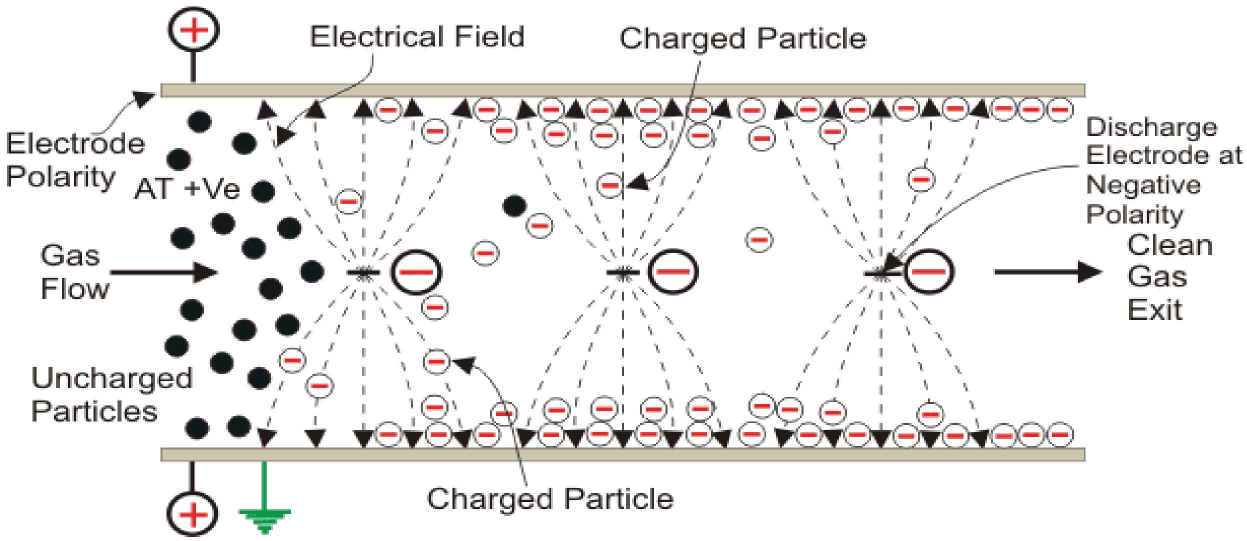
The basic idea of an ESP:

- Charging
- Collecting
- Removing

Working Principle of Electrostatic Precipitator

It has two sets of electrodes one is positive, and another is negative. The negative electrodes are in the form of rod or wire mesh. Positive electrodes are in the form of plates. The negative electrodes are connected to a negative terminal of high voltage DC source, and positive plates are connected to the positive terminal of the DC source (30kV). The distance between each negative electrode and positive plate and the DC voltage applied across them are so adjusted that the voltage gradient between each negative electrode and adjacent positive plate becomes quite high to ionize the medium between these.





The air molecules in the field between the electrodes become ionized, and hence there will be **plenty of free electrons and ions in the space**. The entire system is enclosed by a metallic container on which one side is provided with an inlet of the flue gases, and the opposite side is provided with the outlet of the filtered gases. As soon as the flue gases enter into the electrostatic precipitator, **dust particles in the gases collide with the free electrons available in the medium between the electrodes and the free electrons will be attached to the dust particles. As a result, the dust particles become negatively charged. Then these negatively charged particles will be attracted due to electrostatic force of the positive plates.** Consequently, the charged dust particles move towards the positive plates and deposited on positive plates. Here, the extra electron from the dust particles will be removed on positive plates, and the particles then fall due to gravitational force. We call the positive plates as collecting plates. The flue gases after travelling through the electrostatic precipitator become almost free from ash particles and ultimately get discharged to the atmosphere through the chimney. **Hoppers** are fitted below the electrostatic precipitator chamber for collecting dust particles. Water spray may be used on the top to accelerate the removal of the dust from the collecting plates.

Turbines

Based on operating principle the steam turbine is classified as two types

1. Impulse turbine
2. Reaction turbine

Impulse Turbine

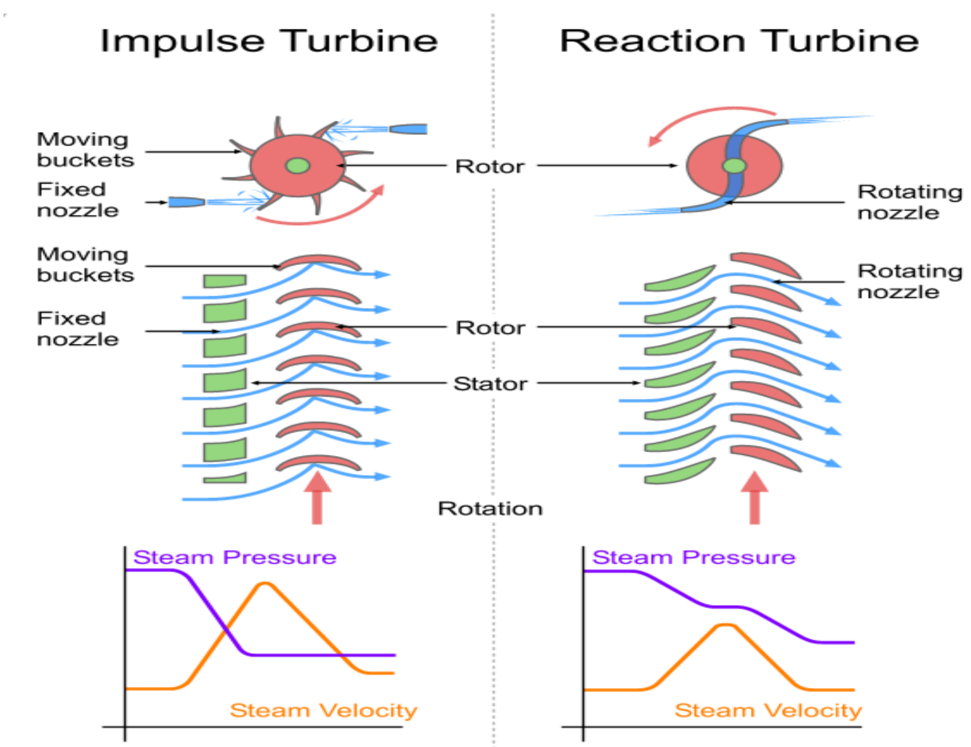
In principle, the impulse steam turbine consists of a casing containing **stationary steam nozzles** and a rotor with **moving or rotating buckets**. When the steam passes through the stationary nozzles and is directed at high velocity against the rotor buckets. The rotor buckets starts to rotate at high speed.

Events take place in the nozzle

- The steam pressure decreases.
- The enthalpy of the steam decreases.
- The steam velocity increases

Impulse Turbine Working:

In the impulse turbine pressure drops and the velocity increases as the steam passes through the nozzles. When the steam passes through the moving blades the velocity drops but the pressure remains the same. The fact that the **pressure does not drop across the moving blades** is the distinguishing feature of the impulse turbine. The pressure at the inlet of the moving blades is same as the pressure at the outlet of moving blades.



Reaction Turbine Working:

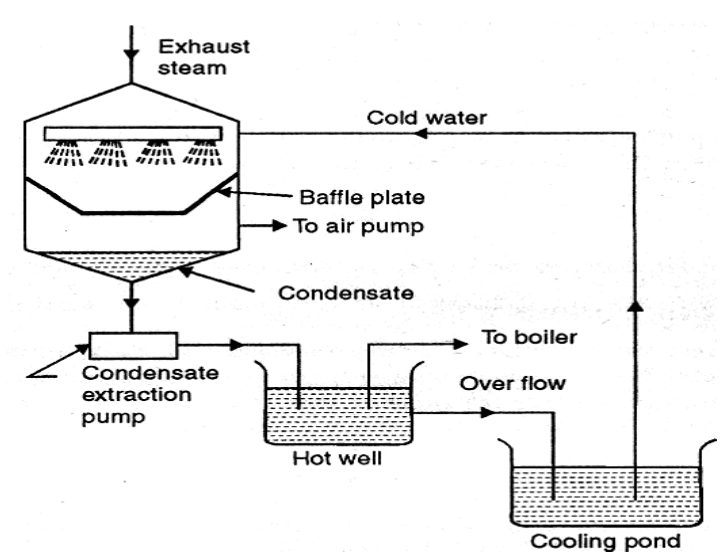
A reaction turbine has rows of fixed blades alternating with rows of moving blades. The steam expands first in the stationary or fixed blades where it gains some velocity as it drops in pressure. Then enters the moving blades where its direction of flow is changed thus producing an impulse force on the moving blades. In addition, however, the steam upon passing through the moving blades, again expands and further drops in pressure giving a reaction force to the blades. This sequence is repeated as the steam passes through additional rows of fixed and moving blades. Note that the steam pressure drops across both the fixed and the moving blades while the absolute velocity rises in the fixed blades and drops in the moving blades. The distinguishing feature of the reaction turbine is the fact that the **pressure drops across the moving blades**.

Condensers

In thermal power plants, the purpose of a condenser is to condense the exhaust steam from a steam turbine and to provide vacuum so that the expansion of steam in the turbine takes place to a very low pressure. This improves power plant efficiency, and also to convert the turbine exhaust steam into pure water (referred to as steam condensate) so that it may be reused in the steam generator or boiler as boiler feed water. This will increase the amount of work from the turbine (Electrical output). There are two types of condensers

i) Jet condenser and ii) Surface condenser

i) Jet condenser: is a mixing type condenser where exhaust steam is condensed mix up with cooling water. In a jet condenser, high power is required for condensation. Design of jet condenser is simple. But after condensation, cooling water cannot be used to boiler as it is not free from salt and other impurities. So good quality water is used in jet condenser for condensation.



As you see in the diagram, exhaust steam, and cooling water enter the top of the parallel jet condenser and mix up together in the condenser shell. This mixture is removed from the bottom of the condenser. Actually, in the condenser, exhausted steam is condensed after mix up with water. The condensate cooling water and air flow's direction is downwards of the condenser and it is separated by two individual pumps which are air pump and condensate pump. A single way air pump is sometimes used for this separation. At the time of separation, a vacuum is created in the condenser chamber. Condensate extraction pump delivers the condensate to the hot well where an overflow pipe is connected to the cooling water tank in which surplus water of hot well is stored.

Advantages of Jet Condenser:-

. Design of the jet condenser is simple.

Less floor area is required as compared to the other condenser.

Jet condensers are cheap.

Disadvantages of Jet Condenser:-

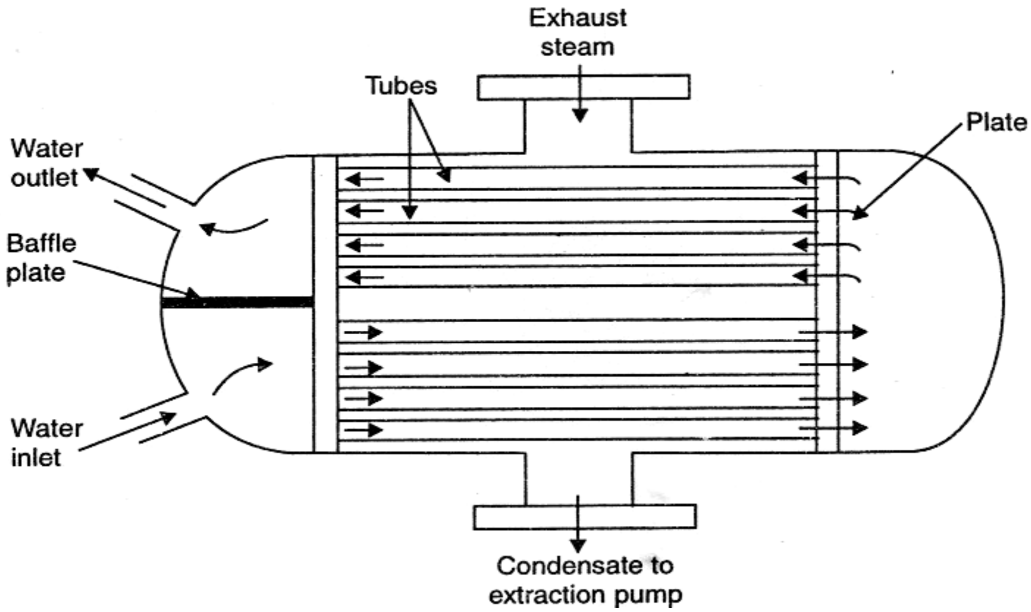
Vacuum efficiency is low.

Pure condensation is not possible. So it cannot be reused.

ii) <u>Surface condenser</u>

Working principle of surface condenser is completely different from jet condenser. In surface condenser exhaust steam and cooling water does not mix up with each other. So condensate remains pure and can be reused in the boiler. Surface condenser is widely used where limited quantity of water is available like ships, land installations etc. To use such a condenser, limited quantity of water feed to the boiler again and again.

The cooling water enters the shell at the lower half section and after traveling through the upper half section comes out through the outlet. The exhaust steam entering shell from the top flows down over the tubes and gets condensed and is finally removed by an extraction pump.



Advantages Of Surface Condenser:-

1. Pure condensation is possible by the surface condenser.
2. Low quality cooling water can be used for condensation.
3. High vacuum efficiency.

Disadvantages Of Surface Condenser:-

1. Large floor area is required.
2. Large amount of water is required.
3. Construction is not simple.
4. It's need to be operate by the skilled labour.
5. Maintenance cost is high.

Feed Water Heaters

- Feed Water heating improve overall efficiency.
- The dissolved oxygen which would otherwise cause boiler corrosion are removed in the feed water heater.
- Thermal stresses due to cold water entering the boiler drum are avoided.
- Quantity of steam produced by the boiler is increased.
- Some other impurities carried by steam and condensate, due to corrosion in boiler and condenser, are removed outside the boiler.

Deaerator

A deaerator is a device that is widely used for the removal of oxygen and other dissolved gases from the feed water to steam-generating boilers. In particular, dissolved oxygen in boiler feedwaters will cause serious corrosion damage in steam systems by attaching to the walls of metal piping and other metallic equipment and forming oxides (rust).

Problems caused by deposits

- Boiler deposits reduce overall operating efficiency resulting in higher fuel consumption.
- **Corrosion**: corrosion is usually due to reaction of the metal with oxygen
- **Corrosion Fatigue: c**racking in boiler metal may occur due to cyclic stresses created by rapid heating and cooling.
- **Caustic embrittlement**: is a more serious type of boiler metal failure showing up as continuous intergranular cracks. This type of cracking occurs when the metal is stressed, water contains caustic with a trace of silica
- **Concentration of boiler solids :** Chelate residuals in excess of 20 ppm as $CaCO_3$ or improperly applied in chelate treatment may produce boiler system corrosion.

The following water treatment should be done before sending the water to the boiler

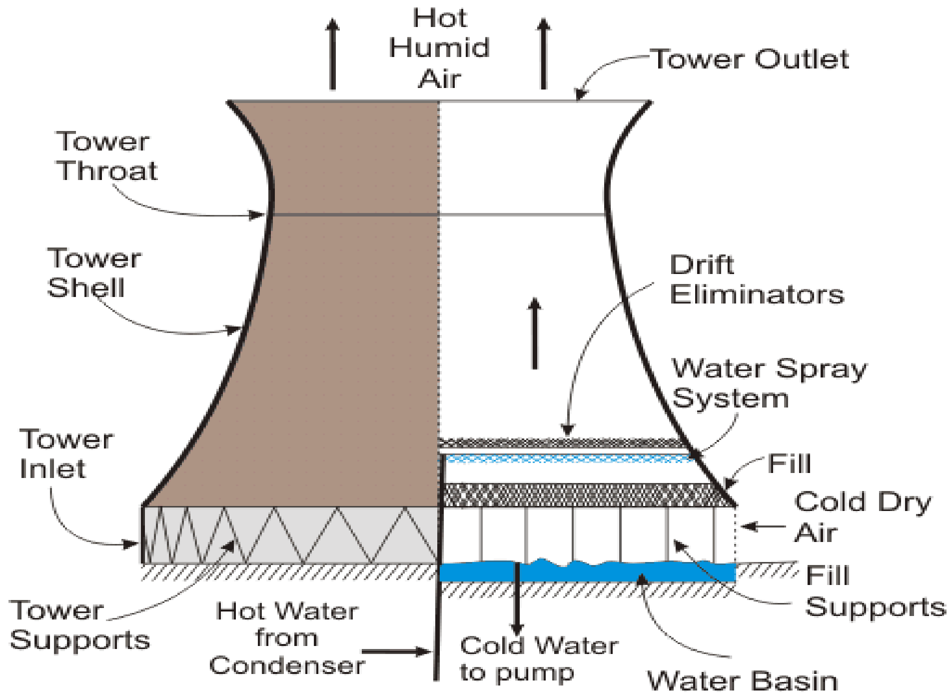
1. Filtration of solid suspended impurities & particles from water
2. Removing dissolved oxygen from the boiler feedwater by deareation
3. Maintaining alkaline conditions in the boiler water

Cooling towers

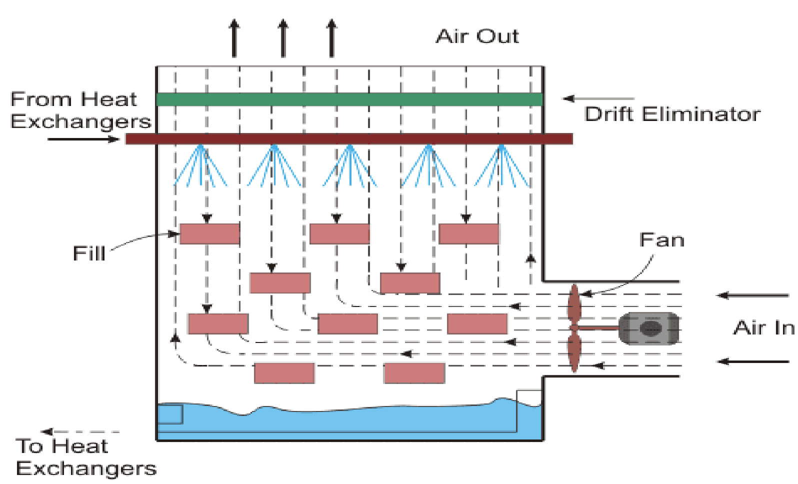
Purpose of a cooling tower is to reduce the temperature of circulating hot water to re-use this water again in the boiler. This hot water is coming from the condenser. Hot water is coming at the inlet of the tower and pumped up to the header. The header contains nozzles and sprinklers which is used to spray water, and it will increase the surface area of water.

Cooling towers can be classified into two types

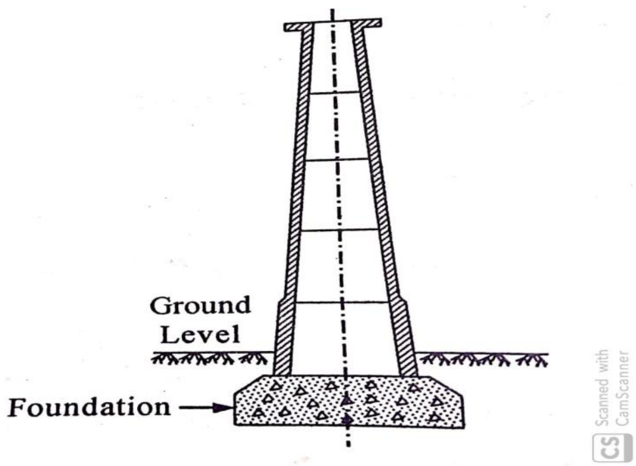
1) Natural Draught Cooling Tower: In this type of cooling tower, fan is not used for circulating air .Because of pressure difference between heated air and surrounding air, air enters in to the cooling tower. It requires large hyperbolic tower, so capital cost is high but operating cost is low because of absence of electrical fan. There are two types of natural draught cooling tower, rectangular timber tower and reinforced concrete hyperbolic tower.



2) Mechanical or Forced Draught Cooling Tower: In this type of cooling tower, fan is used to circulate the air. When power plant runs on peak load, it requires a very high rate of cooling water. To rotate fan, it uses motor with speed around 1000 rpm. Working principle is same as **natural draught cooling tower**, only difference is that here fan is mounted on the cooling tower. If fan is mounted on the top of the tower is called as **induced draught** cooling tower which is most popular for very large capacity installation and requires large capacity of fan. So, **forced draught cooling tower** contains horizontal shaft for the fan and it is placed at bottom of the tower and induced draught cooling tower contains vertical shaft and it is placed at top of the cooling tower.



Chimney



The function of the stack or chimney is to disperse the hot gases, emissions and particulates that leave the boiler at a great height. At these heights the pollutants disperse in a very large area so that ground level concentrations are within permissible levels which are not harmful.

Flue gas stacks higher than 250 meters are common nowadays for larger power plants. Many factors like land type, dispersion pattern, adjacent tall structures, and population density determine the height of the stack.

There is a natural phenomena associated with the chimney or the flue gas stack. This is called the 'chimney or the stack effect'.

chimney or stack effect

The gas temperature inside the flue gas stack is around 140° C. The outside ambient air temperature is around say 30° C. Consider this as two air columns connect at the bottom. The high density and heavier cold air will be always pushing the low density and lighter hot gases up. This causes the natural flow of gases up the flue gas stack. This pressure difference that pushes the hot gas up the flue gas stack or the chimney is the 'chimney or stack effect'.

The net area of chimney depends on the following factors

1) volume of gas to be discharged when the boiler operate at maximum rating

2) Draught to be produced

Chimneys are provided with a lightning conductor, air craft warning lights and various means of access and inspection.

Advantages and Disadvantages of Thermal Power Plant

Advantages

- Initial cost is cheaper in comparison with other plants.
- Less space is required in comparison with hydro power plant.
- Coal is cheaper in comparison with diesel or nuclear fuel.
- Production cost is cheaper than diesel power plant.
- Can be installed anywhere as compared with hydro plant when plenty of water shall be available.
- Can be located near load centre which is not possible in hydro plants.
- Steam engines/turbines can be overloaded upto 125% full load capacity.
- Load demand can be met (changing demand) easily.

Disadvantages

- Operating cost and maintenance cost is very high as compared with hydro plants.
- Coal handling, ash disposal is difficult.
- Pollution due to heat, smoke, ash.
- Water-requirement to produce steam is much more.
- Erection time is much more.
- Initiation time is also more (plant to put for production).
- Overall efficiency is less.

Nuclear Power Station

Nuclear power plants is a type of thermal power plant that use the process of nuclear fission in order to generate electricity. They do this by using nuclear reactors in combination with the Rankine cycle, where the heat generated by the reactor converts water into steam, which spins a turbine and a generator

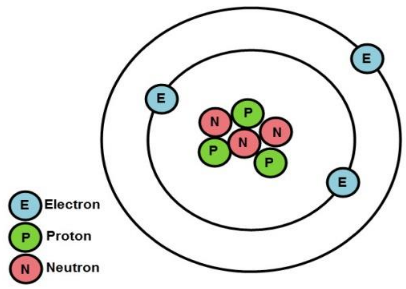
Factors to be consider for Site Selection for Nuclear Power Plant generator.

