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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

(R18A0207) POWER SYSTEMS - I

For

B.Tech (EEE) – II YEAR – II SEMESTER

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UNIT-1

THERMAL POWER STATIONS

INTRODUCTION:

- Thermal energy is the major source of power generation in India. More than 60% of electric power is produced by steam plants in India. India has large deposit of coal (about 170 billion tones), 5^{th} largest in world. Indian coals are classified as A-G grade coals.
- In Steam power plants, the heat of combustion of fossil fuels is utilized by the boilers to raise steam at high pressure and temperature. The steam so produced is used in driving the steam turbines or sometimes steam engines couples to generators and thus in generating electrical energy.
- Steam turbines or steam engines used in steam power plants not only act as prime movers but also as drives for auxiliary equipment, such as pumps, stokers fans etc.
- Steam power plants may be installed either to generate electrical energy only or generate electrical energy along with generation of steam for industrial purposes such as in paper mills, textile mills, sugar mills and refineries, chemical works, plastic manufacture, food manufacture etc.
- The steam for process purposes is extracted from a certain section of turbine and the remaining steam is allowed to expand in the turbine. Alternatively the exhaust steam may be used for process purposes.
- Thermal stations can be private industrial plants and central station.

Coal Classification

Coal Type	kJ/kg	kWh/kg	kCal/kg
Peat	8000	28800000	1912
Lignite	20000	72000000	4780
Bituminous	27000	97200000	6453
Anthracite	30000	108000000	7170

Advantages and Disadvantages of a Thermal Power Plant

Advantages:

- Less initial cost as compared to other generating stations.
- It requires less land as compared to hydro power plant.
- The fuel (i.e. coal) is cheaper.

- The cost of generation is lesser than that of diesel power plants.

Disadvantages:

- It pollutes the atmosphere due to the production of large amount of smoke. This is one of the causes of global warming.
- The overall efficiency of a thermal power station is low (less than 30%).
- Requires long time for erection and put into action.
- Costlier in operating in comparison with that of Hydro and Nuclear power plants.
- Requirement of water in huge quantity.

Selection of site for thermal power plant

- **Nearness to the load centre:** The power plant should be as near as possible to the load centre to the centre of load .So that the transmission cost and losses are minimum. This factor is most important when Dc supply system is adopted. However in the case of AC supply when transformation of energy from lower voltage to higher voltage and vice versa is possible power plants can be erected at places other than that of load provided other conditions are favorable.
- **Water resources:** For the construction and operating of power plant large volumes of water are required for the following reasons
  - To raise the steam in boiler.
  - For cooling purpose such as in condensers
  - As a carrying medium such as disposal of ash.
  - For drinking purposes.
  - This could be supplied from either rivers or underground water resources. Therefore having enough water supplies in defined vicinity can be a factor in the selection of the site.
- **Availability of Coal:** Huge amount of coal is required for raising the steam. Since the government policy is to use the only low grade coal with 30 to 40 % ash content for power generation purposes, the steam power plants should be located near the coal mines to avoid the transport of coal & ash.
- **Land Requirement:** The land is required not only for setting up the plant but for other purposes also such as staff colony, coal storage, ash disposal etc.

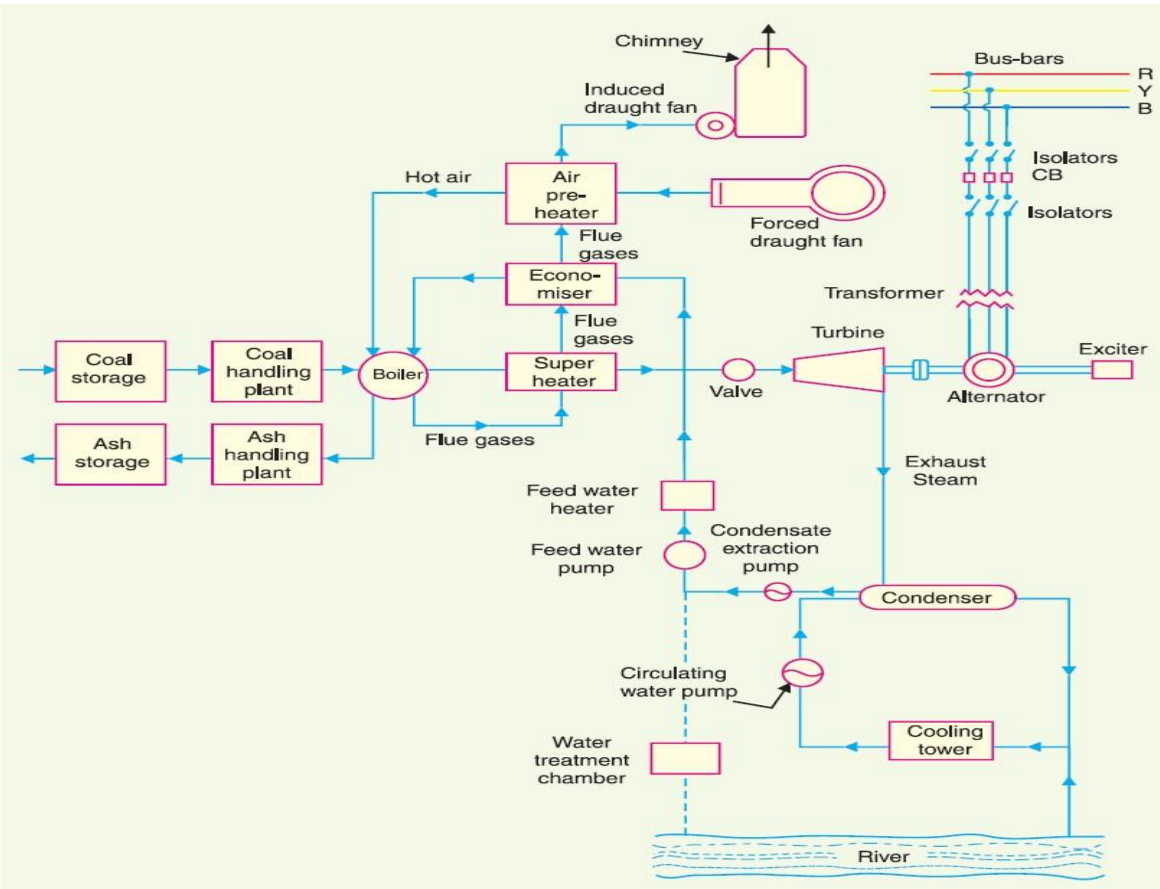
   - **Eg:** For 2000MW plant, the land requirement may be of the order of 200-250 acres. As the cost of the land adds up to the final cost of the plant, it should be available at a reasonable price. Land should be available for future extension.

- **Transportation Facilities**: The facilities must be available for transportation of heavy equipment and fuels e.g near railway station.
- **Labour supplies:** Skilled and unskilled laborers should be available at reasonable rates near the site of the plant.
- **Ash Disposal:** Ash is the main waste product of the steam power plant and with low grade coal, it may be 3.5 tones per day , some suitable means for disposal of ash should be though of. It may be purchased by building contractors, or it can be used for brick making near the plant site. If the site is near the coal mine it can be dumped into the disused mines. In case of site located near a river,sea or lake ash can be dumped into it.
- **Distance from populated area:** The continuous burning of coal at the power station Produces smoke, fumes and ash which pollute the surrounding area. Such a pollution due to smoke is dangerous for the people living around the area. Hence, the site of a plant should be at a considerable distance from the populated area.

Major Components of a Thermal Power Plant

- **Coal Handling Plant**
- **Pulverizing Plant**
- **Draft or Draught fan**
- **Boiler**
- **Ash Handling Plant**
- **Turbine and Generator**
- **Condenser**
- **Cooling Tower And Ponds**
- **Feed Water Heater**
- **Economiser**

- **Super heater and Reheater**
- **Air pre heater**
- **Alternator with Exciter**
- **Protection and control equipment**
- **Instrumentation**



Schematic arrangement of Steam Power Station

- A boiler (or steam generator) is a closed vessel in which water, under pressure, is converted into steam. The heat is transferred to 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

- ❖ Generally water tube boilers are used for electric power stations.