- Site selection for a nuclear power plant is a critical process that requires careful consideration of various factors to ensure the safety, efficiency, and long-term viability of the facility.
- **Geological Stability:** The site should be located in an area that is geologically stable and not prone to seismic activity, landslides, or other geological hazards. Geological studies should be conducted to assess the suitability of the site.
- **Proximity to Population Centers:** The site should be located at a safe distance from densely populated areas to minimize potential risks in the event of an accident.
- **Proximity to Water Source:** Sufficient and reliable water sources are essential for operational needs. The plant should be located near a large and dependable water supply, such as a river or a lake.
- **Transportation Infrastructure:** The site should have good transportation infrastructure, including access to major roads, railways, and ports, to facilitate the transportation of construction materials, fuel, and equipment.
- **Elevation and Flooding Risk:** The site should be located at an adequate elevation to minimize the risk of flooding, particularly in coastal areas or near large rivers.
- **Climate and Weather Conditions:** The site should be exceptional for extreme weather conditions, such as hurricanes, tornadoes, or extreme temperatures, without compromising safety.
- **Availability of Skilled Workforce:** The availability of a skilled workforce in the region is crucial for the successful operation and maintenance of the nuclear power plant.
- **Environmental Impact:** A comprehensive environmental impact assessment should be conducted to identify and mitigate potential adverse effects on the environment and local communities.
- **Public Acceptance:** The local community's acceptance and support for the construction and operation of the nuclear power plant are crucial factors in the site selection process.

Nuclear Power Plants in India

- Kudankulam Nuclear Power Plant. It is located in Kudankulam, Tamil Nadu,2000 MW
- Tarapur Atomic Power Station (TAPS). It is located in Tarapur, Maharashtra,1400MW
- Rajasthan Atomic Power Station (RAPS). It is located in Rawatbhata, Rajasthan,900MW
- The largest nuclear power plant in the world in terms of installed capacity is the Kashiwazaki-Kariwa Nuclear Power Plant in Japan,7965MW

Atom : The smallest particle of a chemical element that can exist. The nucleus is the central part of the structure of the atom and consists of protons and neutrons .



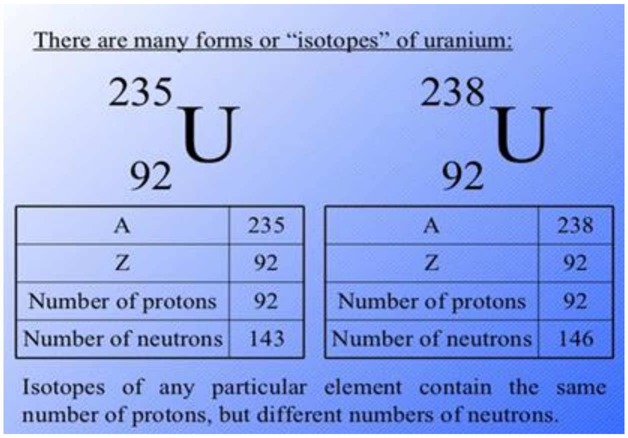
The negatively charged electrons are the lightest subatomic particles. The protons, positively charged, weigh about 1,836 times more than electrons. Neutrons, the only ones that have no electrical charge, weigh approximately the same as protons.

Atomic number (Z): Indicates the number of protons present in an atom, which is equal to that of electrons. All atoms with the same number of protons belong to the same element and have the same chemical properties. For example all the atoms with one proton will be of hydrogen (Z = 1), all the atoms with two protons will be of helium (Z = 2).

Mass number (A): It is the sum of protons and neutrons contained in the element. Isotopes are two atoms with the same number of protons, but different numbers of neutrons. The isotopes of the same element have chemical and physical properties very similar to each other.

Mass number (A) = Atomic number (Z) + Number of neutrons in nucleus.

Isotopes are defined as the atoms consist of same number of protons but different number of neutrons in the nucleus is known as isotopes. It happens that the atoms of an element do not all have the same number of neutrons in the nucleus. This is called an isotope.



Isotopes can be found with excess or lack of neutrons. These atoms can exist for some time, but are unstable. Unstable atoms are radioactive: their nuclei change or decay by emitting radiation. The **enrichment** of uranium is, precisely, the conversion of an isotope of uranium into another isotope of more unstable uranium.

Nuclear fuel is a substance that is used in nuclear power stations to produce heat to power Turbines. Heat is created when nuclear fuel undergoes Nuclear Fission. Most nuclear fuels contain heavy fissile elements that are capable of nuclear fission, such as uranium-235 or plutonium-239. In Nuclear Power Plant for the Production of heat energy Uranium, thorium & plutonium fuels are used.

Nuclear Materials

- **Uranium-235(U235)**
- **Plutonium-239 (Pu-239)**
- **Uranium-238 (U-238)**
- **Thorium-232 (Th-232)**
- **Plutonium-241 (Pu-241)**
- **Neptunium-239 (Np-239)**
- **Americium-241 (Am-241)**
- **Cesium-137 (Cs-137)**

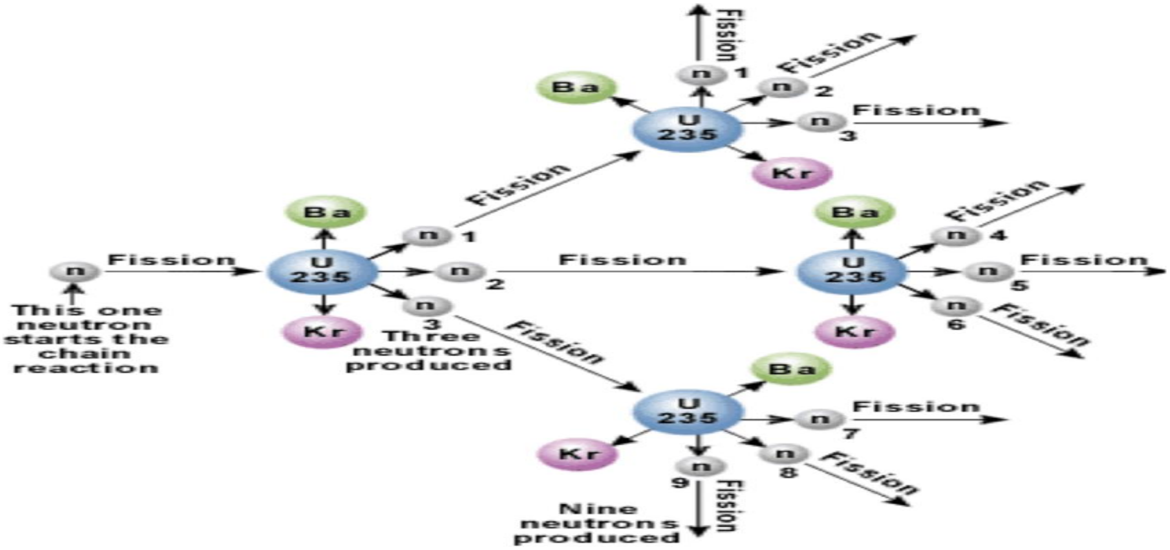
Nuclear Fission and Chain Reaction

Nuclear fission is a process in which the nucleus of an atom splits into two smaller nuclei, releasing a large amount of energy in the form of heat and additional neutron. In other words, fission the process in which a nucleus is divided into two or more fragments, neutrons and energy are released.

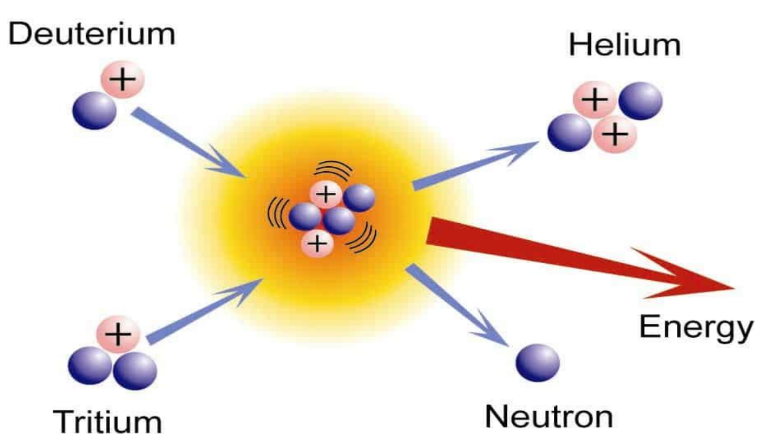
Each fission of uranium-235 releases additional neutrons, as shown in this figure below.

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \longrightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3^{1}_{0}\mathrm{n}$$

If one fission reaction produces three neutrons, these three neutrons can cause three additional fissions. If those three fissions release nine neutrons, those nine neutrons split other nuclei, and could then produce nine more fissions and release 27 neutrons, and so on, resulting in a nuclear chain reaction as shown in this figure. This situation in the figure above is one type of nuclear chain reaction; a continuous series of nuclear fission reactions, a self-sustaining process in which one reaction initiates the next.



NUCLEAR FUSION



Nuclear fusion**,** in which two light nuclei combine to produce a heavier, more stable nucleus, is the opposite of nuclear fission

For example, in a typical fusion reaction, two deuterium atoms combine to produce helium-3, a process known as deuterium–deuterium fusion (D–D fusion):

$$2\,{}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

In another reaction, a deuterium atom and a tritium atom fuse to produce helium-4 a process known as deuterium–tritium fusion (D–T fusion):

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

Nuclear fission	**Nuclear fusion**
1) Fission is the splitting of a large atom into two or more smaller ones.	1) Fusion is the fusing of two or more lighter atoms into a larger one.
2) Fission reaction does not normally occur in nature.	2) Fusion occurs in stars, such as the sun.
3) Fission produces many highly radioactive particles.	3) Few radioactive particles are produced by fusion reaction, but if a fission "trigger" is used, radioactive particles will result from that.
4) Critical mass of the substance and high-speed neutrons are required.	4) High density, high temperature environment is required.
5) Takes little energy to split two atoms in a fission reaction.	5) Extremely high energy is required to bring two or more protons close enough that nuclear forces overcome their electrostatic repulsion.
6) The energy released by fission is a million times greater than that released in chemical reactions, but lower than the energy released by nuclear fusion.	6) The energy released by fusion is three to four times greater than the energy released by fission.

7) One class of nuclear weapon is a fission bomb, also known as an atomic bomb or atom bomb.	7) One class of nuclear weapon is the hydrogen bomb, which uses a fission reaction to "trigger" a fusion reaction.
8) Fission is used in nuclear power plants.	8) Fusion is an experimental technology for producing power.
9) Uranium is the primary fuel used in power plants.	9) Hydrogen isotopes (Deuterium,Tritium) are the primary fuel used in experimental fusion power plants.

Difference between Nuclear fission and Nuclear fusion

Schematic Arrangement of Nuclear Power Station

The whole arrangement can be divided into the following main stages:

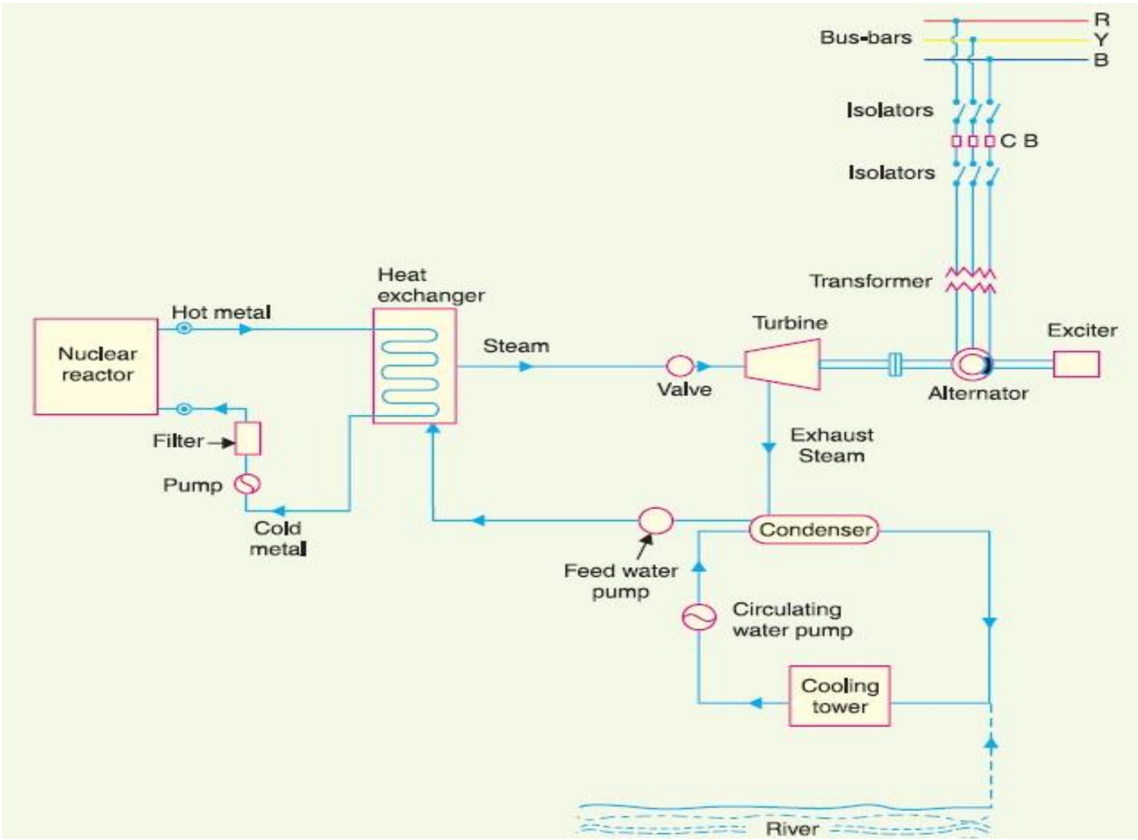
(*i*) Nuclear reactor **(*ii*)** Heat exchanger **(*iii*)** Steam turbine **(*iv*)** Alternator.

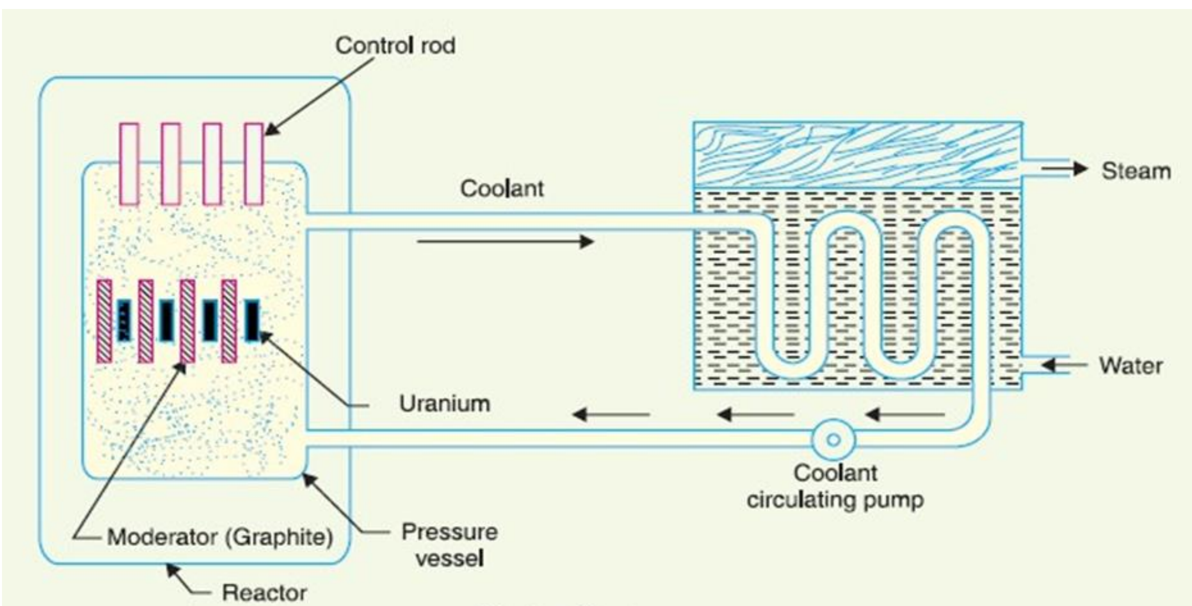
(i) **Nuclear reactor.** It is an apparatus in which nuclear fuel (U-235) is subjected to nuclear fission. It controls the *chain reaction* that starts once the fission is done. If the chain reaction is not controlled, the result will be an explosion due to the fast increase in the energy released. A nuclear reactor is a cylindrical stout pressure vessel and houses fuel rods of Uranium, moderator and control rods. The fuel rods constitute the fission material and release huge amount of energy when bombarded with slow moving neutrons. The moderator consists of graphite rods which enclose the fuel rods. The moderator slows down the neutrons before they bombard the fuel rods. The control rods are of cadmium and are inserted into the reactor. Cadmium is strong neutron absorber and thus regulates the supply of neutrons for fission. When the control rods are pushed in deep enough, they absorb most of fission neutrons and hence few are available for chain reaction which, therefore, stops. However, as they are being withdrawn, more and more of these fission neutrons cause fission and hence the *intensity* of chain reaction (or heat produced) is increased. Therefore, by pulling out the control rods, power of the nuclear reactor is increased, whereas by pushing them in, it is reduced. In actual practice, the lowering or raising of control rods is accomplished automatically according to the requirement of load. The heat produced in the reactor is removed by the coolant, generally a sodium metal. The coolant carries the heat to the heat exchanger.

(ii) **Heat exchanger.** The coolant gives up heat to the heat exchanger which is utilized in raising the steam. After giving up heat, the coolant is again fed to the reactor.

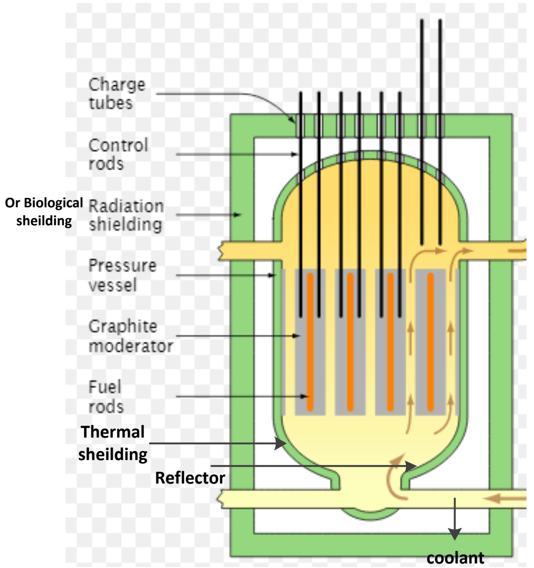
(iii) **Steam turbine.** The steam produced in the heat exchanger is led to the steam turbine through a valve. After doing a useful work in the turbine, the steam is exhausted to condenser. The condenser condenses the steam which is fed to the heat exchanger through feed water pump.

(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.





Nuclear Reactor



Nuclear Reactor

1. Reactor Core
2. Moderator
3. Control Rods
4. Fuel Rods
5. Coolants
6. Reflector
7. Thermal Shielding
8. Reactor Vessel
9. Biological Shielding

Reactor Core : It contains the fuel rods which are made of Fissile materials.

Moderator: A moderator in a nuclear reactor is a material used to slow down fast-moving neutrons produced during nuclear fission reactions. The primary purpose of a moderator is to increase the probability of neutron interactions with fissile nuclei.The moderators used are **beryllium, graphite, heavy water and ordinary water.**

Properties of Moderator:

- Moderator should possess high thermal conductivity
- Mainly they are available in pure state only
- In solid moderators we observe high melting point and in liquid moderators we can observe low melting point
- It offers resistance to the corrosion.
- Under radiation and heat it should be stable
- Mainly it has to slow down the neutrons.

Control rods:

By using the control rods the rate of a chain reaction is regulated. The control rods are made up of **Cadmium, Boron** and are placed to absorb neutrons.

Properties of control rods:

- It should possess acceptable heat transfer properties.
- Under radiation and heat they are stable

- Control rods are corrosion resistance.
- For absorption they should have sufficient cross sectional area.
- Under all conditions they should be strong and be able to shut down the reactor suddenly.
-

Fuel rods: Uranium claded (surrounded by) with aluminium, Zirconium and stainless steel.

Reflectors : During the fission process the neutrons produced will be partly absorbed by the coolant, moderator, structural material, fuel rods. The unabsorbed neutrons try to leave the reactor core. The losses are decreased by surrounding the core reactor by a material which is known as reflector. By using the reflector the neutrons are sent back to the core. The riveted neutrons can cause the fission and it improves the reactor neutrons economy. In most of the cases the reflector are made up of Beryllium and Graphite.

Coolants: The heat released by fission in nuclear reactors must be captured and transferred for use in electricity generation. Reactors use coolants that remove heat from the core where the fuel is processed and carry it to steam generators. Air, Helium, Hydrogen, CO_2 , Light water, Heavy water, Liquid Sodium, Lithium and Potassium are used as coolants.

Thermal Shielding: Usually constructed with iron and helps in giving protection from α, β, γ radiation as well as neutron, and it prevents the reactor wall from getting heated. Coolant flows through the wall to take away heat.

Reactor Vessel : Reactor core, Reflector ,Thermal shielding are all enclosed in the main body of the reactor called as Reactor Vessel or Tank.

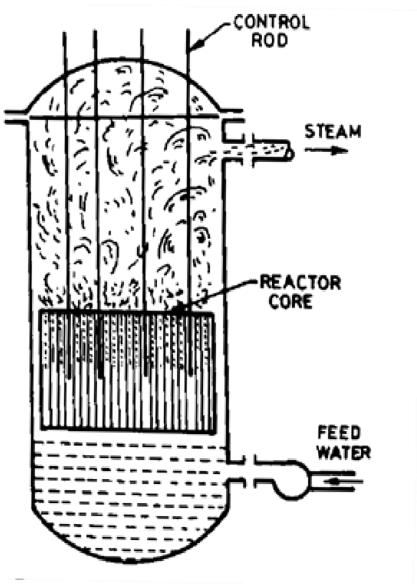
Biological Shielding: The whole reactor is enclosed in a biological shield to prevent escape of neutrons, radiation. Lead , iron and dense concrete shields are used

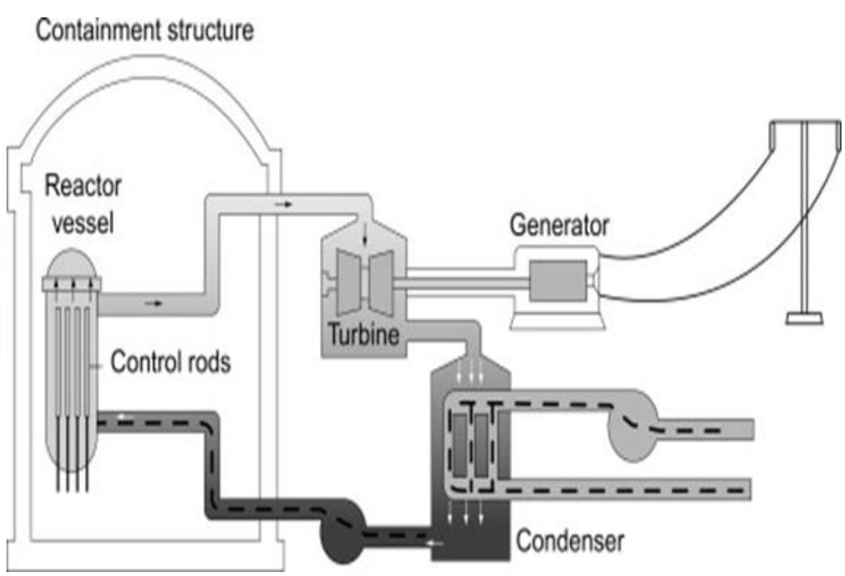
Types of Nuclear Reactors

- Boiling Water Reactor
- Pressurized Water Reactor (PWR)
- Fast Breeder Reactor

Boiling Water Reactor

This is the simplest type of Water Reactor. It has steel pressure vessel surrounded by a concrete shield. Fuel used is enriched Uranium Oxide. Ordinary water is used as both Moderator and Coolant. The steam is generated in the reactor itself. Feed water enters the reactor vessel at the bottom and takes the heat produced due to fission of fuel gets converted into steam. The steam leaving the reactor at the top and after passing through the condenser returns to the Reactor. Uranium Fuel elements are arranged in a particular lattice form inside the pressure vessel containing water.





Advantages :

This reactor is small in size, high steam pressure can be obtained, simple construction, elimination of Heat Exchanger resulting in reduction in cost and gain in thermal efficiency.

Disadvantages:

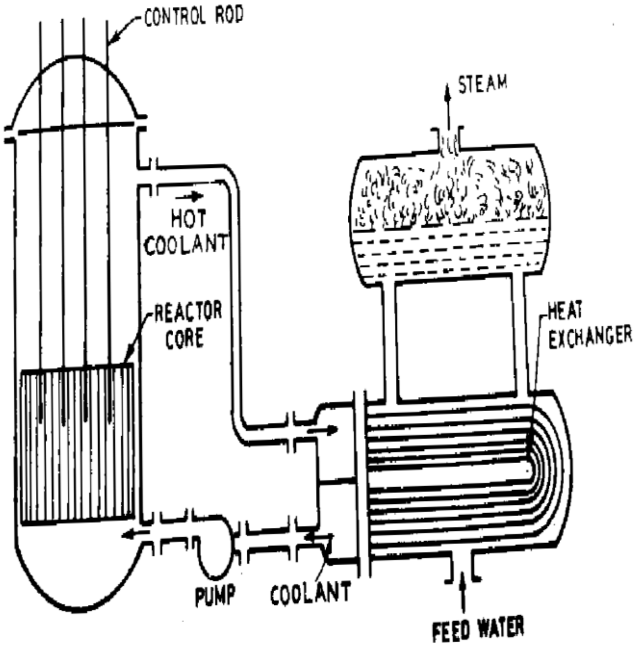
In view of direct cycle there is a danger of radioactive contamination of steam, wastage of steam during light loads, less thermal efficiency, cannot meet sudden load demands.

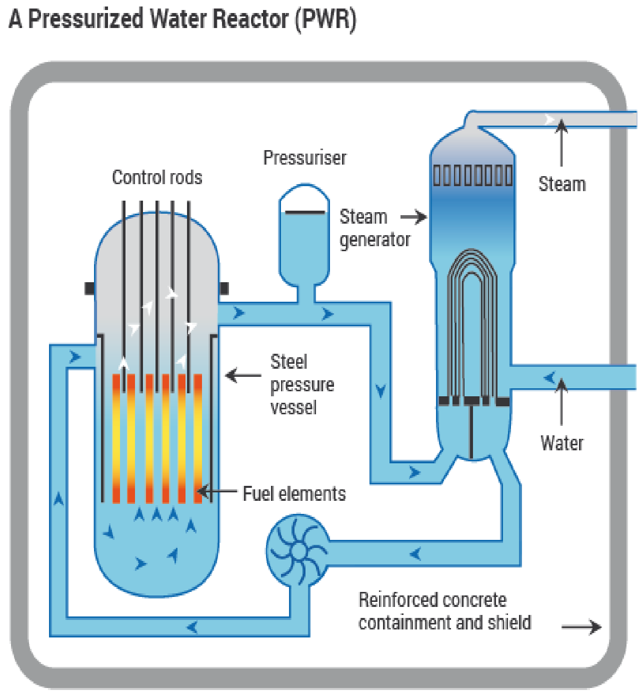
Pressurized Water Reactor (PWR)

It is a Thermal Reactor uses Uranium Oxide clad with Stainless steel or Zirconium alloy as fuel. Water under pressure is used as both Moderator and Coolant. The pressure vessel is made of steel. The pressure vessel and the heat exchanger are surrounded by a concrete shield. In this reactor bulk boiling water is prevented as the water is pressurized to about 150 atmosphere.

The hot water from the reactor flows to a heat exchanger where its heat is transferred to the feed water to generate the steam. The secondary cooling operates at a low pressure. The primary coolant then flows from the heat exchanger to the primary circulating pump which pumps it back to reactor. The steam is condensed in the Condenser and the condensate returns to heat exchanger forming a closed circuit.

Advantages





Advantages

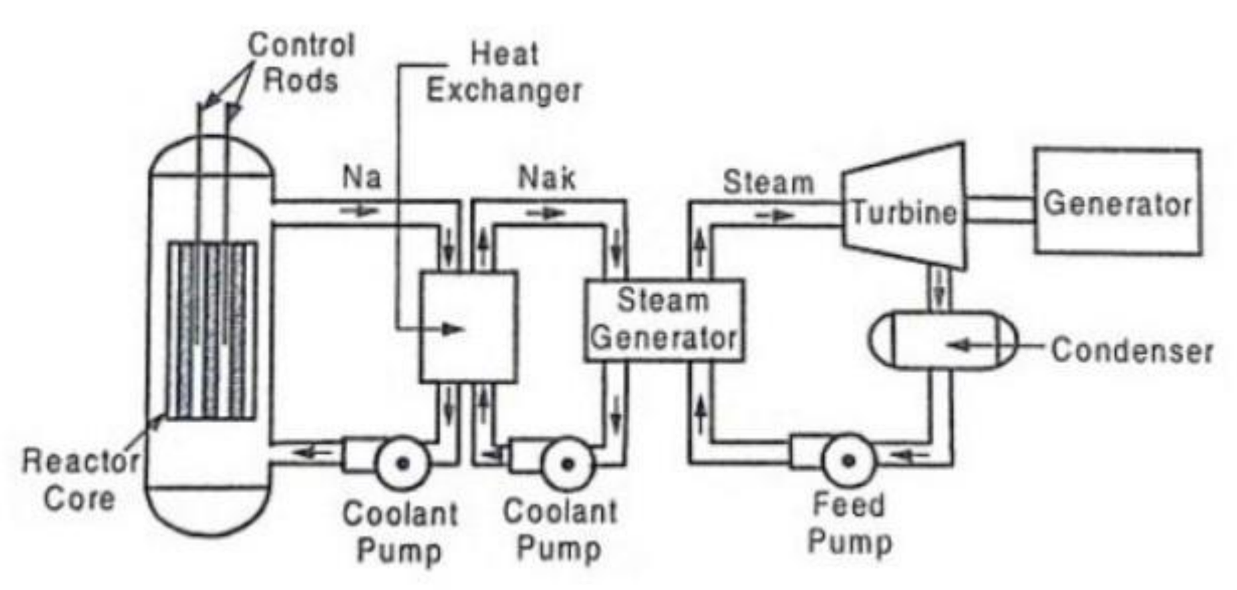
1. Compact in design
2. Possibility of breeding Plutonium
3. Isolation of radioactive materials from main steam system
4. Cheap light water can be used as a Coolant cum Moderator
5. High power density

Disadvantages

1. Requirement of a high pressure water system which requires a strong pressure vessel.
2. Formation of low temperature steam
3. Use of expensive cladding material for prevention of corrosion
4. High losses from heat exchanger
5. High power consumption by auxiliaries
6. Requirement of more elaborate safety devices

Fast Breeder Reactor

A Fast Breeder Reactor (FBR) is a unique type of nuclear reactor that produces electricity while also "breeding" more nuclear fuel. It uses fast-moving particles to create strong nuclear reactions involving uranium-238 (U-238) and transforms it into plutonium-239 (Pu-239), which is excellent for causing further reactions. This dual function makes FBRs efficient generators of power and creators of new fuel, contributing to sustainable energy production**.**



Two heat exchangers are used. The reactor core is cooled by liquid metal (Sodium or Pottasium .In the second heat exchanger the coolant is again liquid metal (Sodium or Pottasium) which transfers heat to feed water to generate steam. This prevents the possibility of a sodium-water reaction with the radioactive sodium. In fast breeder reactors neutron shielding is provided by Boron, Light water, Oil or Graphite. Gamma ray shielding is accomplished by Lead, concrete with added Magnetite or Barium etc.

Nuclear Waste Management

Nuclear waste disposal strategies vary based on the radioactivity levels and potential hazards associated with different categories of waste. Low-level waste (LLW), intermediate-level waste (ILW), and high-level waste (HLW). Each category requires different levels of containment, isolation, and long-term management due to their varying radioactivity and potential risks to human health and the environment.

Low-Level Nuclear Waste

- Low-level waste (LLW) in nuclear power plants refers to radioactive materials that have been used or come into contact with radiation during various plant operations. This waste category includes items such as contaminated protective clothing, gloves, tools, filters, resins, and other materials.

- LLW has relatively low levels of radioactivity compared to more hazardous waste types, and its radioactivity decreases over time.
- Low-level wastes make 90% of the total volume of waste arising from nuclear generation, but they contain just 1% of the radioactivity.

Intermediate-Level Nuclear Waste.

- Intermediate-level nuclear waste (ILW) refers to radioactive materials with higher levels of radioactivity than low-level waste (LLW) but lower than high-level waste (HLW).
- This waste category includes materials like reactor and coolant related equipment used during maintenance and operations.
- Intermediate-level wastes make 7% of the total volume of waste arising from nuclear generation, but they contain 4% of the radioactivity.

High Level Nuclear waste

- High-level radioactive wastes are the highly radioactive materials produced as a byproduct of the reactions that occur inside nuclear reactors.
- High-level wastes make just 3% of the total volume of waste arising from nuclear generation, but they contain 95% of the radioactivity, the radioactive nature is very high as compare to LLW and ILW.

Low and Intermediate Level Nuclear Waste Management.

- LLW is usually solidified, sealed in containers, and then buried in special disposal sites called near-surface repositories. These sites are designed to keep the waste safely isolated from people and the environment.
- ILW waste is typically encased in concrete or metal containers to prevent the release of radiation and these can be store it special facilities or dispose of it in deep underground repositories like engineering landfills.

High Level Nuclear Waste Management System

This is the most dangerous type of nuclear waste. It's mainly the used fuel from reactors. It's extremely radioactive and generates a lot of heat. To dispose of HLW, some countries plan to put it deep underground in a place called a geological repository. This is like burying it really deep in stable rock formations, so it's isolated and won't harm people or the environment. Deep geological repository is a type of long-term storage that isolates waste in geological structures that are expected to be stable for more number of years, with a number of natural and engineered barriers.

Advantages of Nuclear Power Plant

- Low Greenhouse Gas Emissions: Nuclear power plants produce minimal greenhouse gas emissions during operation, helping to mitigate climate change.
- High Energy Density: Nuclear fuel contains a large amount of energy in a small volume, providing a steady and reliable source of power.
- Base Load Power: Nuclear power plants can provide a consistent and reliable source of electricity, suitable for meeting the base load demand.
- Fuel Availability: Uranium, the primary fuel for nuclear reactors, is relatively abundant, and technology exists to reprocess and recycle of used fuel, extending its availability.
- Reduced Dependence on Fossil Fuels: Nuclear power reduces the reliance on fossil fuels like coal, oil, and natural gas, which are finite and contribute to air pollution.
- Economic Benefits: Nuclear power plants create jobs in construction, operation, and maintenance, contributing to local economies.
- Energy Security: Nuclear power can enhance a country's energy security by diversifying its energy sources and reducing dependence on imported fuels.
- Low Land Footprint: Nuclear power plants require less land compared to other power plants.

Disadvantages of Nuclear Power Plant

- Radioactive Waste: Nuclear reactors generate radioactive waste that requires careful handling, storage, and disposal, posing long-term environmental and health risks.
- Nuclear Accidents: Nuclear accidents involve unplanned events in nuclear facilities that release dangerous radioactive materials. They can harm human health, damage the environment, and lead to evacuations.
- High Initial Costs: The construction of nuclear power plants involves significant upfront costs, including safety measures and specialized infrastructure.
- Limited Fuel Supply: While uranium is available, high-quality reserves are finite, and accessing uranium can involve geopolitical challenges.
- Nuclear Proliferation: The spread of nuclear technology increases the risk of weapons proliferation, as it can provide a cover for the development of nuclear weapons.

- Long Licensing and Approval Process: Regulatory hurdles and public concerns can lead to lengthy approval processes for building new nuclear power plants.
- Safety Concerns: The potential for human error, natural disasters or technical failures can compromise the safety of nuclear power plants and their surrounding areas.
-

SUBSTATIONS

Classification of substations:

Air Insulated Substations - Indoor & Outdoor substations, Substations layouts of 33/11 kV showing the location of all the substation equipment. Bus bar arrangements in the Sub-Stations: Simple arrangements like single bus bar, sectionalized single bus bar, double bus bar with one and two circuit breakers, main and transfer bus bar system with relevant diagrams.

Gas Insulated Substations (GIS) – Advantages of Gas insulated substations, different types of gas insulated substations, single line diagram of gas insulated substations, constructional aspects of GIS, Installation and maintenance of GIS, Comparison of Air insulated substations and Gas insulated substations.

University question paper questions

1 a) Explain about the 33/11 kV substation showing the location of all the substation equipment's.
b) Explain the merits and demerits of indoor substations over outdoor substations.

2 a) Explain single bus bar arrangement and list its merits and demerits
b) List the different types of GIS and explain any one type with a neat lay out diagram

3 a) Explain the factors to be considered when selecting a location for a substation.
b) What are the factors to be considered for selecting bus bars?

4 a) Explain about main and transfer bus bar system with relevant diagrams.
b) List the advantages and disadvantages of Gas-insulated substation.

5 a) Explain with a neat layout diagram of a double bus bar with Bypass isolator arrangement
b) Draw the single line diagram of GIS? Explain.

6 a) Explain the double bus bar with one and two circuit breakers with neat diagrams.
b) Explain the installation and maintenance of gas insulated substation

7 a) Explain about the 33/11 kV substation showing the location of all the substation equipments.
b) What are the advantages and disadvantages of outdoor substation as compared to indoor substation?

8 Explain the following with circuit diagrams.
i) Single bus bar arrangement with sectionalization. ii) Main and transfer bus bar arrangements.

Selection and Location of Site for a Substation:

The following factors are considered while making site selection for a substation:

1. Type of Substation:

The category of substation is important for its location. For example a step-up substation, which is generally a point where power from various sources (generating machines or generating stations) is pooled and stepped up for long distance transmission, should be located as close to the generating stations as possible to minimize the transmission losses. Similarly a step-down substation should be located nearer to the load centre to reduce transmission losses, cost of distribution system and better reliability of supply.

2. Availability of Suitable and Sufficient Land:

The land proposed for a substation should be normally level and open from all sides. It should not be water logged particularly in rainy season. The site selected for a substation should be such that approach of transmission lines and their take off can be easily possible without any obstruction. According to the latest practice the land required for various types of substations is given below

S.no	Type of substation	Area Required
1	400 KV substation	50 acres
2	220 KV substation	25 acres
3	132 KV substation	10 acres

The places nearer to aerodrome, shooting practice grounds etc., should be avoided.

3. <u>Communication Facility:</u>

Suitable communication facility is desirable at a proposed substation both during and after its construction. It is better, therefore, to select the site along-side on existing road to facilitate an easier and cheaper transportation.

4. <u>Atmospheric Pollution</u>:

Atmosphere around factories, which may produce metal corroding gases, air fumes, conductive dust etc., and nearer to sea coasts, where air may be more humid and may be salt laden, is detrimental to the proper running of power system and therefore substations should not be located near factories or sea coast.

5. <u>Availability of Essential Amenities to the Staff</u>:

The site should be such where staff can be provided essential amenities like school, hospital, drinking water, housing etc.

6. <u>Drainage facility</u>

The site selected for the proposed substation should have proper drainage arrangement or possibility of making effective drainage arrangement to avoid pollution of air and growth of micro-organisms detrimental to equipment and health

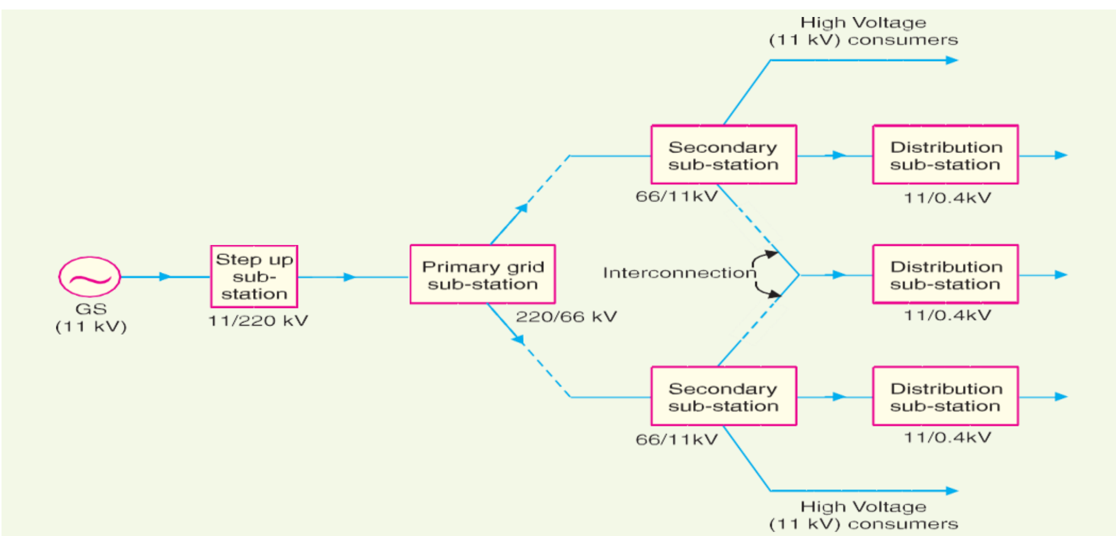


Fig. 25.1

Classification of Substations

I) Based on Nature of Duties

(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 the city. At a secondary sub-station, the voltage is further stepped down to 11 kV. The 11 kV lines run along the important road sides of the city. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations. 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 consumer's 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.

II) Based on Service

1. Transformer Substation: 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 substations. Most of the sub-stations in the power system are of this type.

2. Switching Substation: 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.

3. Converting Substation: 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.

4. Industrial Substation: Those substations used at the industries for industrial power supply at high voltages.

5. Power factor Correction Substation: 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.

6. Railway Substation: These are the substations used exclusively for Railway networks. These substations draw power from the local grid and convert it to the requirement of the railwaylines.

III) <u>Based on Operating Voltage</u>

1. **High Voltage Substations** (HV Substations) – Involving voltages between 11 KV and 66 KV.
2. **Extra High Voltage** Substations – Involving voltages between 132 kV and 400 KV.
3. **Ultra High Voltage** – Operating voltage above 400 KV.

IV) <u>Based on Importance</u>

1. Grid Substations – This substation is used for transferring the bulk power from one point to another. If any fault occurs on the substation, then the continuity of whole of the supply is affected by it.

2. Town Substations – These substations step down the voltage at 33/11 kV for more distribution in the towns. If there is any fault occurs in this substation, then the supply of the whole town is blocked.

V) <u>Based on Design</u>

1. Indoor sub-stations. For voltages up to 11 kV, the equipment of the sub-station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages up to 66 kV.

2. Outdoor sub-stations. For voltages beyond 66 kV, equipment is invariably installed outdoor. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor. Outdoor substations are of two types

Pole Mounted Substations – Such Substations are erected for distributions of power in the localities. Single stout pole or H-pole and 4-pole structures with relevant platforms are operating for transformers of capacity up to 25 KVA, 125 KVA, and above 125KVA.

Foundation Mounted Substations – Such types of substations are used for mounting the transformers having capacity 33,000 volts or above.

3. Underground sub-stations. In thickly populated areas, the space available for equipment and building is limited and the cost of land is high. Under such situations, the sub-station is created underground.

VI) <u>Based on Configuration</u>

1. Air Insulated Substations: These uses air as insulation, generally of outdoorsubstations

2. Gas Insulated Substations: These uses gas as insulation, generally of indoor substations

3. Composite Substations: These uses both Air and Gas as insulation

<u>Indoor Substations</u>

In these type of substations the apparatus are installed within the substation building. Such stations are usually for a voltage up to 11KV but can be erected up to 33KV and 66KV when the surrounding atmosphere is contaminated with impurities such as metal corroding gases and fumes, conductive dust, fog etc.. The switchgear on primary side consists of oil circuit breakers only. The high voltage supply is given to the primary of the transformer through circuit breaker. From the bus bar various feeder emerges out. The panel of each feeder consists of isolator switch and circuit breaker. In addition to circuit breaker the panel is provided with measuring instruments.

According to the construction, the Indoor substations are classified as

1. Substation of Integrally built type
2. Substation of Composite built type
3. Unit type Factory Fabricated Substation with metal clad switches

Outdoor Substation

These Substations are built outdoors and are of two types mainly

1. Pole Mounted Substation: Such Substations are erected for mounting distribution transformers of capacity 250KVA. Such Substations are cheapest, simple and smaller. All the equipment is of outdoor type and mounted on the supporting structure of HT distribution line.

2. Foundation Mounted Substation: These are built entirely in the open and in such Substation all the equipment is assembled into one unit usually enclosed by a fence from the safety point of view. Substation for primary and secondary transmission and for secondary distribution above 250KVA is of Foundation type.