Fire Tube Boiler

- ❖ The boiler is named so because the products of combustion pass through the tubes which are surrounded by water.
- ❖ Depending on whether the tube is vertical or horizontal the fire tube boiler is divided into two types
  - Vertical tube boiler
  - Horizontal tube boiler
- ❖ A fire tube boiler is simple, compact and rugged in construction. Its initial cost is low.
- ❖ Water being more and circulation being poor they cannot meet quickly to changes in steam demand.
- ❖ As water and steam, both are in the same shell, higher pressure of steam are not possible, the maximum pressure which can be had is 17.5 kg/cm^2 with a capacity of 15,000kg of steam per hour.
- ❖ For the same output the outer shell of a fire tube boiler is much larger than that of a water tube boiler.
- ❖ In the event of a sudden and major tube failure. Steam explosions may be caused in the furnace due to rush of high pressure water into the hot combustion chamber which may generate large quantities of steam in the furnace.
- ❖ Fire tube boilers use is therefore limited to low cost small size and low pressure plants.

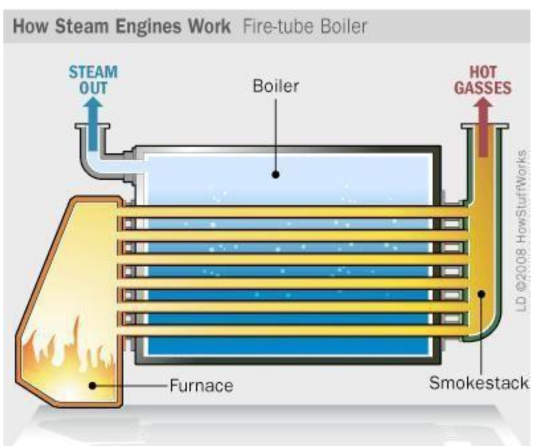


Figure: Fire Tube Boiler

Water Tube Boilers

- In this boiler, the water flows inside the tubes and hot gases flow outside the tube.
- Water tube boiler are classified as
- Vertical tube boiler
- Horizontal tube boiler
- Inclined tube boiler
- The circulation of water in the boiler is may be natural or forced.
- For Central steam power plants large capacity of water tube boilers are used.
- The tubes are always external to the drum they can be built in smaller size and therefore withstand high pressure.
- The boiler drum contains both steam and water, the former being trapped from the top of the drum where the highest concentration of dry steam exists.

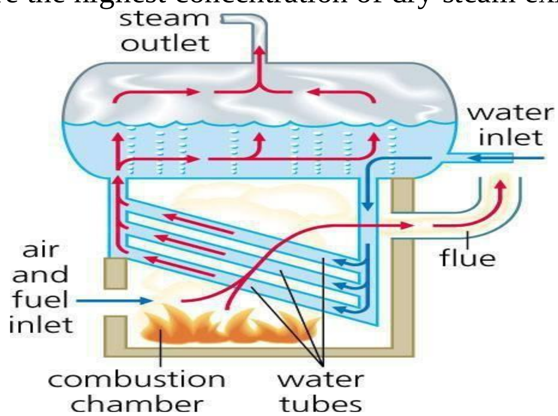


Figure: Water tube boiler

SUPERHEATER AND REHEATERS

- The function of the super heater is to remove the last trash of moisture from the saturated steam leaving the boiler tubes and also increases its temperature above the saturation temperature.
- For this purpose the heat of the combustion gases from the furnace is utilized.
- Super heated steam is that steam which contains more heat than the saturated steam at the same pressure. The additional heat provides more energy to the turbine hence

power output is more.

- ❖ Superheated steam causes lesser erosion of the turbine blades and can be transmitted for longer distance with little heat loss
- ❖ A super heater may be convention type, radiant type or combination. However, convention super heaters are more commonly used.

Figure: Super heaters

REHEATER

- ❖ In addition to super heater modern boiler has reheater also. The function of the reheater is to superheat the partly expanded steam from the turbine, this ensure that the steam remain dry through the last stage of the turbine.
- ❖ A reheater may be convention type, radiant type or combination.

Feed Water Heaters: These heaters are used to heat the feed water by means of blend steam before it is supplied to the boiler. Necessity of heating feed water before feeding it back to the boiler arises due to the following reasons.

- ❖ 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 precipitated outside the boiler.

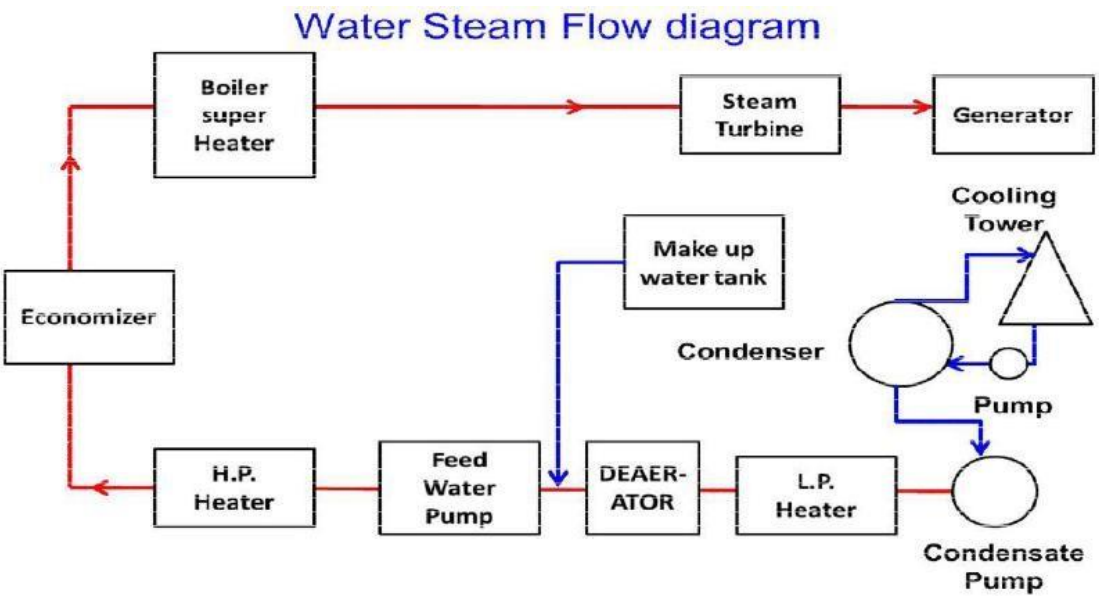


Figure: Water steam flow diagram

ECONOMIZER

❖ Boilers are provided with economizer and air pre-heaters to recover heat from the flue gases. An increase of about 20% in boiler efficiency is achieved by providing both economizer and air pre-heaters.

❖ Economizer alone gives only 10-12% efficiency increase, causes saving in fuel consumption 5-15 %. The feed water from the high pressure heaters enters the economizer and picks up heat from the flue gases after the low temperature super heater.

❖ Economizer can be classified as an inline or staggered arrangement based on the type of tube arrangement.

❖ For pressure of 70 Kg/cm^2 or more economizer becomes a necessity.

❖ The tubes are arranged in parallel continuous loops.

❖ Feed water flows through the tubes and the flue gases outside the tubes across them.

The feed water should be sufficiently pure not to cause forming of scales and cause internal corrosion and under boiler pressure.

- The temperature of the feed water entering the economizer should be high enough so that moister from the flue gases does not condense on the economizer tubes.

AIR PREHEATERS

- After the flue gases leave economizer, some further heat can be extracted from them and is used to heat the incoming air for combustion.
- Air preheaters may be of following types:
  - Plate type
  - Tubular type
  - Regenerative type
- Cooling of flue gases by 20^{0}increase the efficiency of the plant by 1%.
- The use of air preheaters is more economical with pulverized fuel boilers because the temperature of flue gases going out is sufficiently large and high air temperatures (250 to 350^{0} C) is always desirable for better combustion.
- Air preheaters should have high thermal efficiency, reliability of operation, less maintenance charges, should occupy small space, should be reasonable in initial cost and should be accessible.
- In order to avoid corrosion of the air preheaters, the flue gases should not be cooled below the dew point.

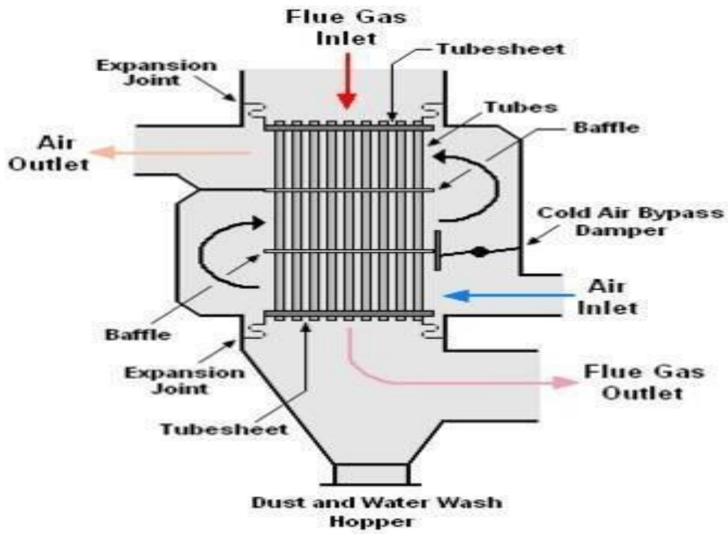


Figure: Air Preheater

STEAM TURBINES

- Steam entering from a small opening attains a very high velocity.
- The velocity attained during expansion depends on the initial and final content of the steam.
- The difference in initial and final heat content represent the heat energy to be converted to kinetic energy.

There are two types of steam turbines:

1) Impluse turbine and 2)Reaction Turbine

Impuse Turbine:

- In this turbine there are alternate rows of moving and fixed blades. The moving blades are mounted on the shaft and fixed blades are fixed to the casing of the turbine.
- A set of fixed nozzle is provided and steam is passed through these nozzles. The P.E in steam due to pressure and internal energy is converted to K.E. The steam comes out of the nozzles with very high velocity and impinges on the rotor blades.
- The direction of steam flow changes without changing its pressure.
- Thus due to the change in momentum the turbine rotor starts rotating.

Reaction Turbine:

- Reaction turbine have no nozzles. These two have alternate rows of moving and fixed blades. The moving blades are mounted on shaft, while fixed blades are fixed in casing of turbine.
- When high pressure steam passes through fixed blades, then steam pressure drops down and velocity of steam increases.
- As steam passes over moving blades, the steam expands and imparts energy,resulting in reduction in pressure and velocity of steam.

Note: Turbines used in thermal power stations are Impuse, Reaction or combined.
Generally multistage turbines are used. H.P steam after doing work in the H.P stage passes over
stage . more workis extracted thereby, with consequent increase in thermal efficiency.

Compounding of steam turbines:

Single stage turbines are of low efficiency.

In compounding, a number of rotors are connected or keyed to the same shaft

Two types of compounding are used: velocity compounding and pressure compounding

Governing of steam turbines:

Governing signifies the process of controlling the volume of steam to meet the load fluctuation.

Figure: Steam Turbines

CONDENSERS

The function of the condenser is to condense the steam exiting the turbine. The condenser helps maintain low pressure at the exhaust.

Two types of condensers are used.

Table: Jet and Surface Condensers

Jet condenser (contact type)	Surface condenser (non-contact type)
Exhaust steam mixes with cooling water.	Steam and water do not mix.
Temperature of the condensate and cooling water is same while leaving the condenser.	Condensate temperature higher than the cooling water temperature at outlet.
Condensate cannot be recovered.	Condensate recovered is fed back to the boiler.
Heat exchanged by direct conduction	Heat transfer through convection.
Low initial cost	High initial cost.
High power required for pumping water.	Condensate is not wasted so pumping power is less.

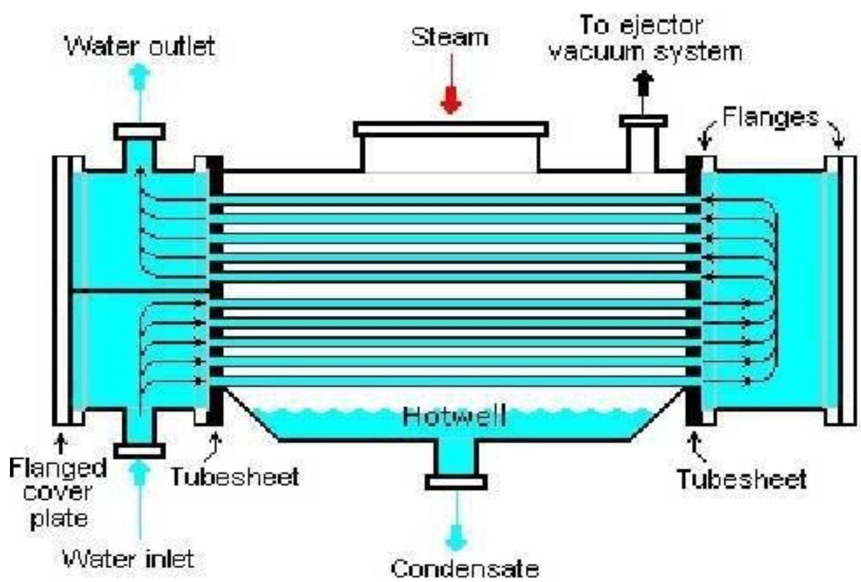
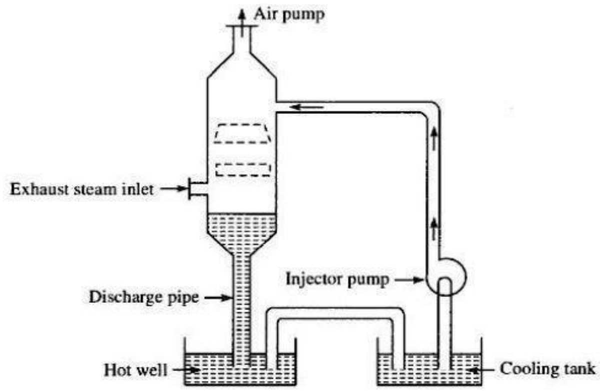


Figure: Surface Condenser



DEAERATORS

- 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 feed waters will cause serious corrosion damage in steam systems by attaching to the walls of metal piping and other metallic equipment and forming oxides (rust).
- There are two basic types of deaerators,
  1. the tray-type an
  2. the spray-type
- The tray-type (also called the cascade-type) includes a vertical domed deaeration section mounted on top of a horizontal cylindrical vessel which serves as the deaerated boiler feedwater storage tank.
- The spray-type consists only of a horizontal (or vertical) cylindrical vessel which serves as both the deaeration section and the boiler feed water storage tank.

COOLING TOWERS AND SPRAY PONDS

- Condensers need huge quantity of water to condense the steam.
- Water is led into the plants by means of circulating water pumps and after passing through the condenser is discharged back into the river.
- If such a source is not available closed cooling water circuit is used where the

warm water coming out of the condenser is cooled and reused.

- In such cases ponds and cooling towers are used where the water loses heat to the atmosphere.

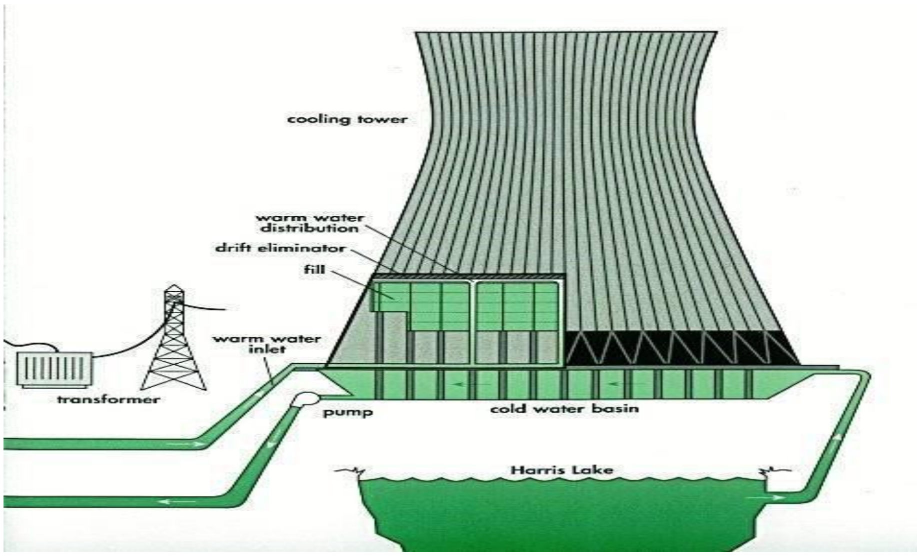
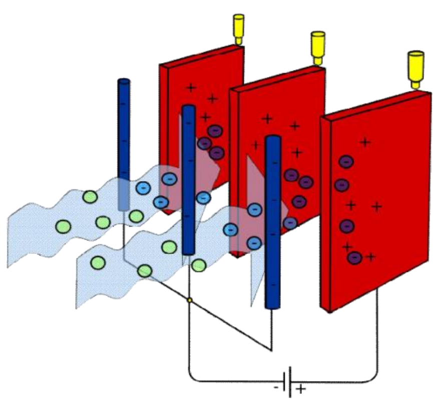


Figure : Cooling Tower

ELECTROSTATIC PRECIPITATORS

❖ An electrostatic precipitator (ESP), or electrostatic air cleaner is a particulate collection device that removes particles from a flowing gas (such as air) using the force of an induced electrostatic charge.