Comparison between Indoor and Outdoor Substation

S.No.	Particular	Outdoor Sub-station	Indoor Sub-station
1	Space required	More	Less
2	Time required for erection	Less	More
3	Future extension	Easy	Difficult
4	Fault location	Easier because the equipment is in full view	Difficult because the equipment is enclosed
5	Capital cost	Low	High
6	Operation	Difficult	Easier
7	Possibility of fault escalation	Less because greater clearances can be provided	More

From the above comparison, it is clear that each type has its own advantages and disadvantages. However, comparative economics (*i.e.* annual cost of operation) is the most powerful factor influencing the choice between indoor and outdoor sub-stations. The greater cost of indoor sub-station prohibits its use. But sometimes non-economic factors (*e.g.* public safety) exert considerable influence in choosing indoor sub-station. In general, most of the sub-stations are of outdoor type and the indoor sub-stations are erected only where outdoor construction is impracticable or prohibited by the local laws.

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 aluminum 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
(iv) Ring type arrangement

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.

4. Circuit breaker. A circuit breaker is 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 up to 66kV while for high (>66 kV) voltages, low oil circuit breakers are used. For still higher voltages, air-blast, vacuum or SF6 circuit breakers are used.

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 utilization voltage. The modern practice is to use 3-phase transformers in sub-stations; although 3 single phase bank of 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.

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) Potential 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.

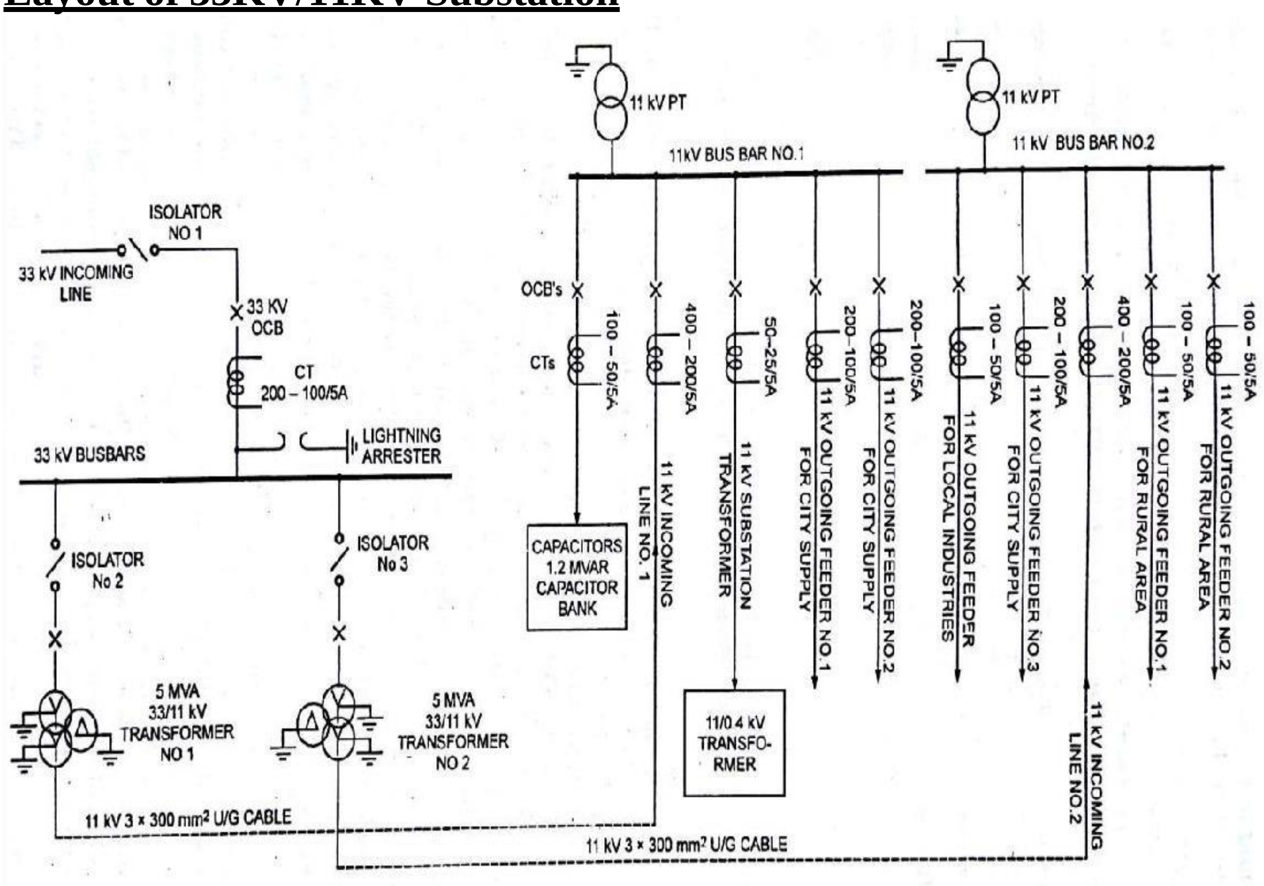
8. Miscellaneous equipment. In addition to above, there may be following equipment in a sub- station

(i) Fuses

(ii) Carrier-Current Equipment

(iii) Sub-Station Auxiliary Supplies

<u>Layout of 33KV/11KV Substation</u>



Electrical Bus-Bar and its Types

Definition: An electrical bus bar is defined as a conductor or a group of conductor used for collecting electric power from the incoming feeders and distributes them to the outgoing feeders. In other words, it is a type of electrical junction in which all the incoming and outgoing electrical current meets. Thus, the electrical bus bar collects the electric power at one location.

The bus bar system consists the isolator and the circuit breaker. On the occurrence of a fault, the circuit breaker is tripped off and the faulty section of the bus bar is easily disconnected from the circuit.

The electrical bus bar is available in rectangular, cross-sectional, round and many other shapes. The rectangular bus bar is mostly used in the power system. The copper and aluminium are used for the manufacturing of the electrical bus bar.

The most common of the bus-bars are 40×4mm (160 mm^2); 40×5 mm (200 mm^2) ; 50×6 mm (300mm^2) ; 60×8 mm (480 mm^2) ; 80×8 (640 mm^2) and 100×10 mm (1000 mm^2).

The various types of bus bar arrangement are used in the power system. The selection of the bus bar is depended on the different factor likes reliability, flexibility, cost etc. The following are the electrical considerations governing the selection of any one particular arrangement.

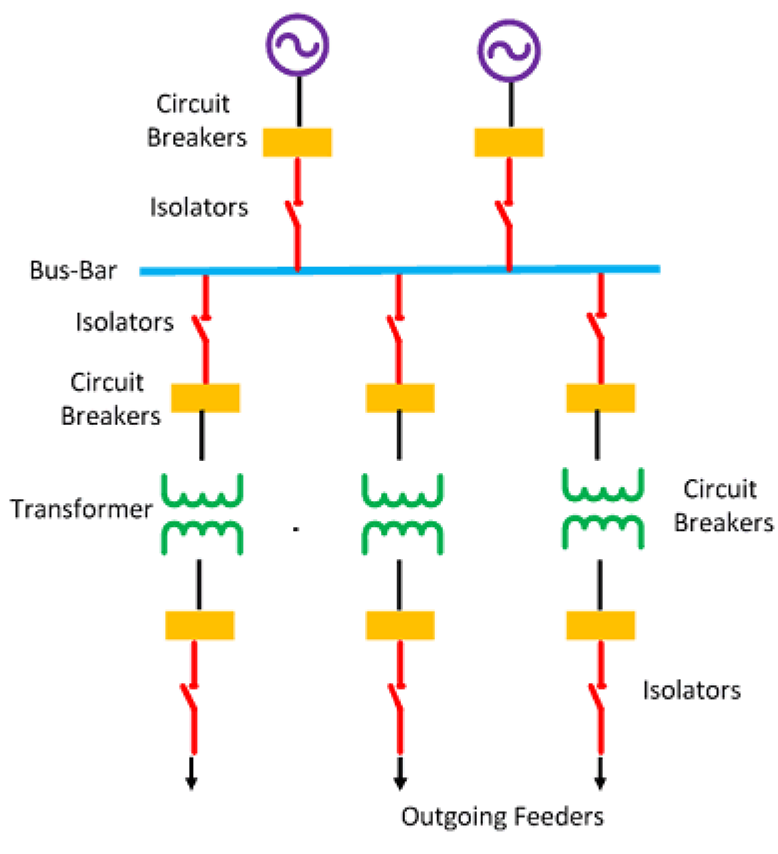
- The bus bar arrangement is simple and easy in maintenance.
- The maintenance of the system did not affect their continuity.
- The installation of the bus bar is cheap.

The small substation where continuity of the supply is not essential uses the single bus bar. But in a large substation, the additional bus bar is used in the system so that the interruption does not occur in their supply. The different type of electrical bus bar arrangement is shown in the figure below.

Single Bus-Bar Arrangement

The arrangement of such type of system is very simple and easy. The system has only one bus bar, All the substation equipment like the transformer, generator, the feeder is connected to this bus bar only. The advantages of single bus bar arrangements are

- It has low initial cost.
- It requires less maintenance
- It is simple in operation



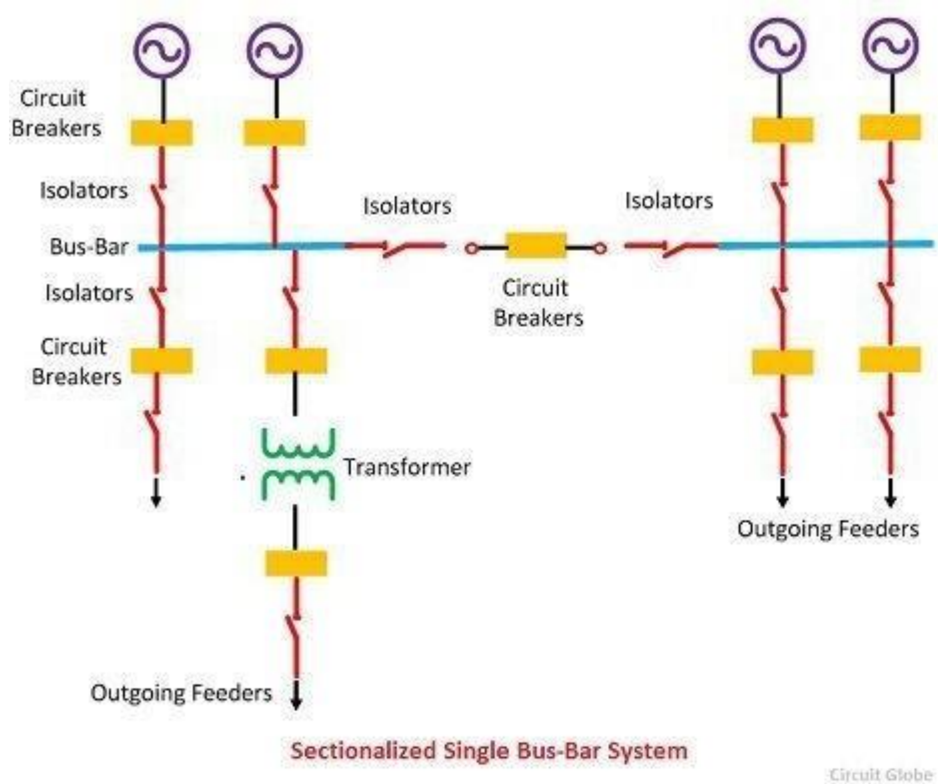
Single Bus-Bar Arrangement

Drawbacks of Single Bus-Bars Arrangement

- The only disadvantage of such type of arrangement is that the complete supply is disturbed on the occurrence of the fault.
- The arrangement provides the less flexibility and hence used in the small substation where continuity of supply is not essential.

Single Bus-Bar Arrangement with Bus Sectionalized

In this type of bus bar arrangement, the circuit breaker and isolating switches are used. The isolator disconnects the faulty section of the bus bar, hence protects the system from complete shutdown. This type of arrangement uses one addition circuit breaker which does not much increase the cost of the system.



Advantage of single Bus-bar Arrangement with Bus Sectionalisation

The following are the advantages of sectionalized bus bar.

- The faulty section is removed without affecting the continuity of the supply.
- The maintenance of the individual section can be done without disturbing the system supply.

Disadvantages of Single Bus-Bar Arrangement with Sectionalisation

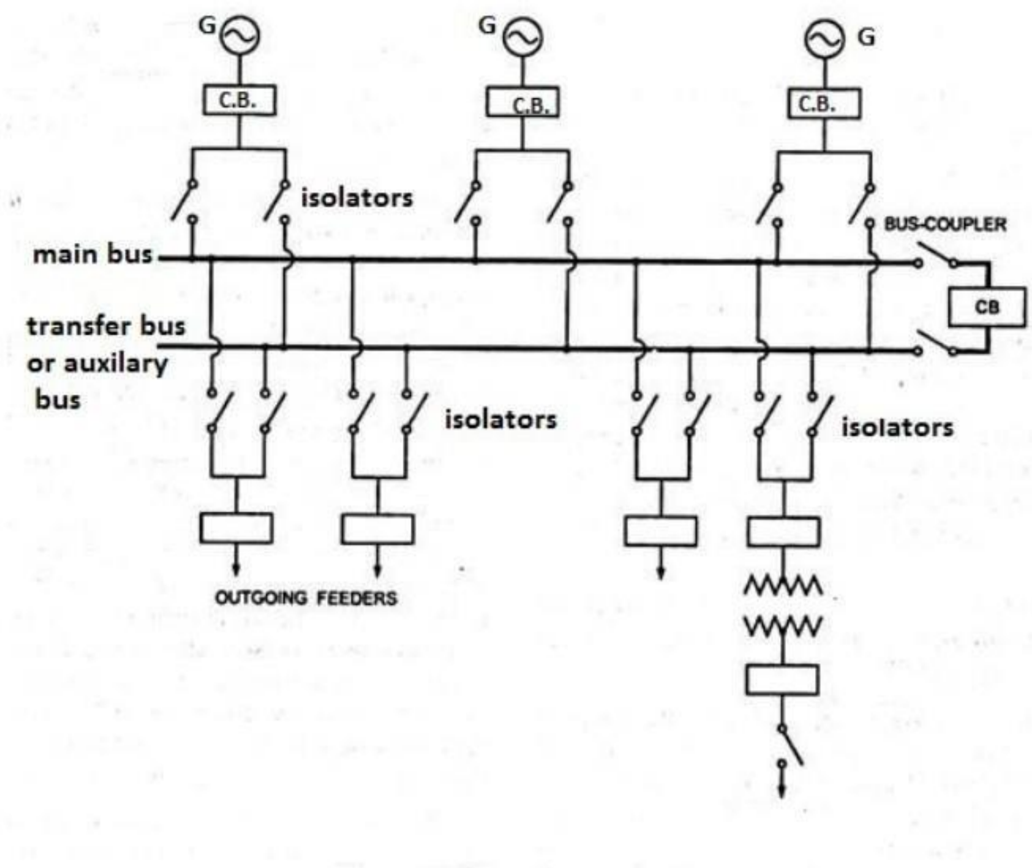
- The system uses the additional circuit breaker and isolator which increases the cost of the system.

Main and Transfer Bus Arrangement

Such type of arrangement uses two type of bus bar namely, main bus bar and the auxiliary bus bar. The bus bar arrangement uses bus coupler which connects the isolating switches and circuit breaker to the bus bar. The bus coupler is also used for transferring the load from one bus to another in case of overloading. The following are the steps of transferring the load from one bus to another.

1. Close the bus 9 coupler (Circuit breaker) so as to make the two buses at the same potential
2. Close the isolators on the reserve bus
3. Open the isolators on the main bus

Thus, the load is transferred from the main bus to reserve bus.



Advantages of Main and Transfer Bus Arrangement

- The continuity of the supply remains same even in the fault. When the fault occurs on any of the buses the entire load is shifted to another bus.

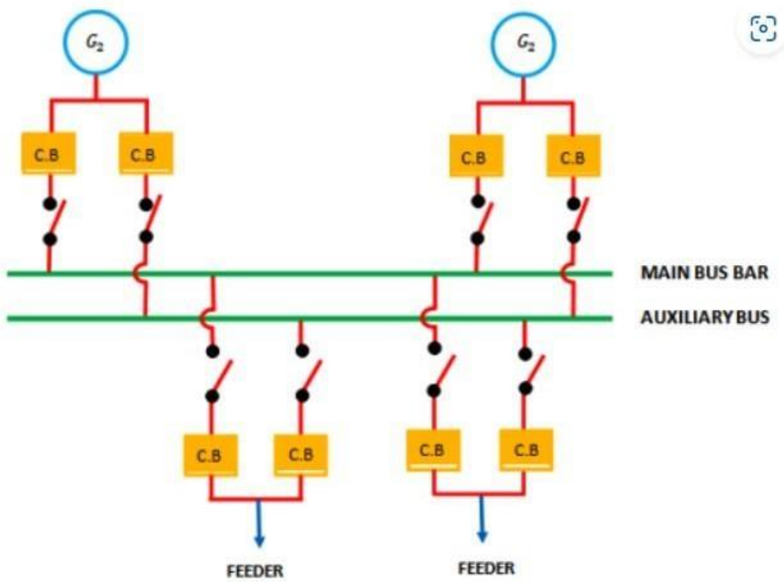
- The repair and maintenance can easily be done on the bus bar without disturbing their continuity.
- The maintenance cost of the arrangement is less.
- The potential of the bus is used for the operation of the relay.
- The load can easily be shifted on any of the buses.

Disadvantages of Main and Transfer Bus Arrangement

- In such type of arrangements, two bus bars are used which increases the cost of the system.

Double Bus Double Breaker Arrangement

This type of arrangement requires two bus bar and two circuit breakers. It does not require any additional equipment like bus coupler and switch.



Advantages of Double Bus Double Breaker

- This type of arrangement provides the maximum reliability and flexibility in the supply. Because the fault and maintenance would not disturb their continuity.
- The continuity of the supply remains same because the load is transferrable from one bus to another on the occurrence of the fault.

Disadvantages of double bus Double breaker

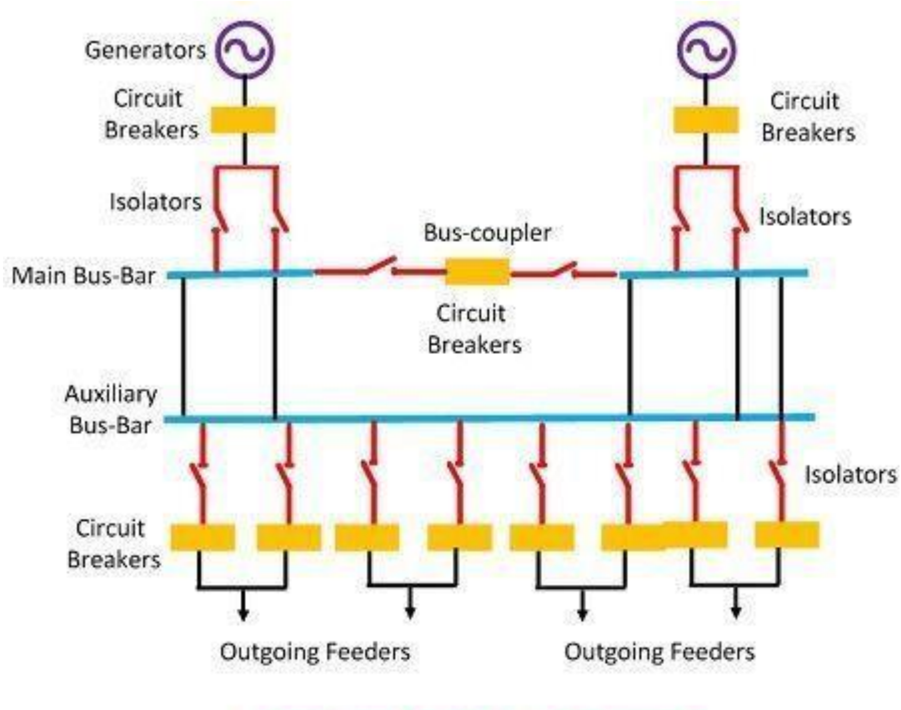
- In such type of arrangement two buses and two circuit breakers are used which increases the cost of the system.

- Their maintenance cost is very high.

Because of its higher cost, such type of bus-bars is seldom used in substations

Sectionalized Double Bus Bar Arrangement.

In this type of bus arrangement, the sectionalized main bus bar is used along with the auxiliary bus bar. Any section of the busbar removes from the circuit for maintenance and it is connected to any of the auxiliary bus bars. But such type of arrangement increases the cost of the system. Sectionalisation of the auxiliary bus bar is not required because it would increase the cost of the system.



Sectionalized Double Bus Arrangement

What are the advantages of a gas-insulated substation over a conventional substation?

- The conventional substation would require a huge amount of space when compared to the gas insulated substation
- In the conventional substation, each and every part is exposed to air and due to this, it will be polluted. While in case of the gas insulated substation the major parts are situated in a metal enclosure
- The conventional substation parts are subjected to contamination, in the case of the gas insulated substation there won't be any contamination due to the metal enclosure
- Flashovers and breakdowns would occur frequently in the case of the conventional substation
- Less maintenance is needed for gas insulated substations while the conventional substation would require huge maintenance

- The installation of the gas insulated substation can be done quickly but it is not possible in the conventional type
- The necessity of concrete work for the conventional substation is really high when compared to the gas insulated type.

Gas-Insulated Sub-Stations

A gas insulated substation (GIS) is a substation that uses a superior dielectric gas, sulfur hexafluoride (SF6).

The basic principle of gas-insulated equipment:

• Is that the high-voltage current- carrying parts are within a metal enclosure and are held in a concentric configuration.

• The space between the conductor and the enclosure is filled with sulfur hexafluoride gas under moderate pressure.