❖ the basic idea of an ESP:
❖ *Charging*
❖ *collecting.*
❖ *removing*

- Every particle either has or can be given a charge—positive or negative.
- We impart a negative charge to all the particles in a gas stream in ESP.
- Then a grounded plate having a positive charge is set up.
- The negatively charged particle would migrate to the grounded collection plate and be captured.
- The particles would quickly collect on the plate, creating a dust layer. The dust layer would accumulate until we removed it.
- The structural design and operation of the discharge electrodes (rigid-frame, wires or plate) and collection electrodes.
    - tubular type ESP
    - plate type ESP
- The method of charging
    - single-stage ESP
    - two-stage ESP
- The temperature of operation
    - cold-side ESP
    - hot-side ESP
- The method of particle removal from collection surfaces
    - wet ESP
    - Dry ESP

Ash Handling Plant

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. The steam power plant produces 5000 of tons ash daily (2000MW)

The ash may be

- 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 ESP which got carried out with the flue gas is generally called Fly ash. It also consists of Air pre heater ash & Economizer ash (it is about 2 % of the total ash content).

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
- and 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.
- Deep ponds may be made and ash can be dumped into these ponds to fill them completely
- When sea born coal is used, barrage may take the ash to sea for disposal into water grave.

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

- Belt conveyor system
- Pneumatic system
- Hydraulic system
- Steam jet system

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.
- It can deliver 3 tonnes of ash per hour with a speed of 0.3m/minute.

 The life of belt is 5 years. it is used in small power plant

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

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.

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.

NUCLEAR POWER STATION

Basics

- Atoms consist of nucleus and electrons.
- The nucleus is composed of protons and neutrons.
- Protons are positively charged whereas neutrons are electrically neutral.
- Atoms with nuclei having same number of protons but difference in their masses are called isotopes. They are identical in terms of their chemical properties but differ with respect to nuclear properties.
- Natural Uranium consists of $_{92}U^{238}$ (99.282%), $_{92}U^{235}$ (0.712%) and $_{92}U^{234}$
- $92U^{235}$ is used as fuel in nuclear power plants.

Energy from Nuclear Reactions

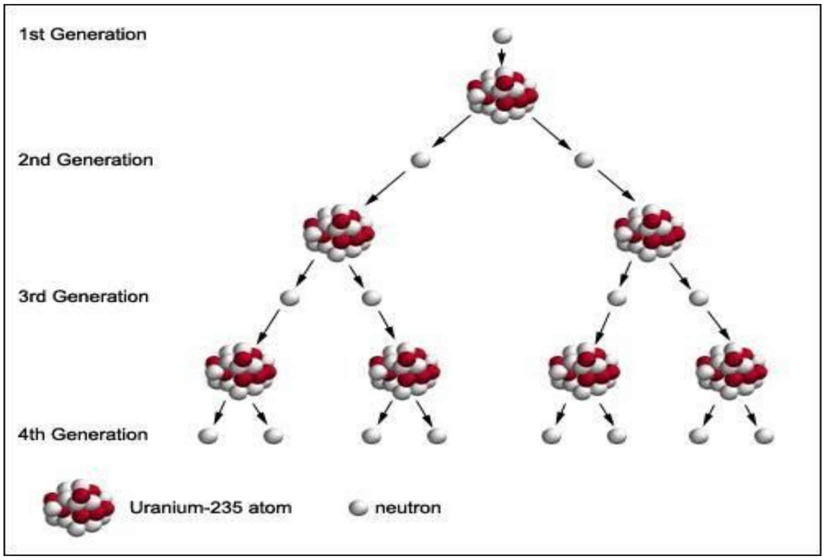
- The sum of masses of protons and neutrons exceeds the mass of the atomic nucleus and this difference is called mass defect Δm.

- In a nuclear reaction the mass defect is converted into energy known as binding energy according to Einstein's equation ($E=\Delta m\ c^2$).
- Fissioning one amu of mass results in release of 931 MeV of energy.
- It has been found that element having higher and lower mass numbers are unstable. Thus the lower mass numbers can be fused or the higher mass numbers can be fissioned to produce more stable elements.
- This results in two types of nuclear reactions known as fusion and fission.
- The total energy per fission reaction of U^{235} is about 200 MeV.
- Fuel burn-up rate is the amount of energy in MW/days produced by each metric ton of fuel.

Nuclear Fission

Nuclear fission is the reaction by which a heavy nucleus (that is one with a high value of Z) is hit with a small particle, as a result of which it splits into two (occasionally more) smaller nuclei.

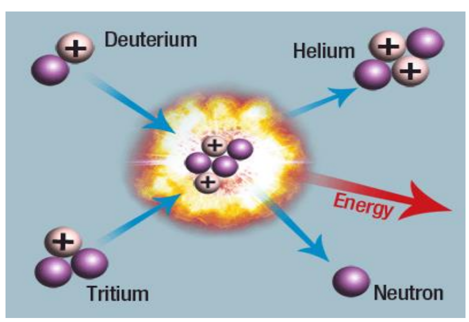
Before the reaction		After the reaction	
${}^{1}_{0}n$	1.008665	${}^{140}_{54}Xe$	139.9216
${}^{235}_{92}U$	235.0439	${}^{94}_{38}Sr$	93.9154
		$2\ {}^{1}_{0}n$	2.0173
Total mass	236.0526	Total mass	235.8543



Nuclear Fusion

Fusion is the opposite of fission, it is the joining together of two light nuclei to form a heavier one (plus a small fragment). For example if two 2H nuclei (two deuterons) can be made to come together they can form He and a neutron.

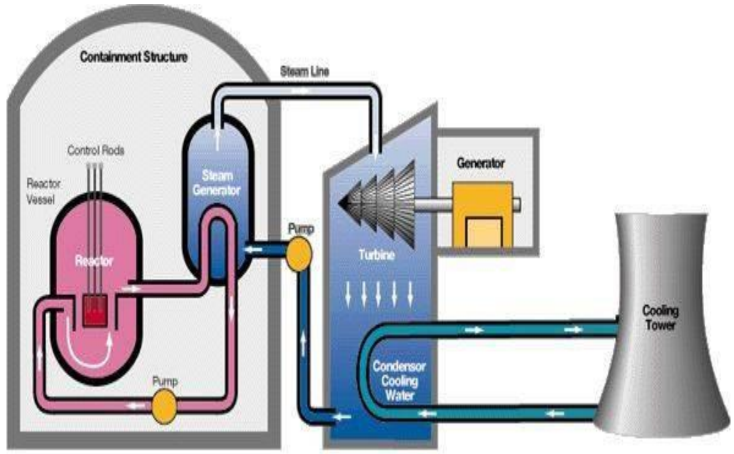
$$^{2}H + {}^{2}H \rightarrow {}^{3}He + n$$



Nuclear Fusion

Nuclear Power Plant

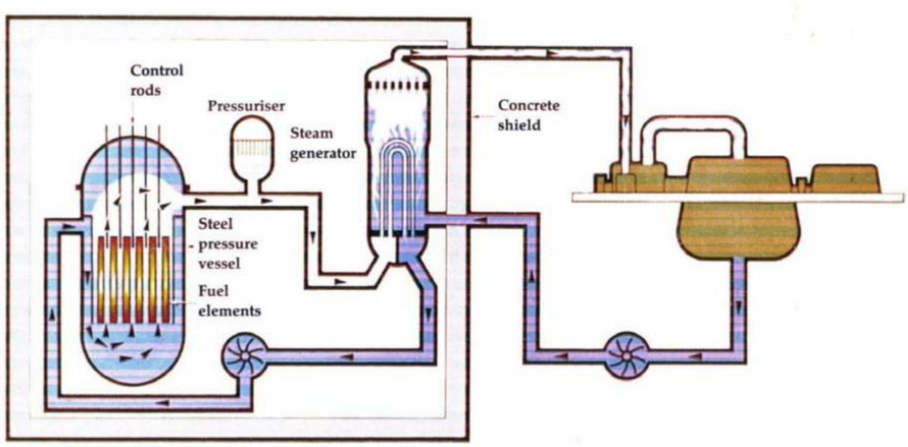
- A nuclear power plant is a thermal power station in which the heat source is one or more nuclear reactors. As in a conventional thermal power station the heat is used to generate steam which drives a steam turbine connected to a generator which produces electricity.



Schematic of a Nuclear Power Plant

Pressurized Water Reactor (PWR)

- The most widely used reactor type in the world is the Pressurized Water Reactor (PWR) which uses enriched (about 3.2% U235) uranium dioxide as a fuel in zirconium alloy cans.
- The fuel, which is arranged in arrays of fuel "pins" and interspersed with the movable control rods, is held in a steel vessel through which water at high pressure (to suppress boiling) is pumped to act as both a coolant and a moderator.
- The high-pressure water is then passed through a steam generator, which raises steam in the usual way.

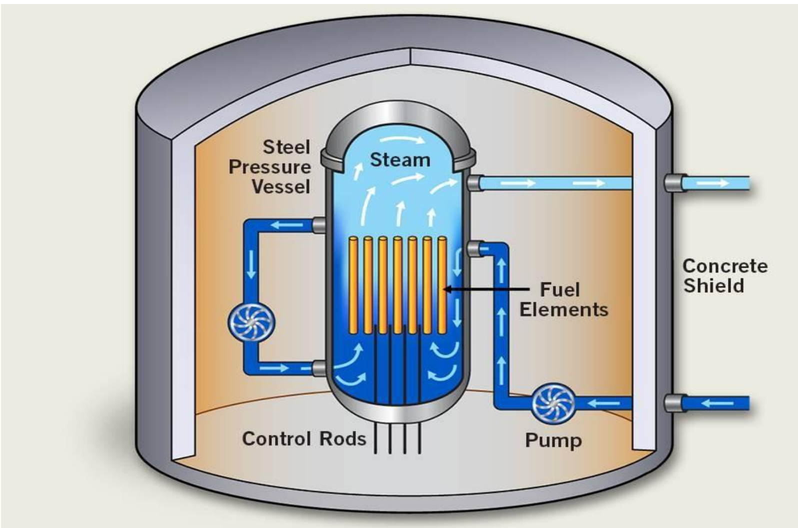


Pressurized Water Reactor

Boiling Water Reactors (BWR)

- The second type of water cooled and moderated reactor does away with the steam generator and, by allowing the water within the reactor circuit to boil, it raises steam directly for electrical power generation. Such reactors, known as Boiling Water Reactors (BWRs), throughout the world.

Boiling Water Reactor



- This, however, leads to some radioactive contamination of the steam circuit and turbine, which then requires shielding of these components in addition to that surrounding the reactor.

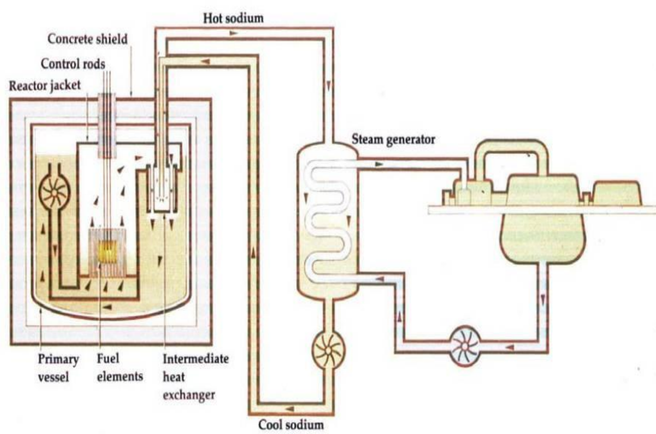
Fast Breeder Reactors

- All of today's commercially successful reactor systems are "thermal" reactors, using slow or thermal neutrons to maintain the fission chain reaction in the U^{235} fuel. Even with the enrichment levels used in the fuel for such reactors, however, by far the largest numbers of atoms present are U^{238}, which are not fissile.
- Consequently, when these atoms absorb an extra neutron, their nuclei do not split but are converted into another element, Plutonium.
- Plutonium is fissile and some of it is consumed in situ, while some remains in the spent fuel together with unused U^{235}. These fissile components can be separated from the fission

product wastes and recycled to reduce the consumption of uranium in thermal reactors by up to 40%, although clearly thermal reactors still require a substantial net feed of natural uranium.

- It is possible, however, to design a reactor which overall produces more fissile material in the form of Plutonium than it consumes. This is the fast reactor in which the neutrons are unmoderated, hence the term "fast".

- The physics of this type of reactor dictates a core with a high fissile concentration, typically around 20%, and made of Plutonium. In order to make it breed, the active core is surrounded by material (largely U238) left over from the thermal reactor enrichment process. This material is referred to as fertile, because it converts to fissile material when irradiated during operation of the reactor.
- The successful development of fast reactors has considerable appeal in principle. This is because they have the potential to increase the energy available from a given quantity of uranium by a factor of fifty or more, and can utilize the existing stocks of depleted uranium, which would otherwise have no value.



Fast Breeder Reactors

Factors for Site Selection of NPPs

1. Availability of Water: working fluid
2. Distance from Populated Area: danger of radioactivity
3. Nearness to the load centre: reduction in transmission cost
4. Disposal of Waste: radioactive waste

5. Accessibility by Rail and Road: transport of heavy equipment

Advantages of NPPs

1. Reduces demand for fossil fuels
2. Quantity of nuclear fuel is much less: thus reducing transport and resulting costs
3. Area of land required is less: compared to a conventional plant of similar capacity
4. Production of fissile material
5. Location independent of geographical factors: except water requirement

Disadvantages of NPPs

1. Not available for variable loads (load factor-0.8): as the reactors cannot be controlled to respond quickly
2. Economical reason should be substantial
3. Risk of leakage of radioactive material
4. Further investigation on life cycle assessment and reliability needs to be done
5. Perception problems

Comparison of PWR and BWR

PWR	BWR
Advantages	Advantages
• Relatively compact in size • Possibility of breeding plutonium by providing a blanket of U-238 • High power density • Containment of fission products due to heat exchanger • Inexpensive 'light water' can be used as moderator, coolant and reflector • Positive power demand coefficient i.e. the reactor responds to load increase	• Elimination of heat exchanger circuit results in reduction in cost and gain in thermal efficiency (to about 30%) • Pressure inside in the reactor vessel is considerably lower resulting in lighter and less costly design • BWR cycle is more efficient than PWR as the outlet temperature of steam is much higher • Metal surface temperature is lower since boiling of water is inside the reactor • BWR is more stable than PWR and hence is commonly known as a self-controlled reactor

Disadvantages	Disadvantages
• Moderator remains under high pressure and hence a strong pressure vessel is required • Expensive cladding material is required to prevent corrosion • Heat loss occurs due to heat exchanger • Elaborate safety devices are required • Lacks flexibility i.e. the reactor needs to be shut down for recharging and there is difficulty in fuel element	• Possibility of radio-active contamination in the turbine mechanism • Wastage of steam may result in lowering of thermal efficiency on part load operation • Power density of BWR is nearly half that of PWR resulting in large size vessel • Possibility of burn-out of fuel is more as water boiling is on the surface of fuel. • BWR cannot meet a sudden increase in load