Advantages of GIS Sub-Stations

1. It occupies very less space (1/10th) compared to ordinary substations. Hence these Gas Insulated Substations (GIS) are most preferred where area for substation is small (eg: Cities)
2. Most reliable compared to Air Insulated Substations, number of outages due to the fault is less
3. Maintenance Free
4. Can be used at places of high altitudes and places of unfair weather conditions
5. Limitations of Air Insulated Sub Stations makes use of Gas Insulated Substations

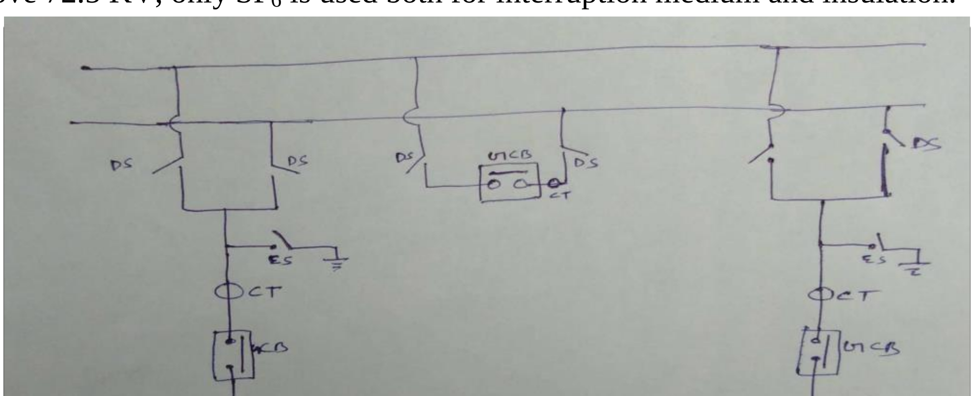
CONSTRUCTIONAL ASPECTS OF GIS

Gas insulated components of substation are generally,

- Gas circuit
- Seals and gaskets
- Electrical bus bars.
- Electrical isolators or disconnectors(DS)
- Gas circuit breakers(GCT)
- Current transformers(CT)
- Voltage transformers(VT)
- Earth switches(ES)
- Surge arrestors or lightning arresters(LA)

Single Line Diagram of GIS Substation

In gas insulated medium voltage switchgear, vacuum technology is used as interrupting purpose and SF_6 gas is used as insulation material. Although for both interruption and insulation, SF_6 gas is used in many medium voltage GIS system. But for such equipment's rated SF_6 gas pressures are different for interruption and insulation. SF_6 gas pressure for insulating purpose is generally kept below 2.5 bar whereas SF_6 gas pressure for interrupting purpose is ranged from 5 bar to 7 bar. As vacuum technology is not available for high voltage, so for **GIS or gas insulated switchgear** system above 72.5 KV, only SF_6 is used both for interruption medium and insulation.



Types of GIS

There are different types of gas insulated metal enclosed switchgears available depending upon their constructional feature.

i) Isolated Phase GIS

In this configuration, each phase of the bay is assembled separately. That is, for each phase, one pole of circuit breaker, one pole electrical isolator, one current transformer are assembled together. This type of GIS requires larger bay width as compared to other gas insulated switchgear system.

ii) Integrated 3 Phase GIS

In this configuration all three phase of circuit breaker, 3 phases of disconnectors and three phase current transformer are placed in an individual metal enclosure. The arrangement forms a three phase module for the element. The size of this type of module is one third of the isolated phase GIS.

iii) Hybrid GIS System

It is a suitable combination of isolated phase and three phase common elements. Here three phase common bus bar system simplifies the connection from the bus bar. The isolated phase equipment prevents phase to phase faults. This is an optimum design considering, both facts in mind, i.e. space requirement and maintenance facility.

iv) Compact GIS

In this GIS or gas insulated switchgear system than one functional element are encapsulate in a single metal enclosure. For example, in some design, a three phase circuit breaker, current transformer, earth switches, even other feeder elements are covered together in a single metal capsule.

v) Highly Integrated System

This design was introduced in the year of 2000, where, total substation equipments are placed together in single enclosure housing. This single unit gas insulated substation has gained user appreciation as it is a complete solution for an outdoor substation, in a single unit. As such, only equipment (HIS) is substitute of a total outdoor switch yard.

SF6 Gas Properties

In Gas Insulated Substations SF6 gas will be used as insulating medium.SF6 gas has the following properties

1. It is non-toxic and is chemically very stable
2. It is manmade and can’t be extinct easily
3. Life time is high
4. Insulation strength is three times that of air
5. It is colourless and is heavier than air
6. It is water insoluble
7. It is non-inflammable

Merits of SF6 Gas Insulated Substation:

Safe: Gas insulated Substations are very safe and operating personnel are protected by the earthed metal enclosures. While the Substation in operating condition the Operating personnel can touch the compartment.

Reliable: The complete enclosure of all live parts guards against any impairment of the insulation system.

Space Saving: SF6 switchgear installations take up only 10% of the space required for the conventional installations.

Economical: Initial high investment is required for installation but the cost can be comparable for the less maintenance, reliable, safe operation against conventional substation.

Maintenance Free: An extremely careful selection of materials, an expedient design and a high standard of manufacturing quality assure long service life with practically no maintenance requirement.

Low Weight: Low weight due to aluminum enclosure corresponds to low cost foundations and buildings.

Shop assembled: Quick site assembly ensured by extensive pre assembly and testing of complete feeders or large units in the factory.

<u>Demerits of SF6 Gas Insulated Substation</u>:

1. Cost is higher compared to Air Insulated Substation or conventional substation.
2. Procurement of SF6 gas and supply of gas to the site is problematic
3. Normally this type of substations are indoor type and requires separate building
4. Maintaining Cleanliness is very important. Dust or moisture inside the compartment causes the flash over's
5. When fault occurs internally, the outage period will be very long. The damage effect will also be severe.

Comparison of Air and Gas Insulated Substations

- Physical Design:

AIS: Components are installed in the open air, using support structures. Larger land area is typically required.

GIS: Components are enclosed in gas-tight compartments, allowing for a compact design. Requires less land area and can be installed vertically.

- Insulation Medium:

AIS: Uses air as the primary insulation medium.

GIS: Uses gas (typically sulfur hexafluoride, SF6) as the insulation medium.

- Environmental Impact:

AIS: Generally has a lower environmental impact due to the use of ambient air as the insulating medium.

GIS: SF6 gas used in GIS has a high global warming potential, contributing to environmental concerns.

- Cost:

AIS: Typically has lower upfront costs due to simpler construction and standard components.

GIS: Higher initial costs due to specialized components, sealed enclosures, and gas insulation.

- Maintenance:

AIS: Easier access to components for maintenance and repairs. Requires more frequent maintenance due to exposure to weather.

GIS: Less frequent maintenance due to sealed enclosures, but maintenance tasks can be more complex.

- Safety:

AIS: Components are exposed, posing potential safety risks to personnel due to live parts.

GIS: Enclosed design enhances safety by reducing the risk of accidental contact with live parts.

Reliability:

AIS: Prone to environmental factors (dust, pollution, weather) that can impact reliability.

GIS: Sealed design protects equipment from external factors, enhancing reliability.

- Space Efficiency:
  AIS: Requires more land area for installation due to the open design.
  GIS: Requires less land area due to compact design, suitable for areas with space constraints.
- Flexibility and Expansion:
  AIS: Offers more flexibility for future expansions or modifications.
  GIS: Limited flexibility for modifications due to the confined space within the sealed enclosures.
- Construction Time:
  AIS: Generally quicker to construct due to simpler design and installation.
  GIS: Construction can be more time-consuming due to specialized components and assembly processes.

- Operating Altitude and Weather:
  AIS: Can be more suitable for extreme altitudes and harsh weather conditions due to its robust and open design.
  GIS: Designed to withstand harsh conditions, but the gas insulation might pose challenges at very high altitudes.

- Visual Impact:
  AIS: Can have a larger visual impact on the surrounding landscape due to the need for larger support structures.
  GIS: Minimal visual impact due to compact and enclosed design.
- Remote Monitoring and Control:
  AIS: Generally offers less advanced remote monitoring and control capabilities.
  GIS: Often equipped with advanced monitoring and control systems

UNIT-3

UNIT-3

TRANSMISSION LINE PARAMETERS

→ TYPES OF CONDUCTORS (TYPES OF OVERHEAD CONDUCTORS):

Conductor is a physical medium to carry electrical energy from one place to other. It is an important component of overhead and underground electrical transmission and distribution systems.

The choice of conductors depends on cost and efficiency.

An ideal conductor has the following features:

1. It has maximum conductivity.
2. It has high tensile strength.
3. It has least specific gravity i.e., weight/unit volume.
4. It has less cost without sacrifing other factors.

a, AAC b, AAAC c, ACAR d, ACSR.

→ a, **AAC (All Aluminium Conductors):** All Aluminium conductors are made up of one or more strands of aluminium wire depending upon the specific applications.

It has lesser strength and more sag for span length than any other category (than any other OH conductor) therefore it is used for lesser span i.e., it is applicable at distribution levels.

→ b, **ACAR Conductor (Alluminium Conductor Aluminium Alloy Reinforced):**

Reinforce: The process of giving strength to any object.

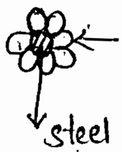
ACAR is formed by concentrically stranded wires of aluminium or high strength Aluminium - Magnesium - silicon (AL-Mg-Si) alloy core.

ACAR - is formed by Concentrically standard wires of Aluminium on high strength Aluminium, magnesium, silicon alloy core

ACAR are used for overhead distribution and T/M Lines requiring all aluminium Conductors!

c, **AAAC : (All Aluminium Alloy conductors) :** AAAC conductors are made out of high strength aluminium-magnesium-silicon alloy.

d, **ACSR (Alluminium conductor steel Reinforced) :** ACSR is concentrically stranded conductor with one or more layers of harddrawn aluminium wire ~~and~~ on galvanized steel wire core. The core can be single wire or stranded depending on the size.



Aluminium has less weight than copper so Al cost is less compared to copper.

MAJOR FEATURES OF ACSR :

1. High Tensile strength
2. Better Sag Properties (less sag for span length)
3. Economic design
4. Best suited for transmission lines with long span.
5. ACSR may consists of 7 or 19 strands of steel surrounding aluminium strands concentrically.
6. ACSR's are specified by x/y/z

   where x → No. of aluminium strands.

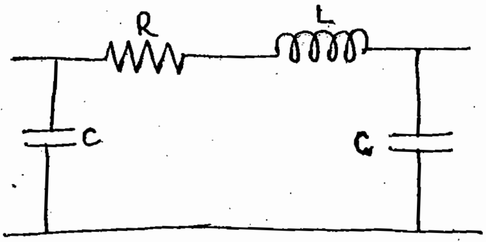
   y → No. of steel strands

   z → Diameter of each strand.

TRANSMISSION LINE PARAMETERS :

Transmission line have 3 electrical parameters.

1. Resistance 2. Inductance 3. Capacitance.



Resistance and inductance will be in series whereas capacitance is between line and ground or between the two lines. So the Capacitance is coming as a shunt or parallel connection.

1. Resistance : Resistance of overhead conductor opposes the electrical current passing through it.

Calculation of resistance for solid conductor :

The dc resistance at temperature T is given by

$$R_{dc}^{T} = \frac{\rho^T l}{a}$$

where $\rho^T \longrightarrow$ conductor resistivity at temperature T.

$l \longrightarrow$ length of the conductor in mts.

$a \longrightarrow$ cross-sectional area of conductor in m^2

Electrical Resistivity is an intrinsic (nature) property that quantifies how strongly given material opposes the flow of electrical current.

The resistance of over head conductor (transmission line conductors) mainly depends on the following factors :

1. Temperature
2. Twisting or spiraling (By twisting effective length of conductor decreases)
3. Frequency (skin effect)

1. Temperature : The resistance of a conductor will increases with increase in temperature. Resistivity of conducting material varies linearly over normal operating temperatures.

2. Twisting or spiraling: We use stranded conductors and these conductors are twisted. (spiraling) so because of twisting the effective length of conductor gets decreased so the actual length of each strand will be much longer compared to the effective length of conductor.

3. Skin effect : Due to skin effect the effective area of the cross-section of the conductor through which current flows is reduced. Consequently, the resistance of the conductor is slightly increased that carrying ac current.

By experimentally finding out of the resistance, by finding out the losses in the conductor.

$\therefore$ R_{ac} or Effective resistance of conductor $\Big\}$ = $\dfrac{\text{Power losses in conductor}}{I^2}$

In general the ac resistance will be about 4-5% more than the dc resistance.

R_{ac} is always more than R_{dc} because of skin effect.

In a single-phase or 2-wire dc line the total resistance is equal to the double the resistance of either conductor. In case of 3-phase transmission line resistance/phase is the resistance of one conductor.

INDUCTANCE (LINE INDUCTANCE) : When alternating current flows through a conductor, a change in flux is set up which links the conductor due to this flux linkages the conductor possess inductance.

Mathematically Inductance is defined as flux linkages per amperes.

Inductance $L = \dfrac{N\phi}{I}$ Amp

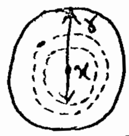
$L = \dfrac{\psi}{I}$ wb-turns/amp

For determination of inductance of a circuit, determination of flux linkages is essential. Basically there are 2 types of flux linkages :

1. Flux linkages of a conductor due to internal flux.
2. Flux linkages of a conductor due to external flux.

→ FLUX LINKAGES OF A CONDUCTOR DUE TO INTERNAL FLUX:

Consider a long straight cylindrical conductor of radius 'r' mts and carrying a current of 'I' amp as shown in fig.



In overhead lines it may be assumed that the current is uniformly distributed. The current inside a line of force of radius 'x' at $I_x = \frac{I}{\pi r^2} \times \pi x^2$

$$= \frac{Ix^2}{r^2}$$

Field strength inside the conductor at a distance 'x' from the centre. $H_x = \frac{I_x}{2\pi x \text{ distance}}$

$$= \frac{Ix^2}{2\pi x \times r^2} = \frac{Ix}{2\pi r^2} \text{ AT/m}$$

Magnetic field strength H measured in amperes × turns per meter

$H = \frac{IN}{\text{meter}}$

$H = \frac{AT}{m}$

Flux density $B_x = \mu_0 \mu_r H_x$.

Flux density corresponding 'x' circle $\mu_r = 1$

$$\therefore B_x = \mu_0 H_x$$

$$B_x = \frac{\mu_0 Ix}{2\pi r^2}$$

Now the flux $d\phi$ to cylindrical shell of radial thickness dx and axial length 1m

$$d\phi = B_x \times \text{area of cylindrical shell}$$

$$d\phi = B_x dx \times 1$$

$$\therefore d\phi = \frac{\mu_0 Ix}{2\pi r^2} dx \text{ wb.}$$

This flux links with only the current lying with the circle of radius 'x' i.e., $\frac{x^2}{r^2}$

$\therefore$ Linkages of the shell $d\psi = d\phi \times \frac{x^2}{r^2}$

$$= \frac{\mu_0 Ix}{2\pi r^2} dx \times \frac{x^2}{r^2}$$

$$d\psi = \frac{\mu_0 Ix^3}{2\pi r^4} dx \text{ wb-turns}$$

Total flux linkages from centre of the conductor and upto surface of the conductor.

$$\psi_{int} = \int_0^r \frac{\mu_0 I x^3}{2\pi r^4} dx$$

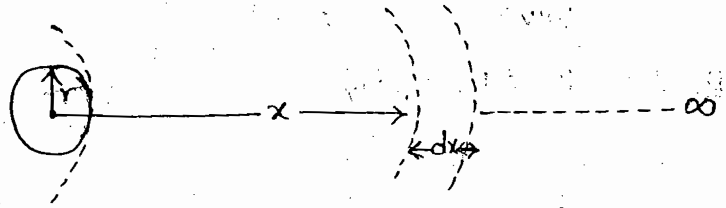
$$\psi_{int} = \frac{\mu_0 I}{2\pi r^4} \int_0^r x^3 dx$$

$$\psi_{int} = \frac{\mu_0 I}{2\pi \cancel{r^4}} \left(\frac{\cancel{r^4}}{4} \right)$$

$$\therefore \psi_{int} = \frac{\mu_0 I}{8\pi}$$

→ EXTERNAL FLUX LINKAGES OF A CONDUCTOR (or) FLUX LINKAGES DUE TO EXTERNAL FLUX

Now let us calculate external flux linkages. The external flux extends from the surface of the conductor to infinity shown in figure.



The field intensity and a distance 'x' mts (from the centre) to outside the conductor is given by $H_x = \frac{I}{2\pi x \text{ distance}}$

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

The flux density $B_x = \mu_0 \mu_r H_x$

$$\mu_r = 1$$

$$\therefore B_x = \frac{\mu_0 I}{2\pi x} \text{ wb/m}^2$$

Now flux $d\phi$ to a cylindrical shell of thickness 'dx' & axial length 1m is

$$d\phi = dx \times 1 \times B_x$$

$$d\phi = \frac{\mu_0 I}{2\pi x} dx.$$

This flux $d\phi$ links all the current in the entire conductor.

$$d\psi = \frac{\mu_0 I}{2\pi x} dx \text{ wb-turns.}$$

Total flux linkages of the conductor from surface to infinity

$$\psi_{ext} = \int_{r}^{\infty} \frac{\mu_0 I}{2\pi x}\, dx \quad wb\text{-}t/m$$

$\therefore$ Overall flux linkages $\psi_T = \psi_{int} + \psi_{ext}$

$$= \frac{\mu_0 I}{8\pi} + \int_{r}^{\infty} \frac{\mu_0 I}{2\pi x}\, dx$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_{r}^{\infty}\frac{dx}{x}\right] \quad wb\text{-}T/m.$$

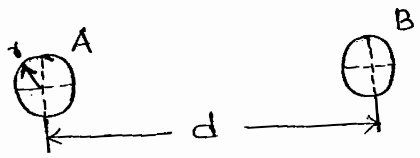
Note: The conductor A carrying current I_A & conductor B carrying current I_B. These two conductors separated at a distance 'd_1' from their centre point.

The external flux due to I_A links with conductor 'B' from d_1 to ∞ and it is given by $= \frac{\mu_0 I_A}{2\pi}\int_{d_1}^{\infty}\frac{dx}{x}$

Similarly the external flux due to I_B links with conductor 'A' from d_1 to ∞ and it is given by $= \frac{\mu_0 I_B}{2\pi}\int_{d_1}^{\infty}\frac{dx}{x}$

** INDUCTANCE OF SINGLE PHASE TWO WIRE LINE:

Consider a single phase overhead line consisting of two parallel conductors A & B spaced 'd' mts apart as shown in below fig.



Conductors A & B carry the same amount of current but in opposite direction i.e., $I_A = -I_B$ $[\because I_A + I_B = 0]$

In order to find the inductance of conductor A (or B). We shall 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 the current I_B in the conductor B.

Flux linkages with conductor A due to its own current I_A is

$$\Rightarrow \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\int_{r}^{\infty}\frac{dx}{x}\right] \longrightarrow ①$$

Flux linkages with conductor A due to current I_B in conductor B.

$$\Rightarrow \frac{\mu_0 I_B}{2\pi}\int_{d}^{\infty}\frac{dx}{x} \longrightarrow ②$$

∴ Total flux linkages with conductor 'A' is

$$\psi_A = eq ① + eq ②$$

$$\psi_A = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\int_{r}^{\infty}\frac{dx}{x}\right] + \frac{\mu_0 I_B}{2\pi}\int_{d}^{\infty}\frac{dx}{x}$$

$$= \frac{\mu_0}{2\pi}\left[\left[I_A\cdot\frac{1}{4}+I_A\int_{r}^{\infty}\frac{dx}{x}\right]+I_B\int_{d}^{\infty}\frac{dx}{x}\right]$$

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

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

But $I_A+I_B=0$

$I_A = -I_B$

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

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

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

$$= \frac{4\pi\times10^{-7}}{2\pi} I_A\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

$$\psi_A = 2\times10^{-7} I_A\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

∴ Inductance of conductor 'A' $L_A = \frac{\psi_A}{I_A} = 2\times10^{-7}\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$ H/m

Inductance of single phase 2 wire (or) loop inductance $= 2 \times L_A$

$$= 4\times10^{-7}\left[\frac{1}{4} + \log_e \frac{d}{r}\right]$$

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

Loop inductance $= 2L_a$ H/m

$$= 2\times10^{-7}\left[\tfrac{1}{2} + 2\log_e\left(\tfrac{d}{r}\right)\right] \text{ H/m}$$

$$= 10^{-7}\left[1 + 4\log_e\left(\tfrac{d}{r}\right)\right] \text{ H/m} = 0.4\log_e\left(\tfrac{d}{r'}\right) \text{ mH/km}$$

Alternate form of expression

$$L_A = 2\times10^{-7}\left[\tfrac{1}{4} + \log_e\left(\tfrac{d}{r}\right)\right]$$

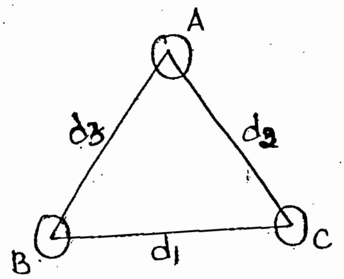
$$= 2\times10^{-7}\left[\log_e e^{1/4} + \log_e\left(\tfrac{d}{r}\right)\right]$$

$$L_A = 2\times10^{-7}\log\left(\frac{d}{r e^{-1/4}}\right) = 2\times10^{-7}\log\left(\frac{d}{r'}\right)$$

where $r' = r e^{-1/4}$ effective radius of conductor for calculation of inductance. i.e (GMR) $\boxed{r' = 0.7788r}$

INDUCTANCE OF 3-ϕ OVERHEAD LINE :

The fig. below shows the 3 conductors A, B and c of a 3-ϕ line carrying currents I_A, I_B, I_C respectively. Let d_1, d_2, d_3 be the space in between the conductors as shown in below.



Let us assume that loads are balanced i.e., $I_A + I_B + I_C = 0$

consider the flux linkages with conductor A due to its own current and also due to the mutual inductance effects of I_B & I_C.

Flux linkages with conductor A because of its own current is

$$\frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^{\infty}\frac{dx}{x}\right] \longrightarrow ①$$

Flux linkages with conductor 'A' due to I_B is

$$\frac{\mu_0 I_B}{2\pi}\left[\int_{d_3}^{\infty}\frac{dx}{x}\right] \longrightarrow ②$$

Flux linkages with conductor 'A' because of I_C is

$$\frac{\mu_0 I_C}{2\pi}\left[\int_{d_2}^{\infty}\frac{dx}{x}\right] \longrightarrow ③$$

∴ The total flux linkages with conductor A is

$$\psi_A = eq① + eq② + eq③$$

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

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

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

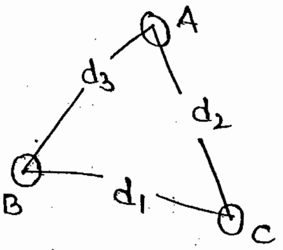
$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I_A + (I_A+I_B+I_C)\log_e\infty - I_B\log_e d_3 - I_C\log_e d_2 - I_A\log_e r\right]$$

We know that $I_A+I_B+I_C=0$

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

Case: I Symmetrically Spacing : [single circuit]

Three conductors A, B and C are placed symmetrically corners of an equilateral triangle of side "d", when $d_1=d_2=d_3=d$. Under such conditions then flux linkages with conductor A becomes.



$$d_1 = d_2 = d_3 = d.$$

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

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

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

$I_A+I_B+I_C=0$

$I_B+I_C=-I_A$

$-(I_B+I_C)=I_A$

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

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

$$\psi_A = \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

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

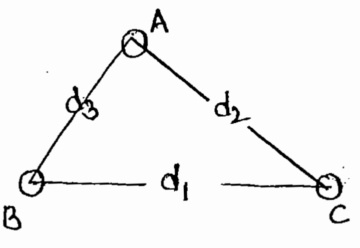
$$=\frac{\mu_0 \cancel{I_A}}{2\pi \cancel{I_A}}\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

$$L_A = 2\times10^{-7}\left[\frac{1}{4}+\log_e\frac{d}{r}\right] H/m.$$

Case:2 Unsymmetrical spacing : [single circuit]

When 3-phase line conductors are not equivalent equi-distant 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.