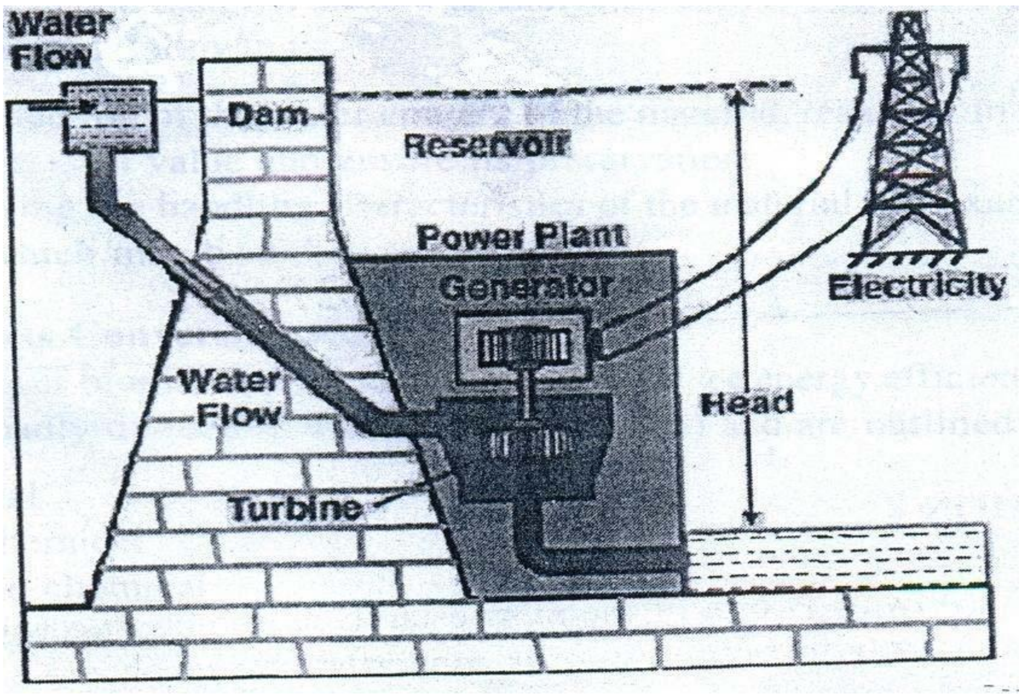
UNIT 2

HYDRO ELECTRIC POWER STSTION & HYDRAULIC TURBINES

HYDROPOWER

Hydro-energy is known as traditional renewable energy source. It is based on natural circulating water flow and its drop from higher to lower land surface that constitutes the potential. In order to convert this potential to applicable electric energy, water flow should be led to and drive a hydraulic turbine, transforming hydro energy into mechanical energy, the latter again drives a connected generator transforming the mechanical energy into electric energy. As hydro energy exploitation and its utilization are completed at the same time. I.e. the exploitation of first energy source and the conversion of secondary energy source occur simultaneously, unlike the coal power generation which should have two orders; first order is exploitation of fuel, second order is generation, so hydropower has the advantages over thermal power generation.

Mankind has used the energy of falling water for many centuries, at first in mechanical form and since the late 19^{th} century by further conversion to electrical energy. Historically, hydropower was developed on a small scale to serve localities in the vicinity of the plants. With the expansion and increasing load transfer capability of transmission networks, power generation was concentrated in increasingly larger units and to benefit from the economies resulting from development on a larger scale.



General Layout of a dam based hydroelectric plant

Sites selected for development tended to be the most economically attractive; in this regard, higher heads and proximity to load centers were significant factors. For this reason, development was not restricted to large sites, and hydro stations today range from less than 1 MWe capacity to more than 10,000 MWe. The efficiency of hydroelectric generation is more than twice that of competing thermal power stations.

TYPES OF PROJECT

Capacity, unit size and selection of Equipment, their Characteristics and Specifications for design of hydro power station depend upon type of hydroelectric development and classification with respect to head and size. There are three main types of hydropower schemes that can be categorized in terms of how the flow at a given site is controlled or modified. These are:

Run-of-river plants (no active storage); and

Plants with significant storage
Pumped storage

In a run-of-river project, the natural flow of the river is relatively uncontrolled. In a storage project, the filling and emptying of the impounded storage along with the pattern of the natural stream flow controls the flow in the river downstream from the storage impoundment.

Run-of-river plants can be located at the downstream end of a canal fall, open flume, or pipeline diverting the stream's flow around a water supply dam or falls. The available flow governs the capacity of the plant. The plant has little or no ability to operate at flow rates higher than that available at the moment.

In a conventional plant, a dam, which stores water in a reservoir or lake impoundment, controls the river flows. Water is released according to electric, irrigation, water supply, or flood control needs. Constructing a dam and storage reservoir can increase the percentage of time that a project can produce a given level of power. Base load plants-those operated at relatively constant output-may have either a small capacity relative to the river flow or may have a significant storage reservoir. Storage reservoirs can be sized for storing water during wet years or wet seasons. Alternatively, they can be sized to provide water for weekly or daily peak generation. A storage reservoir allows using available energy that might otherwise be wasted as spill.

Plants with storage at both head and tailrace are pumped storage project.

Run of the River Schemes or Diversion Schemes

This type of development aims at utilizing the instantaneous discharge of the stream. So the discharge remains restricted to day to day natural yield from the catchments; characteristics of which will depend on the hydrological features. Diurnal storage is sometime provided for optimum benefits. Development of a river in several steps where tail race discharges from head race inflows for downstream power plants forms an interesting variation of this case and may require sometimes special control measures.

Small scale power generation also generally fall in the category and may have special control requirement especially if the power is fed into a large grid.

Storage Schemes

In such schemes annual yield from the catchment is stored in full or partially and then released according to some plan for utilization of storage. Storage may be for single purpose such as power development or may be for multi purpose use which may include irrigation, flood control, etc. therefore, design of storage works and releases from the reservoir will be governed by the intended uses of the stored water. If the scheme is only for power development, then the best use of the water will be by releasing according to the power demand. Schemes with limited storage may be designed as peaking units. If the water project forms a part of the large grid, then the storage is utilized for meeting the peak demands. Such stations could be usefully assigned with the duty of frequency regulation of the system.

Pump Storage Scheme

Principle

The basic principle of pumped storage is to convert the surplus electrical energy available in a system in off-peak periods, to hydraulic potential energy, in order to generate power in periods when the peak demand on the system exceeds the total available capacity of the generating stations.

By using the surplus scheme electrical energy available in the network during low-demand periods, water is pumped from a lower pond to an upper pond. In periods of peak demand, the power station is operated in the generating mode i.e. water from the upper pond is drawn through the same water conduit system to the turbine for generating power.

There are two main types of pumped storage plants:

Pumped-storage plants and

Mixed pumped-storage plants.

Pump-storage plants: In this type only pumped storage operation is envisaged without any scope for conventional generation of power. These are provided in places where the run-off is poor. Further, they are designed only for operation on a day-to-day basis without room for flexibility in operation.

Mixed pumped-storage plants: In this type, in addition to the pumped storage operation, some amount of extra energy can be generated by utilizing the additional natural run-off during a year. These can be designed for operation on a weekly cycle or other form of a longer period by providing for additional storage and afford some amount of flexibility in operation.

CLASSIFICATION OF HYDROPOWER PLANTS

As such there are no hard and fast rules to classify Hydro power plants. Some of the basis is as follows:

Based on Hydraulic Characteristics

Based on Head

Based on Capacity

Based on Turbine Characteristics
Based on Load Characteristics

Based on Interconnection

Hydropower Project based on Hydraulic Characteristics:

Run off river plant (Diversion plant)

Storage plant (Impoundment plant)
Pumped storage plant
Tidal plant

Run off River Plant (Diversion Plant)

In some areas of the world, the flow rate and elevation drops of the water are consistent enough that hydro electric plants can be built directly in the river.

The water is utilized as it comes in the river.

Practically, water is not stored during flood periods as well as during low electricity demand periods, hence water is wasted.

Run off river plant may be without pondage or with pondage.

The plants with pondage are provided with a barrage to store the water, to take care of daily variation.

During good flow conditions – can supply base load and during low flow conditions - can supply peak load

Seasonal changes in river flow and weather conditions affect the plant’s output; hence it is in limited use unless interconnected with grid.

flows that occur in the stream at the intake and flows downstream of the powerhouse are virtually identical to pre-development flows.

Run-of-river facilities use low dams to provide limited storage of water– at most daily pondage.

In a run-off river SHP scheme, through diversion structure water is diverted to water conductor system to the powerhouse.

Water impounded in dam for storage and released in phased manner to generate power and further used for irrigation is shown in (figure 1.5.1).

Site Selection for Hydropower Plants

- **Availability of Water:** Run-off data for many years available
- **Water Storage:** for water availability throughout the year
- **Head of Water:** most economic head, possibility of constructing a dam to get required head
- **Geological Investigations:** strong foundation, earthquake frequency is less
- **Water Pollution:** excessive corrosion and damage to metallic structures
- **Sedimentation:** capacity reduces due to gradual deposition of silt
- **Social and Environmental Effects:** submergence of areas, effect on biodiversity (e.g. western ghat), cultural and historic aspects
- **Access to Site:** for transportation of construction material and heavy machinery new railway lines or roads may be needed
- **Multipurpose:** power generation, irrigation, flood control, navigation, recreation; because initial cost of power plant is high because of civil engineering construction work

Classification of Hydropower Plants

According to water flow regulation:

1. Runoff river plants without pondage
2. Runoff river plants with pondage
3. Hydroelectric plants with storage reservoir

According to Load:

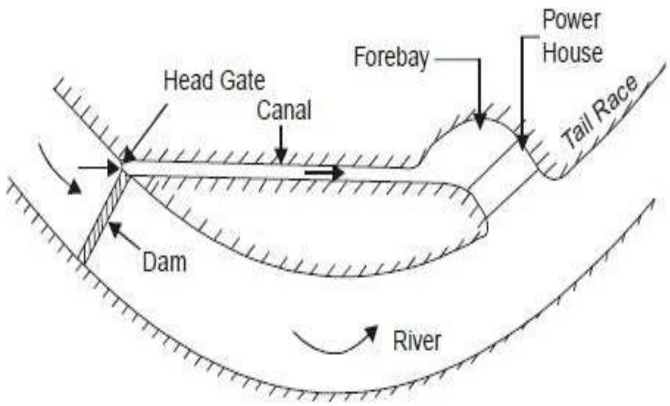
1. Base load plants
2. Peak load plants
3. Pumped storage plants

According to head:

1. High head plants (>100m)
2. Medium head plants (30-100 m)
3. Low head plants (<30 m)

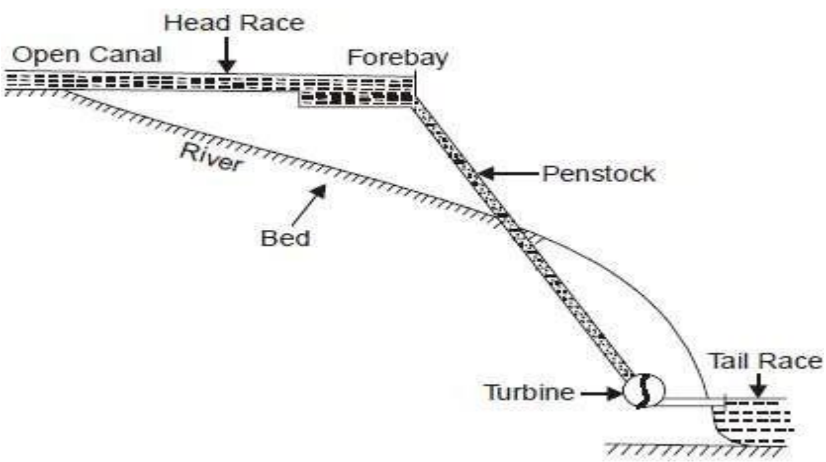
Low head plant

- Operating head is less than 15m.
- Vertical shaft Francis turbine or Kaplan turbine.
- Small dam is required.



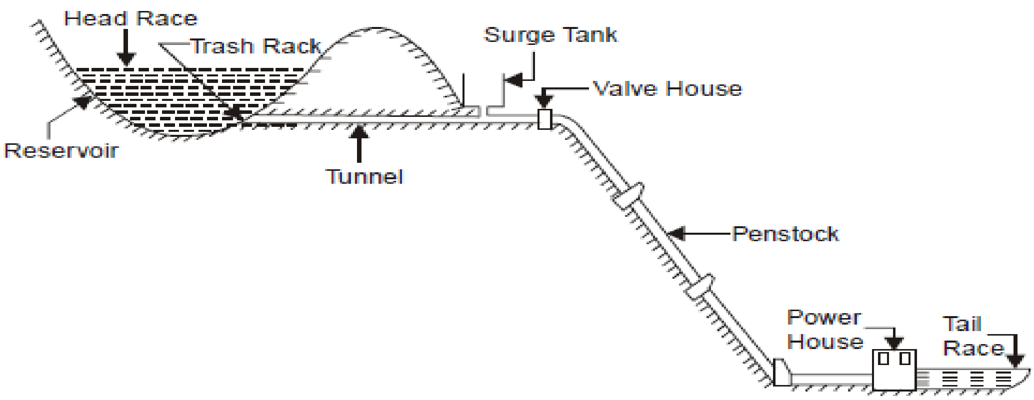
Medium head plant

- Operating head is less than 15 to 50m.
- Francis turbines.
- Forebay is provided at the beginning of the penstock.



High head plant

- Operating head exceed 50m.
- Pelton turbines.
- Surge tank is attached to the penstock to reduce water hammer effect onthe penstock.



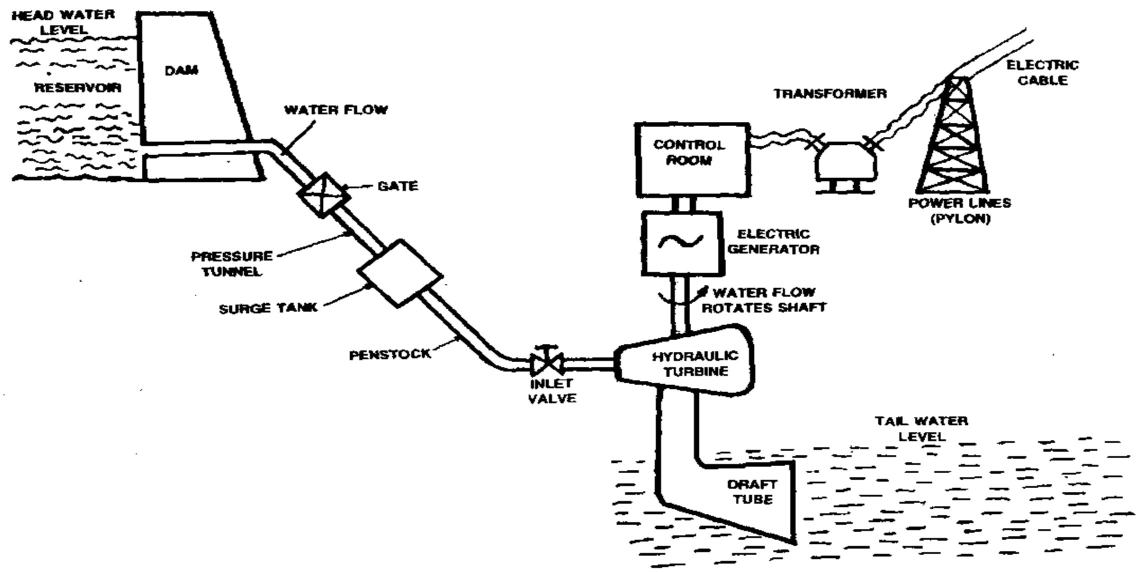


FIG. 3.6: LAYOUT OF HYDRO-ELECTRIC POWER PLANT

Components of a HPP

Schematic of a Hydropower Plant

The various components of HPP are as follows:

1. Catchment area
2. Reservoir
3. Dam
4. Spillways
5. Conduits
6. Surge tanks

7. Draft tubes
8. Power house
9. Switchyard for power evacuation

Dam

- Develops a reservoir to store water
- Builds up head for power generation

Spillway

- To safeguard the dam when water level in the reservoir rises

Intake

- Contains trash racks to filter out debris which may damage the turbine

Forebay

- Enlarged body of water just above the intake

Forebay Conduits

- Headrace is a channel which lead the water to the turbine
- Tailrace is a channel which carries water from the turbine
- A canal is an open waterway excavated in natural ground following its contour.
- A flume is an open channel erected on a surface above ground.
- A tunnel is a closed channel excavated through an obstruction.
- A pipeline is a closed conduit supported on the ground.
- **Penstocks** are closed conduits for supplying water "under pressure" from head pond to the turbines.

Surge Tank

- A surge tank is a small reservoir in which the water level rises or falls to reduce the pressure swings so that they are not transmitted to the penstock.
- Water Hammer
  - Load on the turbine is suddenly reduced
  - Governor closes turbine gates
  - Sudden increase of pressure in the penstock
- Negative Pressure
  - Load on the generator is suddenly increased
  - Governor opens the turbine gates
  - Tends to cause a vacuum in the penstock
- When the gates are closed, water level rises in the surge tank and when the gates are suddenly opened, surge tank provides the initial water supply.

Surge Tank Draft Tubes

The function of the draft tube is to

- To reduce the velocity head losses of the water
- To allow the turbine to be set above the tailrace to facilitate inspection and maintenance

Tailrace:

- A tailrace is required to discharge the water leaving the turbine into the river.
- The design of the tail race should be such that water has a free exit.

Power House

1. Hydraulic turbines
2. Electric generators
3. Governors
4. Gate valves
5. Relief valves
6. Water circulation pumps
7. Air ducts
8. Switch board and instruments
9. Storage batteries
10. Cranes

Switchyard

1. Step up transformers
2. Instrument transformers
3. Transmission lines

Advantages of hydro power plant:

- Water is a renewable energy source.
- Maintenance and operation charges are very low.
- The efficiency of the plant does not change with age.
- In addition to power generation, hydro-electric power plants are also useful for flood control, irrigation purposes, fishery and recreation.
- Have a longer life (100 to 125 years) as they operate at atmospheric temperature.
- Water stored in the hydro-electric power plants can also be used for domestic water supply.
- Since hydro-electric power plants run at low speeds (300 to 400 rpm) there is no requirement of special alloy steel construction materials or specialised mechanical maintenance.