Consider a 3-phase line with conductors A, B and C each of radius 'r' mts. and the spacing between them is d_1, d_2 and d_3. and the current flowing through them be I_A, I_B and I_C respectively.



$d_1 \neq d_2 \neq d_3$

The figure above shows the unsymmetrical 3-phase transmission system.

Let the line currents be

$I_A = I(1+j0)$

$I_B = I[-0.5-j0.866]$

$I_C = I[-0.5+j0.866]$

We know the total flux linkages per mt length of conductor A.

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

$$= \frac{\mu_0}{2\pi}\left[\left[\frac{1}{4} - \log_e r\right]I(1+j0) - I\left[-0.5-j0.866\right]\log_e d_3 - I\left[-0.5+j0.866\right]\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left[\frac{1}{4}I - \log_e r I\right] + 0.5I\log_e d_3 + j0.866\,I\log_e d_3 + 0.5\,I\log_e d_2 - j0.866I\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}I - \log_e r I\right) + 0.5I\left(\log_e d_3 + \log_e d_2\right) + j0.866I\left(\log_e d_3 - \log_e d_2\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - \log_e r I + 0.5I\left[\log_e d_2 d_3\right] + j0.866I\left[\log_e \frac{d_3}{d_2}\right]\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - \log_e r I + I\left[0.5\log_e d_2 d_3\right] + j0.866I\left[\log_e \frac{d_3}{d_2}\right]\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - \log_e r I + I\log_e\sqrt{d_2 d_3} + j0.866I\left[\log_e \frac{d_3}{d_2}\right]\right]$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2 d_3}}{r} + j0.866\left(\log_e \frac{d_3}{d_2}\right)\right]$$

$\therefore$ Inductance of conductor A is $L_A = \frac{\psi_A}{I_A} = \frac{\psi_A}{I}$

$$= 2\times10^{-7}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2 d_3}}{r} + j0.866\left(\log_e \frac{d_3}{d_2}\right)\right] ~~Henry~~\ H/m$$

For similarly inductance of conductors B and C

~~$L_B = 2\times10^{-7}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_1 d_3}}{r} + j\log\ 0.866\ \log_e\right.$~~

$$L_A = 2\times10^{-7}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2 d_3}}{r} + j0.866\left(\log_e\frac{d_3}{d_2}\right)\right]$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_2 d_3}}{r} + j1.732\log_e\frac{d_3}{d_2}\right]\ H/m$$

lly $L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_1 d_3}}{r} + j1.732\log_e\frac{d_1}{d_3}\right]\ H/m$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_1 d_2}}{r} + j1.732\log_e\frac{d_2}{d_1}\right]\ H/m$$

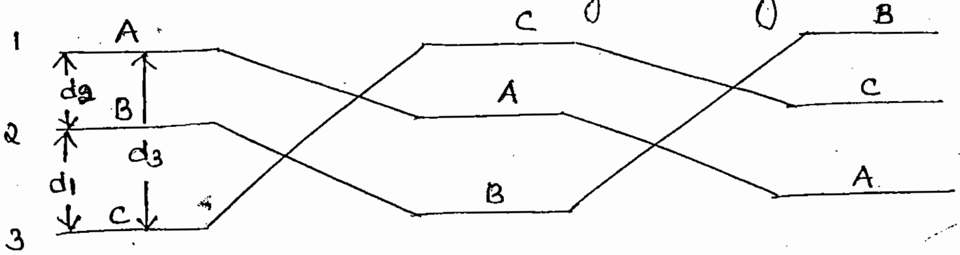
Does we see that the conductors of 3-phase transmission lines are not equidistant from each other i.e., unsymmetrically.

spaced. The flux linkages and inductance of various phases are different which causes unequal voltage drops in the 3-phases even if the currents in the conductors are balanced.

In order that the voltage drops are equal in all the conductors we generally interchange the position of the conductor at regular intervals along the lines called transposition.

The unbalancing effect on account of irregular spacing of conductors is avoided by transposition of conductor as shown in below.

* Due to unsymmetrical spacing, the magnetic field external to the conductors is not zero, thereby causing induced voltages in electric ckts, particularly telephone lines that may result in Telephone interfere



By doing transposition of transmission lines the net inductance of each line conductor becomes average of three-phases inductances. Therefore

Line inductance $L = \dfrac{L_A + L_B + L_C}{3}$

↓

Inductance of Line conductor.

Note:

The effect of transposition is that each conductor has the same average inductance.

$$L_A = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_2 d_3}}{r} + j\,1.732\log_e \frac{d_3}{d_2}\right] H/m$$

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_1 d_3}}{r} + j\,1.732\log_e \frac{d_1}{d_3}\right] H/m$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt{d_1 d_2}}{r} + j\,1.732\log_e \frac{d_2}{d_1}\right] H/m$$

$$L = \frac{1}{3}\times 10^{-7}\left[\frac{3}{2} + 2\left[\log_e \frac{\sqrt{d_2 d_3}}{r} + \log_e \frac{\sqrt{d_1 d_3}}{r} + \log_e \frac{\sqrt{d_1 d_2}}{r}\right] + j\,1.732\left[\log_e \frac{d_3}{d_2} + \log_e \frac{d_1}{d_3} + \log_e \frac{d_2}{d_1}\right]\right]$$

$$L = \frac{1}{3}\times 10^{-7}\left[\frac{3}{2} + 2\left[\log_e \frac{\sqrt{d_2 d_3 d_1 d_3 d_1 d_2}}{r^3}\right] + j\,1.732\left[\log_e \left[\frac{d_1 d_2 d_3}{d_1 d_2 d_3}\right]\right]\right]$$

$$= \frac{1}{3}\times 10^{-7}\left[\frac{3}{2} + 2\left[\log_e \frac{d_1 d_2 d_3}{\sqrt{r^3}}\right] + 0\right]$$

$$= 10^{-7}\left[\frac{1}{2}+2\cdot\frac{1}{3}\log_e \frac{d_1 d_2 d_3}{r^3}\right]$$

$$= 10^{-7}\left[\frac{1}{2}+2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r^3}\right] \Rightarrow 2\times10^{-7}\left[\frac{1}{4}+\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right]$$

* To reduce the communication interference either by transposition of power lines or communication lines.
* Modern power lines are normally not transposed. The transposition, however may be affected at intermediate switching stations.
* Difference in "L" of untransposed line negligibly small.

Concept of GMR and GMD:

GMR → Geometricall mean Radius

GMD → Geometrical mean Distance

GMR → self GMD → D_S

GMD → Mutual GMD → D_M

The use of GMR and GMD simplifies the inductance calculations, particularly related to multiconductor arrangement. (3-phase double circuit) The symbols used for GMR and GMD are D_s and D_M.

i, GMR (or) Self GMD (D_s) : In order to have the concept of GMR sometimes called self GMD. Consider inductance/conductor/metre =

$$2\times10^{-7}\left[\frac{1}{4}+\log_e \frac{d}{r}\right] \longrightarrow ①$$

$$\Rightarrow 2\times10^{-7}\left[\frac{1}{4}\right]+2\times10^{-7}\log_e \frac{d}{r}$$

In the above expression the first term $2\times10^{-7}\left[\frac{1}{4}\right]$ is the inductance due to ~~inter~~ flux within solid conductor. For the many purposes it is desirable to eliminate this term by the introduction of concept called GMR. It can be proved mathematically that by ~~solving~~ solid round conductor of radius 'r'

Self GMD of (or) GMR(D_s) = $0.7788\,r = r'$

Using GMR eq ① becomes

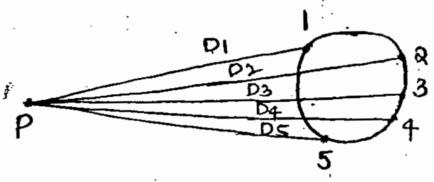
Inductance/conductor/metre $= 2\times10^{-7}\log_e \frac{d}{r'}$

$$= 2\times10^{-7}\log_e \frac{d}{D_s}$$

where D_s = GMR

$$\boxed{D_s = 0.7788\,r = r'}$$

GMD or MUTUAL GMD (D_M): Mutual GMD is the mathematical concept used for the calculation of inductance. By definition the mutual GMD or GMD of a point with respect to no. of points is the geometric mean of the distances between that point and each of the other points.



The GMD of point p w.r.to five points on the circle.

$$GMD_p = \sqrt[5]{D_1 D_2 D_3 D_4 D_5}$$

The concept of GMD is applicable to circular areas also. The GMD between two circular areas will be the distance between the centre of two areas.

1-ϕ system:

$$\text{Inductance/conductor/mt} = 2\times10^{-7}\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

$$= 2\times10^{-7}\left[\log_e\frac{d}{r'}\right]$$

$$= 2\times10^{-7}\log_e\frac{GMD}{GMR}$$

$$= 2\times10^{-7}\log_e\frac{D_M}{D_S}$$

3-ϕ system [single circuit]:

$$\text{Inductance/conductor/mt} = 2\times10^{-7}\left[\frac{1}{4}+\log_e\frac{d}{r}\right]$$

$$= 2\times10^{-7}\left[\frac{1}{4}+\log_e\frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right]$$

$$= 2\times10^{-7}\log_e\frac{\sqrt[3]{d_1 d_2 d_3}}{r'}$$

$$= 2\times10^{-7}\log_e\frac{GMD}{GMR}$$

where $GMD = \sqrt[3]{d_1 d_2 d_3}$

For symmetrical : $d_1 = d_2 = d_3 = d$

where $GMR = r' = 0.7788\, r$

$r \rightarrow$ actual radius of the conductor.

For 3-ϕ Double circuit system :

$$\text{Inductance/phase/mt} = 2\times10^{-7} \log_e \frac{GMD}{GMR}$$

where GMD is equivalent mutual GMD of one phase.

GMR = equivalent self GMD of one phase.

Consider the conductor arrangement of the double circuit as shown in below fig. suppose radius of each conductor is 'r' mts.

a o   o c'

b o   o b'

c o   o a'

Self GMD of each conductor $= 0.7788\, r = r'$

Self GMD of combination aa' $D_{s_1} = (r' D_{aa'}\, r'\, D_{a'a})^{1/4}$

where $D_{aa'}$ = Distance between conductors a and a'

$D_{a'a}$ = Distance between conductors a' and a.

Self GMD of combination bb' $D_{s_2} = (r' D_{bb'}\, r'\, D_{b'b})^{1/4}$

where $D_{bb'}$ = Distance between conductors b and b'

$D_{b'b}$ = Distance between conductors b' and b.

Self GMD of combination cc' $D_{s_3} = (r' D_{cc'}\, r'\, D_{c'c})^{1/4}$

where $D_{cc'}$ = Distance b/w conductors c and c'

$D_{c'c}$ = Distance b/w conductors c' and c.

Equivalent self GMD, $D_s = (D_{s_1} D_{s_2} D_{s_3})^{1/3}$

Mutual GMD between phases a and b is $D_{ab} = (D_{ab}\, D_{ab'}\, D_{a'b}\, D_{a'b'})^{1/4}$

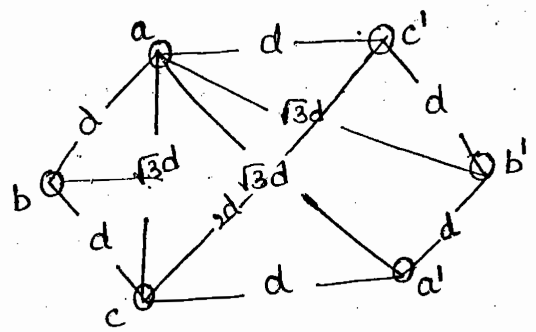
Mutual GMD between phases b and c $D_{BC} = (D_{bc}\, D_{bc'}\, D_{b'c}\, D_{b'c'})$

Mutual GMD between phases c and a $D_{ca} = (D_{ca}\, D_{ca'}\, D_{c'a}\, D_{c'a'})$

Equivalent Mutual GMD of one-phase $D_M = (D_{ab}\, D_{bc}\, D_{ca})^{1/3}$

Calculation of Inductance of 3-ϕ double circuit with symmetrical spacing.

Consider a 3-ϕ double circuit connected in parallel conductors. a, b, c forming one circuit. Conductors a', b', c forming the other one as shown in below fig.



We know inductance/phase/metre $= 2\times10^{-7} \log_e \frac{GMD}{GMR}$

$D_{ab} = D_{bc} = D_{ac'} = D_{c'b'} = D_{ca'} = D_{b'a'} = d$

$D_{ac} = D_{b'c} = D_{c'a'} = D_{bc'} = D_{ba'} = D_{ab'} = \sqrt{3}\, d$

$D_{aa'} = D_{bb'} = D_{cc'} = 2d$

Inductance of phase 'a' $L_A = 2\times10^{-7} \log_e \frac{D_M}{D_s}$

D_M of phase a is

$$= \sqrt[8]{D_{ab}\, D_{ac}\, D_{ab'}\, D_{ac'}\, D_{a'b}\, D_{a'c}\, D_{a'b'}\, D_{a'c'}}$$

$$= \sqrt[8]{d.\sqrt{3}d.\sqrt{3}d.\ d.\sqrt{3}d.\ d\, d.\ \cancel{2d}\ \sqrt{3}d.}$$

$$\boxed{D_M = \sqrt[4]{3}\, d}$$

D_s of phase a is $\sqrt[4]{R' D_{aa'} D_{aa'} R'}$

$$= \sqrt[4]{r' \cdot 2D \cdot 2D \cdot r'} \qquad = \sqrt[4]{r'^2 \cdot 4D^2}$$

$$= (r'^2)^{1/4} (4D^2)^{1/4}$$

$$= (r')^{1/2} (4D)^{1/2}$$

$$= (r')^{1/2} (2)^{1/2} (D)^{1/2}$$

$$= \sqrt{2dr'}$$

$$D_s = \sqrt{2dr'}$$

$$L_A = 2\times10^{-7} \log_e\left(\frac{D_M}{D_s}\right)$$

$$= 2\times10^{-7} \log_e \frac{\sqrt[4]{3D}}{\sqrt{2dr'}}$$

$$= 2\times10^{-7}\left(\frac{1}{2}\log_e \frac{\sqrt{3}d}{2r'}\right)$$

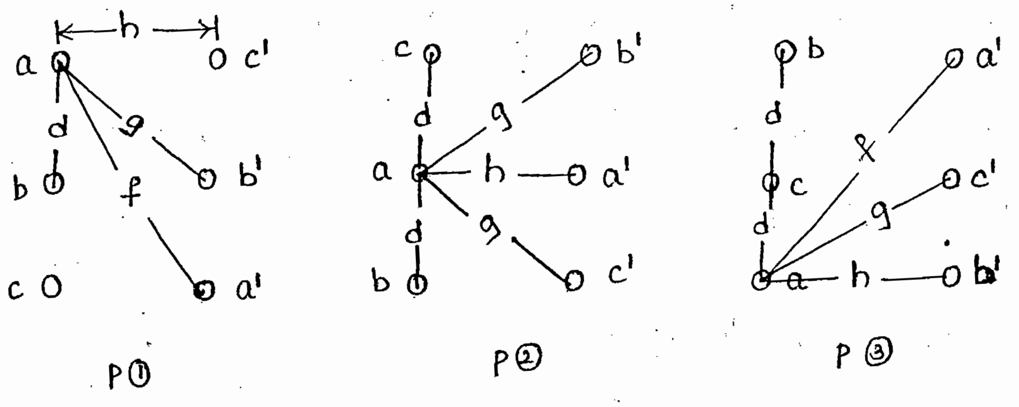
$$L_A = 1\times10^{-7}\left(\log_e \frac{\sqrt{3}d}{2r'}\right) \text{ H/m/ph.}$$

Inductance of each conductor will be $2\times L_A = 2\times10^{-7}\left(\log_e \frac{\sqrt{3}d}{2r'}\right)$ H/m/ph.

2

Calculation of Inductance of 3-ϕ double circuit with asymmetrical passi & (transposed line)

The double circuit line consists of 3 conductors in each circuit as shown in below fig. The three conductors corresponds to 3-phas a, b, c and a', b', c'. Conductors a and a' are combined to form one ph similarly conductors b and b' and c and c' form other phases.



$$\text{Inductance/phase/metre} = 2\times10^{-7}\log_e \frac{GMD}{GMR}$$

where GMD is the equivalent mutual GMD of one phase

GMR is the equivalent self GMD of one phase

Self GMD of phase aa' conductors in position 1 $D_{s_1} = (D_{aa}\, D_{aa'}\, D_{a'a'}\, D_{a'a})^{1/4}$

$$D_{s_1} = (r'f\ r'f)^{1/4}$$
$$= (r'^2 f^2)^{1/4}$$
$$= (r'f)^{1/2}$$
$$D_{s_1} = \sqrt{r'f}$$

Self GMD of phase aa' conductors in position 2 $D_{s_2} = \sqrt{r'h}$

$$(D_{aa'} = D_{a'a} = h)$$

Self GMD of phase aa' conductors in position 3 $D_{s_3} = \sqrt{r'f}$

Equivalent self GMD or GMR, $D_s = (D_{s_1} D_{s_2} D_{s_3})^{1/3}$ $\quad (r'^{1/2} f^{1/2}\, r'^{1/2} h^{1/2}\, r'^{1/2} f^{1/2})^{1/3}$

$$D_s = r'^{1/2}\ f^{1/3}\ h^{1/6}$$

The GMD of conductors in phase a if the conductors in other two phases in position ①

$$GMD\ ① = D_{M①} = (d\ 2d\ hg)^{1/4}$$
$$= 2^{1/4}\ d^{1/2}\ h^{1/4}\ g^{1/4}$$

Similarly GMD ② $D_{M②} = (d \; d \; g \; g)^{1/4}$

$$= d^{1/2} g^{1/2}$$

GMD③ $D_{M③} = (d \; 2d \; g \; . h)^{1/4}$

Equivalent GMD $D_M = (D_{M①} \cdot D_{M②} \cdot D_{M③})^{1/3}$

$$D_M = (2^{1/4} d^{1/2} h^{1/4} g^{1/4} \, d^{1/2} \, g^{1/2} \, d^{1/2} \, 2^{1/4} \, h^{1/4} \, g^{1/4})^{1/3}$$

$$D_M = (2^{1/6} d^{1/2} g^{1/3} h^{1/6})$$

∴ Inductance / phase / metre $= 2 \times 10^{-7} \log_e \frac{GMD}{GMR}$

$$= 2 \times 10^{-7} \log_e \frac{2^{1/6} d^{1/2} g^{1/3} h^{1/6}}{r'^{1/2} f^{1/3} h^{1/6}}$$

$$= 2 \times 10^{-7} \log_e 2^{1/6} \left[\frac{d}{r'}\right]^{1/2} \left[\frac{g}{f}\right]^{1/3} \text{ H/m/ph.}$$

BUNDLED CONDUCTORS :

Bundled conductor is a conductor made up of two or more conductors called the sub-conductors per phase in close proximity compared with spacing between phases. The basic difference between a composite conductor and bundled conductor is that the sub-conductors of bundled conductors are separated from each other by a constant distance varying 0.2 mts to 0.6 mts depending upon designed voltage through out the length of the line with the help of spacers. Where as the wire of composite conductor touches each other.

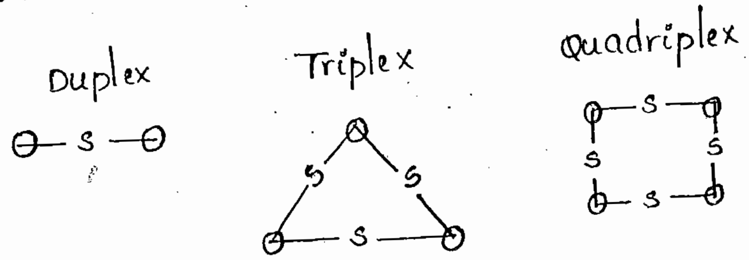
Advantages :

1. The GMR of bundled conductor is more (increased) therefore inductance per phase reduced. It leads to improvement in voltage regulation.
2. Transmission efficiency is increases because decrement of power losses due to corona.

3. Low surge impedance therefore increases the max. power transfer capability.

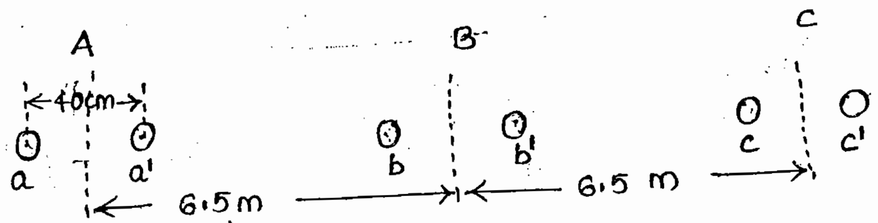
4. Improving Powerfactor.

The following are the different arrangements of bundled conductors :



CALCULATION OF INDUCTANCE OF BUNDLED CONDUCTORS :

1. Determine the inductance/km/phase of a single circuit 460kv line using two sub-conductors/phase. as shown in fig. The diameter of each conductor is 5cm.



$$L/ph/m = 2\times10^{-7} \log_e \frac{GMD}{GMR}$$

where GMD is equivalent GMD of each phase.

GMR is equivalent GMP of each phase.

GMR of each sub-conductor. $r' = 0.7788\times2.5\times10^{-2}$ m.

Equivalent GMR of phase $aa' = D_S = \sqrt{r' B}$

$$= \sqrt{0.7788\times2.5\times10^{-2}\times40\times10^{-2}}$$

$$D_S = 0.088 \text{ m}$$

Equivalent GMD between A and B phases D_{AB} $D_{M①} = (D_{ab}\, D_{ab'}\, D_{a'b}$

$$D_{M①} = (6.5\times6.9\times6.1\times6.5)^{1/4}$$

$$= 6.494 \text{ m}$$

GMD between B and C phases $D_{M②} = (D_{bc}\, D_{bc'}\, D_{b'c}\, D_{b'c'})^{1/4}$

$$= (6.5\times6.9\times6.1\times6.5)^{1/4}$$

$$D_{M②} = 6.494 \text{ m}$$

GMD between c and A phases $D_{M③} = (D_{ca}\, D_{ca'}\, D_{c'a}\, D_{c'a'})^{1/4}$

$$= (13 \times 12.6 \times 13.4 \times 13)^{1/4}$$

$$D_{M③} = 12.997$$

Equivalent GMD of phase aa' $D_M = (D_{M①} \cdot D_{M②} \cdot D_{M③})^{1/3}$

$$D_M = (6.494 \times 6.494 \times 12.997)^{1/3}$$

$$D_M = 8.183$$

Inductance/phase/kilo metre $= 2 \times 10^{-7} \log_e \frac{GMD}{GMR}$

$$= 2 \times 10^{-7} \log_e \frac{8.183}{0.088}$$

$$= 9.0604 \times 10^{-7} = 0.907 \text{ mH/km}.$$

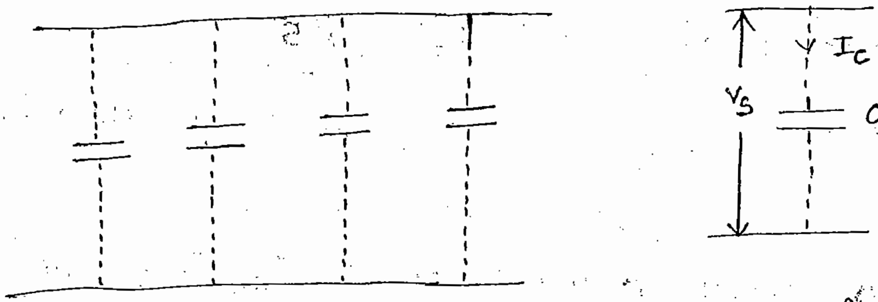
0.907 mH/km

→ **CAPACITANCE** : We know that any two conductors separated by insulating material constitute a capacitance. As any two conductors of an overhead transmission line are separated by air. It acts as an insulation. Therefore capacitance exists b/w any two over-headline conductors. The capacitance b/w the conductor is the charge per unit potential difference

Capacitance $c = \frac{q}{V}$ Farads.

where q = charge of the line in coulomb

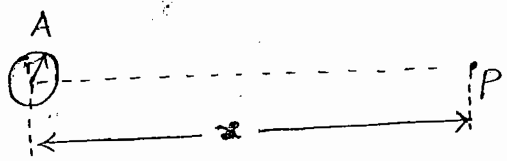
V = potential difference b/w the conductors.



In capacitance calculation the concept of potential is very important.

In general electric potential or potential at any point in an electric field is defined as the workdone in moving a unit positive charge from infinity to that point.

POTENTIAL AT A CHARGED CONDUCTOR : Consider a long straight cylindrical conductor 'a' of radius 'r' mts and having a charge of 'q' coulombs per metre of its length as shown in below fig.



17mH /km

Consider the electric field intensity at a distance 'x' from the centre of conductor is given by

$$E = \frac{q}{2\pi \varepsilon_0 \varepsilon_r x} \; V/m$$

taking air as medium i.e., $\varepsilon_r = 1$, therefore $E = \frac{q}{2\pi \varepsilon_0 x}$ V/m.

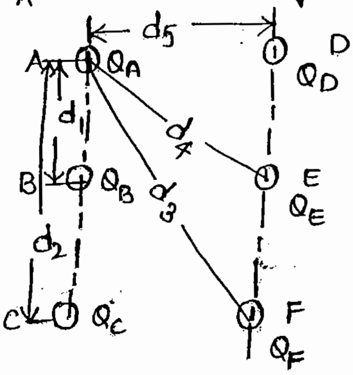
The potential difference b/w conductor A and infinity distant neutral plane. (A plane where E and therefore potential is zero). will be equal to workdone in bringing unit positive charge against 'E' from infinity to conductor surface and is given by

$$V_A = \int_r^{\infty} \frac{q}{2\pi\varepsilon_0 x} \cdot dx$$

$$= \frac{q}{2\pi\varepsilon_0} \int_r^{\infty} \frac{1}{x} \cdot dx$$

potential at conductor in group of charged conductors :

Consider a group of long straight conductors A, B, C etc. operating a potentials such as q_A, q_B, q_C etc. coulomb per metre length exists on the respective conductors as shown in below fig. Let us find the potential at A i.e., V_A in this arrangement.



Potential at A due to its own charge $= \int_{r}^{\infty} \frac{Q_A}{2\pi\varepsilon_0 x} \cdot dx \longrightarrow ①$

Potential at conductor A due to charge $Q_B = \int_{d_1}^{\infty} \frac{Q_B}{2\pi\varepsilon_0 x} \cdot dx \longrightarrow ②$

Potential at conductor A due to charge $Q_c = \int_{d_2}^{\infty} \frac{Q_c}{2\pi\varepsilon_0 x} \cdot dx \longrightarrow ③$

→ Overall potential difference between A and infinite neutral plane is

$V_A = eq ① + eq ② + eq ③$

$$= \int_{r}^{\infty} \frac{Q_A \cdot dx}{2\pi\varepsilon_0 x} + \int_{d_1}^{\infty} \frac{Q_B \cdot dx}{2\pi\varepsilon_0 x} + \int_{d_2}^{\infty} \frac{Q_c}{2\pi\varepsilon_0 x} \cdot dx$$

$$= \frac{1}{2\pi\varepsilon_0 \cancel{x}}\left[\int_{r}^{\infty} \frac{Q_A}{x} \cdot dx + \int_{d_1}^{\infty} \frac{Q_B}{x} dx + \int_{d_2}^{\infty} \frac{Q_c}{x} \cdot dx\right]$$

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

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

$m \log_e n = \log_e (n)^m$

$-\log_e r = (-1)\log_e r$

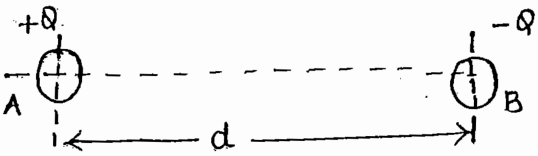
$= \log_e (r)^{-1} = \log_e \frac{1}{r}$

Assuming balanced condition i.e., $Q_A + Q_B + Q_c = 0$.

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

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

→ Capacitance of a single-phase 2 wire line: Consider a single-phase overhead transmission line consisting of 2 parallel conductors A and B spaced 'd' mts apart in air suppose that the radius of each conductor is 'r' mts. Let their respective charges are +Q and −Q coulombs per metre-length.



$$C = \frac{Q}{V_{AB}}$$

The potential difference between conductor A and infinite neutral plane.

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

$$= \frac{Q}{2\pi\varepsilon_0}\left[\int_r^\infty \frac{1}{x}\,dx - \int_d^\infty \frac{1}{x}\,dx\right]$$

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

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

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

Potential difference b/w conductor B and infinite neutral plane

$$V_B = \int_{\cancel{d}\,r}^\infty \frac{-Q}{2\pi\varepsilon_0 x}\,dx + \int_d^\infty \frac{Q}{2\pi\varepsilon_0 x}\,dx$$

$$= \frac{-Q}{2\pi\varepsilon_0}\left[\int_r^\infty +\frac{1}{x}\,dx \cancel{+} - \int_d^\infty \frac{1}{x}\,dx\right]$$

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

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

$$= \frac{-Q}{2\pi\varepsilon_0}\log_e\frac{d}{r} \text{ volts.}$$

Potential difference between conductor A and conductor B i.e.,

$$V_{AB} = V_A - V_B$$

$$= \frac{Q}{2\pi\varepsilon_0}\log_e\frac{d}{r} - \left(-\frac{Q}{2\pi\varepsilon_0}\log_e\frac{d}{r}\right)$$

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

capacitance of conductor A w.r.t. to neutral $C_{AN} = \frac{Q}{V_{AN}} = \frac{Q_A}{V_A}$

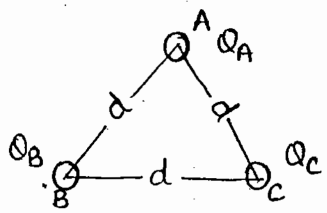
$$\Rightarrow \frac{+\cancel{Q}}{\frac{\cancel{Q}}{2\pi\varepsilon_0}\log_e d/r} \Rightarrow \frac{2\pi\varepsilon_0}{\log_e d/r} \text{ F/m}$$

$$\therefore\ C = \frac{Q}{V_{AB}}$$

$$= \frac{\cancel{Q}}{\frac{\cancel{2Q}}{\cancel{2}\pi\varepsilon_0 \cancel{V_{AB}}}\log_e\frac{d}{r}} \Rightarrow \pi\varepsilon_0 / \log_e\frac{d}{r} \text{ F/m.}$$

CAPACITANCE OF 3-ϕ OVERHEAD LINE : In a three-phase transmission line the capacitance of each conductor is considered instead of capacitance from conductor to conductor. Here again two cases i.e., Symmetrical and unsymmetrical spacing.

1. **Symmetrical spacing :** Consider the three conductors A, B and C. carries charges Q_A, Q_B, Q_C per metre length respectively. Let the conductors be equidistant ('d' mts from each other)



$a^x = b$
$\Downarrow$
$x = \log_a b$

$1 = \log_e e$

$\Rightarrow e^1 = e$

In this case we find the capacitance from line conductor to neutral. potential difference b/w conductor A w.r.to neutral plane is

Let r = Radius of each conductor in mts.

Assume balanced supply i.e., $Q_A + Q_B + Q_C = 0$

$$Q_B + Q_C = -Q_A$$

Overall potential at conductor A w.r.to infinite neutral plane.

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

$m \log_e n$
$\Rightarrow \log_e n^m$
$\Downarrow$

log

$$= \frac{1}{2\pi\varepsilon_0}\left[\int_r^\infty \frac{Q_A}{x}\cdot dx + \int_d^\infty \frac{Q_B}{x}\cdot dx + \int_d^\infty \frac{Q_C}{x}\cdot dx\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left(Q_A\left[\log x\right]_r^\infty + \ldots\right]$$

$$\Rightarrow \frac{Q_A}{2\pi\varepsilon_0}\left[\log\infty - \log r\right] +$$

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

$$= \frac{Q_A}{2\pi\varepsilon_0}\left[\log\infty + \log\frac{1}{r}\right)$$

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

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

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

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

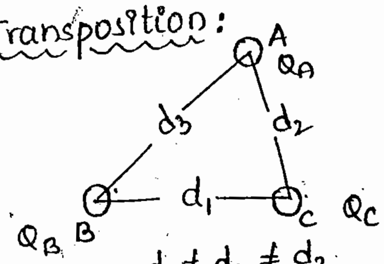
Capacitance of conductor A w.r.to neutral

$$C_A = \frac{Q_A}{V_A} = \frac{\cancel{Q_A}}{\frac{\cancel{Q_A}}{2\pi\varepsilon_0}\log_e \frac{d}{r}}$$

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

2. Unsymmetrical Spacing: In similar manner, we can derive the expressions for capacitance of conductor B and C.

Before Transposition:



$d_1 \neq d_2 \neq d_3$

Let r is the radius of each conductor. The conductors A, B and C carries charges Q_A, Q_B and Q_C per metre-length respectively.

Capacitance of conductor A w.r.to neutral $C_A = \frac{Q_A}{V_A}$

Potential of conductor w.r.to infinite neutral plane

$$V_A = \int_r^\infty \frac{Q_A}{2\pi\varepsilon_0 x}.dx + \int_{d_3}^\infty \frac{Q_B}{2\pi\varepsilon_0 x}.dx + \int_{d_2}^\infty \frac{Q_C}{2\pi\varepsilon_0 x}.dx$$

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[\int_r^\infty \frac{Q_A}{x}.dx + \int_{d_3}^\infty \frac{Q_B}{x}.dx + \int_{d_2}^\infty \frac{Q_C}{x}.dx\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_A\left(\log_e\infty + \log_e\frac{1}{r}\right) + Q_B\left(\log_e\infty + \log_e\frac{1}{d_3}\right) + Q_C\left(\log_e\infty + \log_e\frac{1}{d}\right.\right.$$

$$= \frac{1}{2\pi\varepsilon_0}\left[\log_e\infty\,(Q_A+Q_B+Q_C) + Q_A\log_e\frac{1}{r} + Q_B\log_e\frac{1}{d_3} + Q_C\log_e\frac{1}{d_2}\right]$$

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A\log_e\frac{1}{r} + Q_B\log_e\frac{1}{d_3} + Q_C\log_e\frac{1}{d_2}\right]$$

Assume balanced supply $Q_A = Q_B = Q_C$ (Three conductors carrying equal charges)

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A\log_e\frac{1}{r} + Q_A\left(\log_e\frac{1}{d_3} + \log_e\frac{1}{d_2}\right)\right]$$

$$V_A = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_A \log_e \frac{1}{d_3 d_2})\right]$$

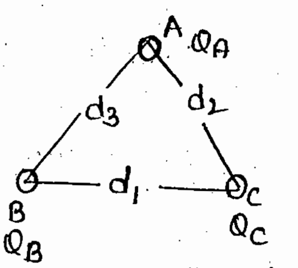
$$= \frac{Q_A}{2\pi\varepsilon_0}\left[\log_e \frac{1}{r d_3 d_2}\right]$$

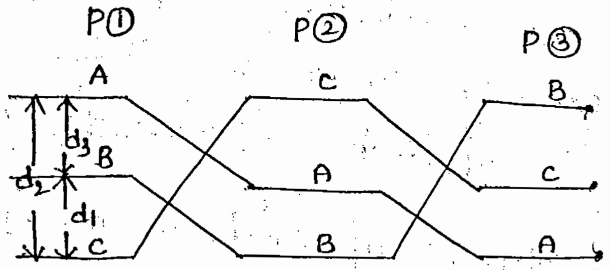
$\therefore$ Capacitance of conductor A w.r.to neutral $C_A = \frac{Q_A}{V_A}$

$$C_A = \frac{\cancel{Q_A}}{\frac{\cancel{Q_A}}{2\pi\varepsilon_0}\log_e\left(\frac{1}{r d_3 d_2}\right)}$$

$$C_A = \frac{2\pi\varepsilon_0}{\log_e\left(\frac{1}{r d_3 d_2}\right)} \text{ F/m}, \quad C_B = \frac{2\pi\varepsilon_0}{\log_e\left(\frac{1}{r d_3 d_1}\right)}, \quad C_C = \frac{2\pi\varepsilon_0}{\log_e\left(\frac{1}{r d_1 d_2}\right)}$$

After Transposition: Consider the three conductors A, B and C carrying charges Q_A, Q_B and Q_C coulombs per metre-length respectively. Radius of each conductor is 'r' mts. Assume balanced supply $Q_A + Q_B + Q_C = 0$





$d_1 \neq d_2 \neq d_3$

Potential of conductor A at p①

$$V_1 = \int_r^\infty \frac{Q_A}{2\pi\varepsilon_0 x}.dx + \int_{d_3}^\infty \frac{Q_B}{2\pi\varepsilon_0 x}.dx + \int_{d_2}^\infty \frac{Q_C}{2\pi\varepsilon_0 x}.dx$$

$$= \frac{1}{2\pi\varepsilon_0}\left[\int_r^\infty \frac{Q_A}{x}.dx + \int_{d_3}^\infty \frac{Q_B}{x}.dx + \int_{d_2}^\infty \frac{Q_C}{x}.dx\right]$$

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

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

$$V_1 = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right]$$

$$V_2 = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_c \log_e \frac{1}{d_3}\right]$$

$$V_3 = \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_c \log_e \frac{1}{d_1}\right]$$

Average voltage on conductor A $V_A = \frac{1}{3}\left[V_1 + V_2 + V_3\right]$

$$V_A = \frac{1}{3}\left[\frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_c \log_e \frac{1}{d_2} + Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} \right.\right.$$
$$\left.\left. Q_c \log_e \frac{1}{d_3} + Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_c \log_e \frac{1}{d_1}\right]\right]$$

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

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

$$= \frac{1}{3} \times \frac{1}{2\pi\varepsilon_0}\left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3}\right]$$

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

$$V_A = \frac{Q_A}{2\pi\varepsilon_0} \log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r} \text{ volts}$$

Therefore capacitance of conductor A w.r.to neutral

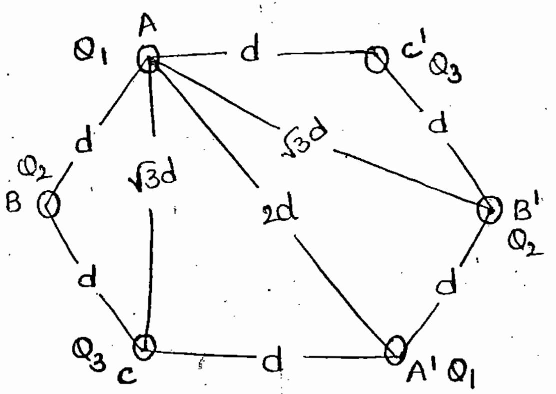
$$C_A = \frac{Q_A}{V_A}$$

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

CALCULATION OF CAPACITANCE OF 3-ϕ OVERHEAD TRANSMISSION LINE DOUBLE CIRCUIT WITH SYMMETRICAL SPACING

Consider a 3-ϕ double circuit connected in parallel conductors A, B and C forming one circuit and conductors A', B' and C' forming another circuit (conductors symmetrically spaced).

Let the charge over conductors A, B and C be the Q_1, Q_2 and Q_3 coulombs per metre-length, then charge over conductors A', B' and C' will obviously Q_1, Q_2, Q_3 coulombs p metre length and $Q_1 + Q_2 + Q_3 = 0.$



$$C_A = \frac{Q_A}{V_A}$$

$$V_A = \int_r^\infty \frac{Q_1}{2\pi\varepsilon_0 x} dx + \int_d^\infty \frac{Q_2}{2\pi\varepsilon_0 x} dx + \int_{\sqrt{3}d}^\infty \frac{Q_3}{2\pi\varepsilon_0 x} \cdot dx + \int_{2d}^\infty \frac{Q_1}{2\pi\varepsilon_0 x} \cdot dx + \int_{\sqrt{3}d}^\infty \frac{Q_2}{2\pi\varepsilon_0 x} \cdot dx + \int_d^\infty \frac{Q_3}{2\pi\varepsilon_0 x} \cdot dx$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_1\int_r^\infty \frac{1}{x}\cdot dx + Q_2\int_d^\infty \frac{1}{x} dx + Q_3\int_{\sqrt{3}d}^\infty \frac{1}{x}\cdot dx + Q_1\int_{2d}^\infty \frac{1}{x}\cdot dx + Q_2\int_{\sqrt{3}d}^\infty \frac{1}{x}\cdot dx + Q_3\int_d^\infty \frac{1}{x}\cdot dx\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\Big[Q_1\left(\log_e\infty + \log_e\tfrac{1}{r}\right) + Q_2\left(\log_e\infty + \log_e\tfrac{1}{d}\right) + Q_3\left(\log_e\infty + \log_e\tfrac{1}{\sqrt{3}d}\right)$$
$$+ Q_1\left(\log_e\infty + \log_e\tfrac{1}{2d}\right) + Q_2\left(\log_e\infty + \log_e\tfrac{1}{\sqrt{3}d}\right) + Q_3\left(\log_e\infty + \log_e\tfrac{1}{d}\right)\Big]$$

$$= \frac{1}{2\pi\varepsilon_0}\Big[2(Q_1+Q_2+Q_3)\log_e\infty + Q_1\left(\log_e\tfrac{1}{r} + \log_e\tfrac{1}{2d}\right) + Q_2\left(\log_e\tfrac{1}{d} + \log_e\tfrac{1}{\sqrt{3}d}\right)$$
$$+ Q_3\left(\log_e\tfrac{1}{\sqrt{3}d} + \log_e\tfrac{1}{d}\right)\Big]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_1 \log_e\frac{1}{r2d} + Q_2\log_e\frac{1}{\sqrt{3}d^2} + Q_3\log_e\frac{1}{\sqrt{3}d^2}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_1\log_e\frac{1}{r2d} + (Q_2+Q_3)\log_e\frac{1}{\sqrt{3}d^2}\right]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q_1\log_e\frac{1}{r2d} - Q_1\log_e\frac{1}{\sqrt{3}d^2}\right]$$

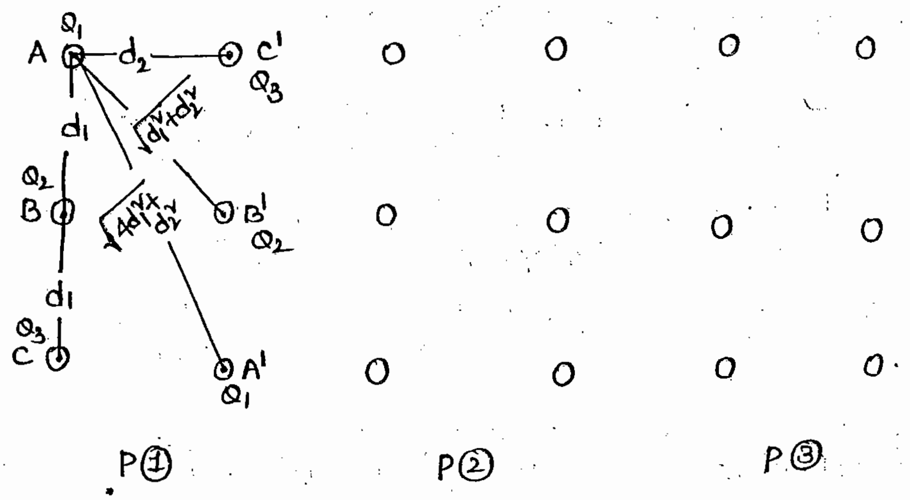
$$= \frac{Q_1}{2\pi\varepsilon_0}\left[\log_e\frac{\sqrt{3}d^{\cancel{2}}}{r2\cancel{d}}\right]$$

$$V_A = \frac{Q_1}{2\pi\varepsilon_0}\left[\log_e\frac{\sqrt{3}d}{2r}\right]$$

$$C_A = \frac{Q_A}{\frac{Q_1}{2\pi\epsilon_0}\left[\log_e \frac{\sqrt{3}d}{2r}\right]}$$

CAPACITANCE OF 3-ϕ DOUBLE CIRCUIT WITH UNSYMMETRICAL SPACING and TRANSPOSED :-

Consider conductors arranged as shown in above fig. Each conductor having radius of 'r' mts. The P①, P② and P③ corresponding to different positions in the transposition of lines.



Capacitance of conductor A w.r.to neutral

$$C_{AN} = \frac{Q_1}{V_{AN}}$$

Potential of conductor A w.r.to infinite neutral plane at P①

$$V_1 = \frac{1}{2\pi\epsilon_0}\left[Q_1\int_r^\infty \frac{dx}{x} + Q_2\int_{d_1}^\infty \frac{dx}{x} + \int_{2d_1}^\infty \frac{dx}{x} Q_3 + Q_1\int_{\sqrt{4d_1^2+d_2^2}}^\infty \frac{dx}{x} + \int_{\sqrt{d_1^2+d_2^2}}^\infty \frac{dx}{x} Q_2 + Q_3\int_{d_2}^\infty \frac{dx}{x}\right]$$

$$= \frac{1}{2\pi\epsilon_0}\Big[Q_1(\log_e\infty + \log 1/r) + Q_2(\log_e\infty + \log_e 1/d_1) + Q_3(\log_e\infty + \log_e 1/2d_1) +$$

$$Q_1(\log_e\infty + \log_e 1/\sqrt{4d_1^2+d_2^2}) + Q_2(\log_e\infty + \log_e\sqrt{d_1^2+d_2^2}) +$$

$$Q_3(\log_e\infty + \log_e 1/d_2)\Big]$$

$$= \frac{1}{2\pi\varepsilon_0}\left[Q(Q_1+Q_2+Q_3)\log_e\infty + Q_1\left(\log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}}\right) + Q_2\left(\log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right)\right.$$
$$\left. + Q_3\left(\log_e\left(\frac{1}{2d_1d_2}\right)\right)\right]$$

$$V_1 = \frac{1}{2\pi\varepsilon_0}\left[Q_1\left(\log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}}\right) + Q_2\left(\log_e \frac{1}{d\sqrt{d_1^2+d_2^2}}\right) + Q_3\left(\log_e \frac{1}{2d_1d_2}\right)\right]$$

Similarly at P ②

$$V_2 = \frac{1}{2\pi\varepsilon_0}\left[Q_1\left(\log_e \frac{1}{rd_2}\right) + Q_2\left(\log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right) + Q_3\left(\log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right)\right]$$

similarly at P ③

$$V_3 = \frac{1}{2\pi\varepsilon_0}\left[Q_1\left(\log_e \cancel{\frac{r}{r\sqrt{}}} \frac{1}{r\sqrt{4d_1^2+d_2^2}}\right) + Q_2\left(\log_e \frac{1}{2d_1d_2}\right) + Q_3\left(\log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right)\right]$$

Average potential of conductor A $V_A = \frac{1}{3}\left[V_1+V_2+V_3\right]$

$$V_A = \frac{1}{3}\left[\frac{1}{2\pi\varepsilon_0}\left[\left(Q_1 \log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}}\right) + \left(Q_2 \log_e \frac{1}{d\sqrt{d_1^2+d_2^2}}\right) + \left(Q_3 \log_e \frac{1}{2d_1d_2}\right) + \right.\right.$$
$$\left(Q_1 \log_e \frac{1}{rd_2}\right) + Q_2 \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}} + Q_3 \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}} +$$
$$\left.\left. Q_1 \log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}} + Q_2 \log_e \frac{1}{2d_1d_2} + Q_3 \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right]\right]$$

$$V_A = \frac{1}{3}\left[\frac{1}{2\pi\varepsilon_0}\left[Q_1\left(\log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}} + \log_e \frac{1}{rd_2} + \log_e \frac{1}{r\sqrt{4d_1^2+d_2^2}}\right) + \right.\right.$$
$$Q_2\left(\log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}} + \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}} + \log_e \frac{1}{2d_1d_2}\right) +$$
$$\left.\left. Q_3\left(\log_e \frac{1}{2d_1d_2} + \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}} + \log_e \frac{1}{d_1\sqrt{d_1^2+d_2^2}}\right)\right]\right]$$

$$V_A = \frac{1}{3}\left\{\frac{1}{2\pi\varepsilon_0}\left[q_1 \log_e \frac{1}{r^3 d_2(4d_1^2+d_2^2)} + q_2 \log_e \frac{1}{2d_1^3d_2(d_1^2+d_2^2)} + \right.\right.$$
$$\left.\left. q_3 \log_e \frac{1}{2d_1^3d_2(d_1^2+d_2^2)}\right]\right\}$$

$$V_A = \frac{1}{6\pi\varepsilon_0}\left\{\left[q_1 \log_e \frac{1}{r^3d_2(4d_1^2+d_2^2)}\right] + (q_2+q_3)\log_e \frac{1}{2d_1^3d_2(d_1^2+d_2^2)}\right\}$$

$$= \frac{q_1}{6\pi\varepsilon_0}\left[\log_e\left(\frac{2d_1^3\cancel{d_2}(d_1^2+d_2^2)}{r^3\cancel{d_2}(4d_1^2+d_2^2)}\right)\right]$$

$$= \frac{q_1}{2\pi\varepsilon_0}\log_e\left[\frac{2^{1/3}.d_1}{r} \times \left(\frac{d_1^2+d_2^2}{4d_1^2+d_2}\right)^{1/3}\right] \text{ volts}$$

$$V_A = \frac{Q_1}{2\pi\epsilon_0} \log_e \frac{2^{1/3} d_1}{r} \left[\frac{d_1^2+d_2^2}{4d_1^2+d_2^2}\right]^{1/3}$$

Capacitance of conductor A w.r.to neutral, $C_{AN} = \frac{Q_1}{V_{AN}} = \frac{Q_1}{V_A}$

$$C_{AN} = \frac{2\pi\epsilon_0}{\log_e \frac{2^{1/3} d_1}{r} \left[\frac{d_1^2+d_2^2}{4d_1^2+d_2^2}\right]^{1/3}} \text{ F/m} \quad ||^{ly} \quad \underset{\text{two lines}}{C_{b/w}} = \frac{4\pi\epsilon_0}{\log_e \frac{2^{1/3} \cdot d_1}{r}\left(\frac{d_1^2+d_2^2}{4d_1^2+d_2^2}\right)^{1/3}}$$

EFFECT OF EARTH ON CAPACITANCE CALCULATIONS :

In the previous capacitance calculations, we neglected the influence of earth on capacitance calculations of transmission line but this not true for extra high voltage (EHV) and the ultra high voltage (UHV) lines. For example, transmission lines above 200 kV voltage level the clearance distance b/w phases is quite comparable with the clearance b/w phases and ground.

The electric field is considerably influenced by the presence of earth, the situation requires the consideration of influence of earth on calculation of capacitance.

Let us consider a charged line of circular cross-section conductor as shown in below fig a.

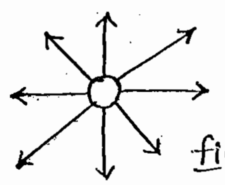
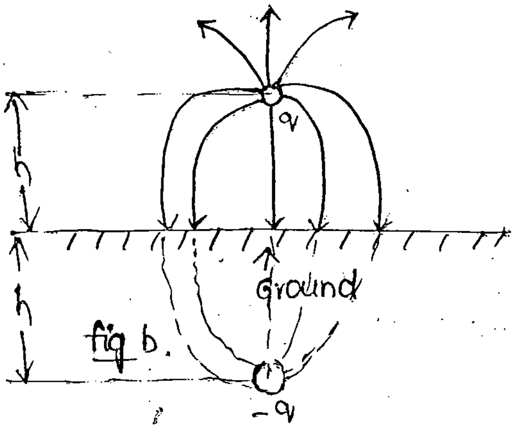


fig a

The fig above is shows the circular line charge is far moved from earth. It's electric field will be as shown above i.e., radial lines of force.

The fig. below shows how the electric field is disturbed. in the presence of earth. This field pattern above ground can be obtained by replacing by the ground and placing an imaginary oppositely charged similar conductor with same distance below the ground line. Here it is imagined but the ground levels mirror, this is called image charge see in fig c. Now the problem is reduced to pair of opposite charges.



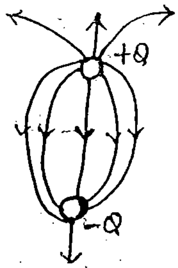


fig : c

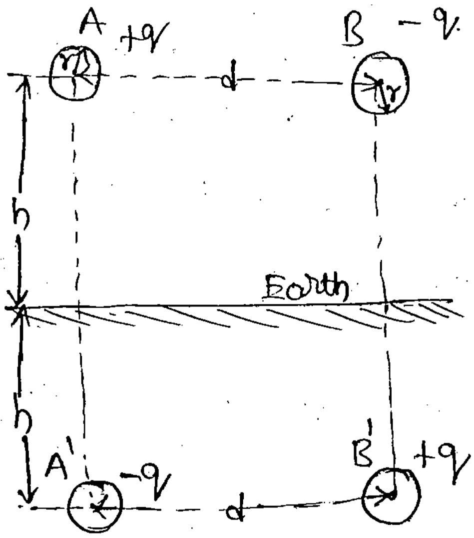
Web sources :

www. skm elecksys.com/2011/04/ influence of earth on capacitance.

~~FORMULAE~~

Effect of earth Capacitance of a 1-ϕ Tr. line :—

Consider a 1-ϕ OH line with two conductors A&B and their image conductors in earth are A' & B' respectively as shown in fig.



charge on conductor A is +q

" " A' is -q

$$V_{AB} = \frac{1}{2\pi\epsilon_0}\left[q_A \log_e \frac{d}{r} + q_B \log_e \frac{r}{d} + q_A' \log_e \frac{\sqrt{4h^2+d^2}}{2h} + q_B' \log_e \frac{2h}{\sqrt{4h^2+d^2}}\right]$$

Substituting $q_A = q_B' = +q$,

$q_A' = q_B = -q$ we get

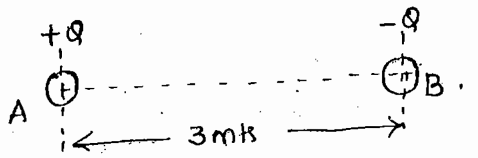
$$V_{AB} = \frac{q}{\pi\epsilon_0} \log_e \frac{2hd}{r\sqrt{(4h^2+d^2)}}$$

$$C_{AB} = \frac{q}{V_{AB}} = \left(\frac{\pi\epsilon_0}{\log_e \frac{d}{r\sqrt{1+\frac{d^2}{4h^2}}}}\right)$$

Problems

1. A single-phase transmission line has 2 parallel conductors 3 mts apart radius of each conductor being 1 cm. calculate the capacitance of the line/km. Given that $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m and also determine capaci of conductor with respect to neutral. (or) capacitance of each line conductor.

Sol



Capacitance of conductor A w.r.to neutral $C_{AN} = \frac{Q_A}{V_{AN}}$

$= \frac{+Q}{\frac{Q}{2\pi\varepsilon_0}\log_e(d/r)} \Rightarrow \frac{2\pi\varepsilon_0}{\log_e(d/r)}$ F/

Radius of each conductor $= 1 \times 10^{-2}$ m

Capacitance of the line conductor $= \frac{\pi\varepsilon_0}{\log_e(d/r)}$

$$= \frac{\pi \times 8.854 \times 10^{-12}}{\log_e\left(\frac{\cancel{2\times10^{-2}}\,3}{1\times10^{-2}}\right)} =$$

$$= 0.4875 \times 10^{-11} \text{ F/m}$$

$$= 0.4875 \times 10^{-8} \text{ F/km}.$$

Capacitance of each line conductor w.r. to neutral $= \frac{2\pi\varepsilon_0}{\log_e(d/r)}$ F/m

$$= \frac{2 \times \pi \times 8.854 \times 10^{-12}}{\log_e(3/1\times10^{-2})}$$

$$= 9.75 \times$$

2. A 3-phase 50 Hz, 66 kV overhead line conductors are placed in a horizontal plane. as shown in below fig. The conductor diameter is 1.25 cm. If the length of line is 100 km, calculate 1. capacitance/phase 2. charging current per phase. Assuming complete transposition of the line.

Sol

Given data:

Frequency $f = 50$ Hz

Voltage $V = 66$ kV

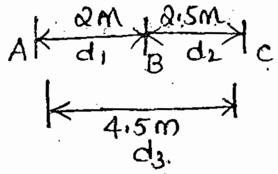
diameter $d = 1.25$ cm

length $l = 100$ km

$C/ph = ?$

$I_c/ph = ?$

$$\text{Capacitance/phase} = \frac{2\pi\varepsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}}$$



$$= \frac{2\times\pi\times 8.854\times 10^{-12}}{\log_e \frac{\sqrt[3]{2\times 2.5\times 4.5}}{6.25\times 10^{-3}}}$$

$$= \frac{5.563\times 10^{-11}}{2.65} = 0.0091\times 10^{-9}\,F/m$$

$$= 0.0091\times 10^{-6}/km$$

Line to neutral capacitance for 100 km length of transmission line

$$= 0.0091\times 10^{-6}\times 100 \cdot F$$

$$= 9.1\times 10^{-7}$$

charging current $I_c = \frac{V_{ph}}{X_c}$

$$V_{ph} = \frac{66\,k}{\sqrt{3}} = 38105.11\ V$$

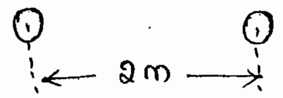
$$X_c = \frac{1}{2\pi f c} = \frac{1}{2\pi\times 50\times 9.1\times 10^{-7}} = 3497.91$$

$$I_c = \frac{38105.11}{3497.91} = 10.89\ A$$

3. Calculate the capacitance of a 100 km long 3-phase 50 Hz overhead transmission consisting of three conductors each of diameter 2 cm. and spaced 2.5 m at the corners of an equilateral triangle.

4. A single-phase line has 2 parallel conductors 2mts apart. The diameter of each conductor is 1.2 cm. Calculate the loop inductance/km.

Sol



$d = 1.2$ cm.

Loop Inductance $= 2\times10^{-7}\left[\frac{1}{2} + 2\log_e \frac{d}{r}\right]$ H/m

$= 2\times10^{-7}\left[\frac{1}{2} + 2\log_e \frac{1.2\times10^{-2}}{0.6\times10^{-2}}\right]$

$= 24.23\times10^{-7}$ H/m

$= 24.23\times10^{-4}$ H/km

$L = 2\times10^{-7}\log_e \frac{GMD}{GMR}$

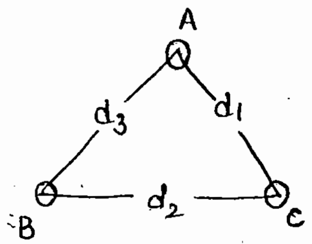
$GMR = 0.7788r = 0.7788\times0.6\times10^{-2} = 4.6728\times10^{-3}$

$GMD = 2$ mts

$L = 12.118\times10^{-7}$ H/m.

5. The 3 conductors of a 3-phase line are arranged at the corners of a triangle of sizes of 2mts, 2.5 mts and 4.5 mts. Calculate the inductance per km, when the conductors are regularly transposed. The diameter of each conductor is 1.24 cm.

Sol



$d_1 = 2$ mts, $d_2 = 2.5$ mts, $d_3 = 4.5$ mts

$d = 1.24$ cm.

$L/ph/m = 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right]$

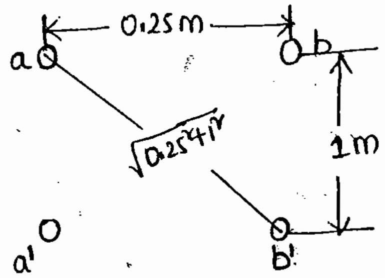
$= 10^{-7}\left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{2\times2.5\times4.5}}{0.62\times10^{-2}}\right]$

$= 12.74\times10^{-7}$ H/m

$= 12.74\times10^{-4}$ H/km.

6. Two conductors of single-phase line, each are 1 cm diameter are arranged in a vertical plane with one conductor bounded 1m above the other. A second identical line is bounded at the same height at the first end spaced horizontally 0.25 mts apart from it. The two upper and lower conductors are connected in parallel. Determine the inductance/km of the resulting double circuit line.

Sol



$$L/ph/m = 2\times10^{-7} \log_e \frac{GMD}{GMR}$$

$$= 2\times10^{-7} \log_e \frac{\text{Mutual GMD}}{\text{Self GMD}}$$

Self GMD or GMR of a and a' phase $= (D_{aa}\, D_{aa'}\, D_{a'a}\, D_{a'a'})^{1/4}$

$$= (r'\, D_{aa'}\, D_{a'a}\, r')^{1/4}$$

$$= (0.7788 \times \overset{0.5}{1} \times 10^{-2} \cdot 1 \times 1 \cdot 0.7788 \times 0.5 \times 10^{-2})^{1/4}$$

$$= 6.24\times10^{-4} = 0.0624 \text{ mts.}$$

Mutual GMD b/w a and b. $= (D_{ab}\, D_{ab'}\, D_{a'b}\, D_{a'b'})^{1/4}$

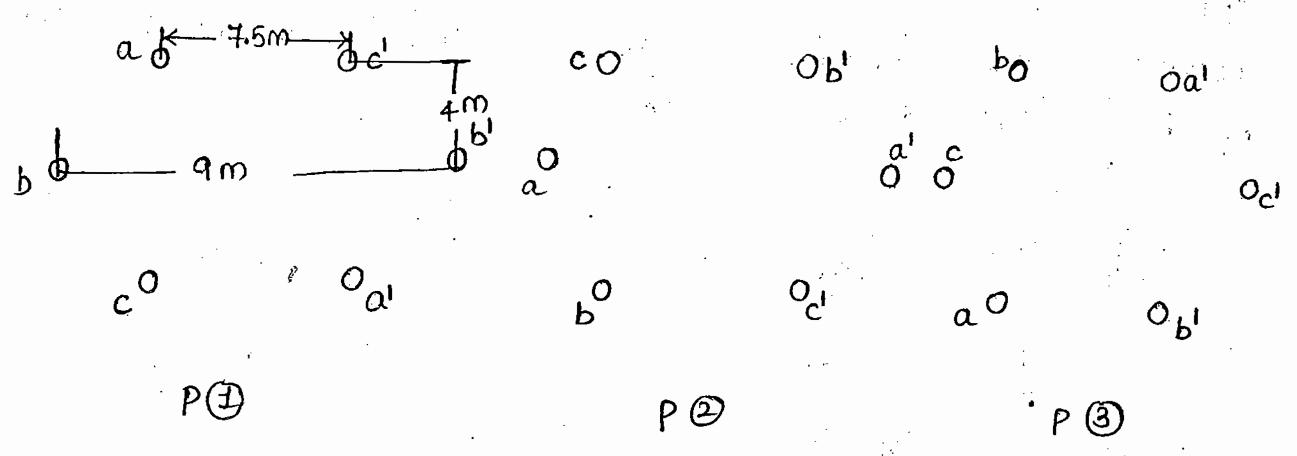
$$= (0.25 \times 1.03 \times 1.03 \times 0.25)^{1/4}$$

$$= \cancel{0.559} \quad 0.5074 \text{ mts.}$$

$\therefore$ Inductance/conductor/m or Inductance/ph/m $= 2\times10^{-7} \log_e \frac{GMD}{GMR}$

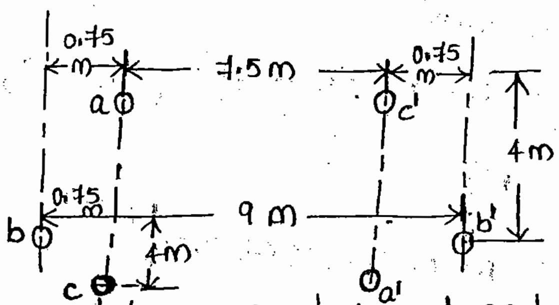
$$= 2\times10^{-7} \log_e \left(\frac{0.5074}{0.0624}\right) = 4.2 \times 10^{-7} \text{ H/m}$$

7. Determine the inductance/km of a transposed double circuit 3-phase line shown in below fig. Each circuit of the line on its own side. The diameter of conductor is 2.532 cm.



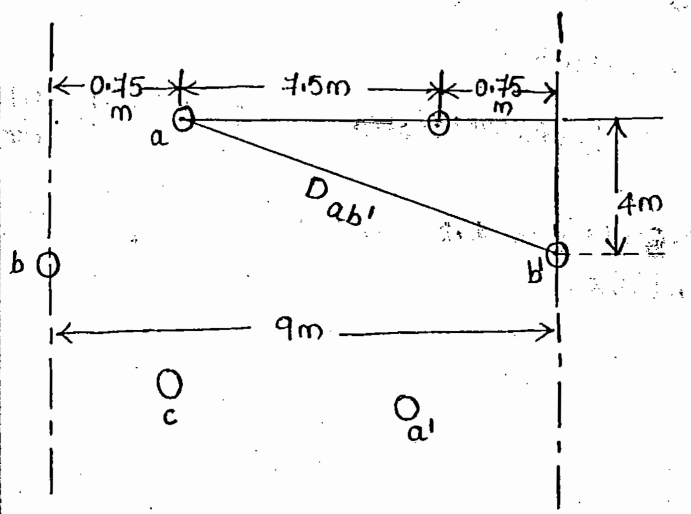
$$\text{Inductance/ph/m} = 2\times10^{-7} \log_e \frac{GMD}{GMR}$$

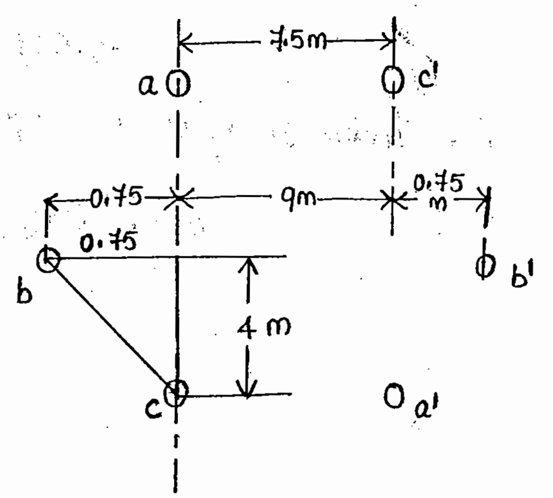
The distance between conductor A to b' $D_{ab'} = \sqrt{4^2+8.25^2} = 9.16$.

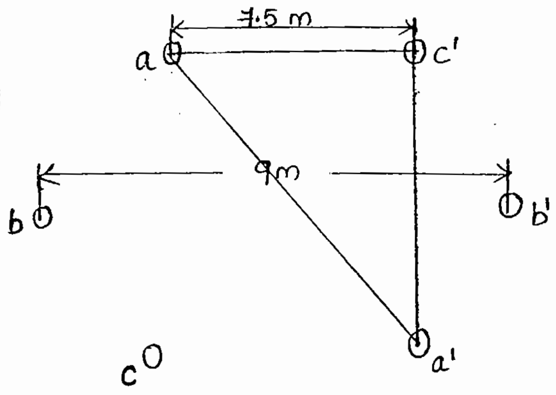


The distance between conductor b and c = The distance between a and b = $\sqrt{4^2+0.75^2} = 4.069$ m.

The distance between a to a' $D_{aa'} = \sqrt{8^2+\cancel{0.75^2}\,7.5^2} = 10.965$ m







7.5 m
a
c'
9m
b
b'
c
a'