Disadvantages of hydro power plant:

- The initial cost of the plant is very high.
- Since they are located far away from the load centre, cost of transmission lines and transmission losses will be more.
- During drought season the power production may be reduced or even stopped due to insufficient water in the reservoir.
- Water in the reservoir is lost by evaporation.

PUMP STORAGE SCHEME

Principle

The basic principle of pumped storage is to convert the surplus electrical energy available in a system in off-peak periods, to hydraulic potential energy, in order to generate power in periods when the peak demand on the system exceeds the total available capacity of the generating stations.

By using the surplus scheme electrical energy available in the network during low-demand periods, water is pumped from a lower pond to an upper pond. In periods of peak demand, the power station is operated in the generating mode i.e. water from the upper pond is drawn through the same water conduit system to the turbine for generating power.

There are two main types of pumped storage plants:

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Pumped Storage Plant

Water is utilized for generation of power during peak demand, while same water is pumped back in the reservoir during off peak demand period, when excess power is available for this purpose.

If turbine is reversible, it can be used as a pump to supply water back to reservoir, otherwise separate pump can be used.

Based on operating cycle it can be classified as:

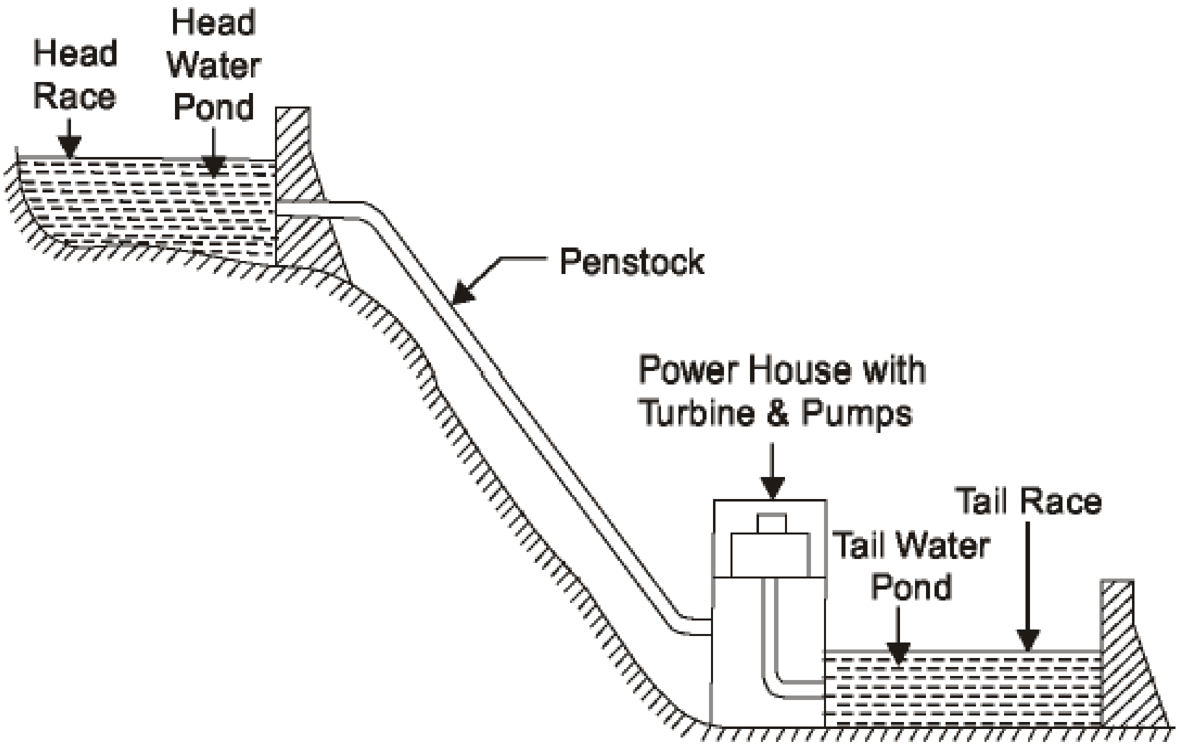
Plant with a daily cycle: water is pumped up from mid night to early morning as well as near lunch time.

Plant with a weekly cycle: water is pumped up during weekend.

Plant with a seasonal cycle: water is pumped up in the winter continuously for several days to be utilized for a continuous power generation in the high demand summer period.

PUMPED STORAGE POWER PLANTS

These plants supply the peak load for the base load power plants and pump all or a portion of their own water supply. The usual construction would be a tail water pond and a head water pond connected through a penstock. The generating pumping plant is at the lower end. During off peak hours, some of the surplus electric energy being generated by the base load plant is utilized to pump the water from tail water pond into the head water pond and this energy will be stored there. During times of peak load, this energy will be released by allowing the water to flow from the head water pond through the water turbine of the pumped storage plant. These plants can be used with hydro, steam and i.e. engine plants. This plant is nothing but a hydraulic accumulator system and is shown. These plants can have either vertical shaft arrangement or horizontal shaft arrangement. In the older plants, there were separate motor driven pumps and turbine driven generators. The improvement was the pump and turbine on the same shaft with the electrical element acting as either generator or motor. The latest design is to use a Francis turbine which is just the reverse of centrifugal pump. When the water flows through it from the head water pond it will act as a turbine and rotate the generator. When rotated in the reverse direction by means of an electric motor, it will act as a pump to shunt the water from the tail water pond to the head water pond



Pumped Storage Plant

Power Estimation

The potential electric power of the water in terms of flow and head can be calculated from the following equation.

$$KW = 9.81 \times Q \times H \times \eta$$

Where,

kW = electric power in kW

Q = quantity of water flowing through the hydraulic turbine in cubic meters per second. Discharge (quantity of water) flowing in a stream and available for power generation has daily and seasonal variation. Optimum discharge for power generation is determined on the basis of energy generation cost.

H = Net available head in meters (gross head – losses)

= overall efficiency of the hydro power plant. For general estimation purposes, η is normally taken as 0.85

Hydrology

- First requirement – Q (discharge)
- Hydrology deals with occurrence and distribution of water over and under earth's surface.
  - Surface Water Hydrology
  - Ground Water Hydrology
- **Watershed, catchment area or drainage area:** length of the river, size and shape of the area it affects, tributaries, lakes, reservoirs etc.
- Investigation of **run-off** for past few years is required for power potential studies of a HPP.

Objectives of Hydrology

- To obtain data regarding the stream flow of water that would be available,
- To predict the yearly possible flow
- To calculate the mean annual rainfall in the area under consideration from a record of the annual rainfall for a number of years, say 25 to 30
- To note the frequency of dry years
- To find maximum rainfall and flood frequency

Various terms related to Hydrology

- Rainfall is also known as precipitation and can be measured by rain gauges.
- Some part of precipitation is lost due to evaporation, interception and transpiration.
- **Transpiration:** Plants absorbing moisture and giving it off to the atmosphere
- Stream flow = precipitation – losses
- Stream flow = surface flow + percolation to ground
- Surface flow is also known as **run-off.**
- **Hydrograph:**
  - Shows the variation of stream flow in m^3/s with time for a particular river site. The time may be hour, week, month or a year.
  - The area under hydrograph gives the total volume of flow

- **Flow duration curve:**
  - Shows the percentage of time during the period when the flow was equal to greater than the given flow.
  - The area under FDC gives the total quantity of run-off during a period

- **Mass curve**
  - Indicates the total volume of run-off in cubic meters up to a certain time.
  - the slope of the curve at any point shows the rate of flow at that time
  - Used for estimating the capacity of storage reservoir
- **Storage:**
  - to ensure water availability during deficient flow and thus increasing the firm capacity

  - Storage also results in more energy production
- **Pondage:**
  - Storing water in small ponds near the power plant as the storage reservoir is away from plant
  - To meet the power demand fluctuations over a short period of time e.g. 24 hours

- **Primary Power:** power that will be available 90 % of the time
- **Secondary Power:** power that will be available 75 % of the time
- **Dump Power:** power that will be available 50 % of the time.
- **Maximum flow estimation:** gives estimation of floods and helps in design of dam and spillway.

HYDROGRAPH & FLOW DURATION CURVE:-

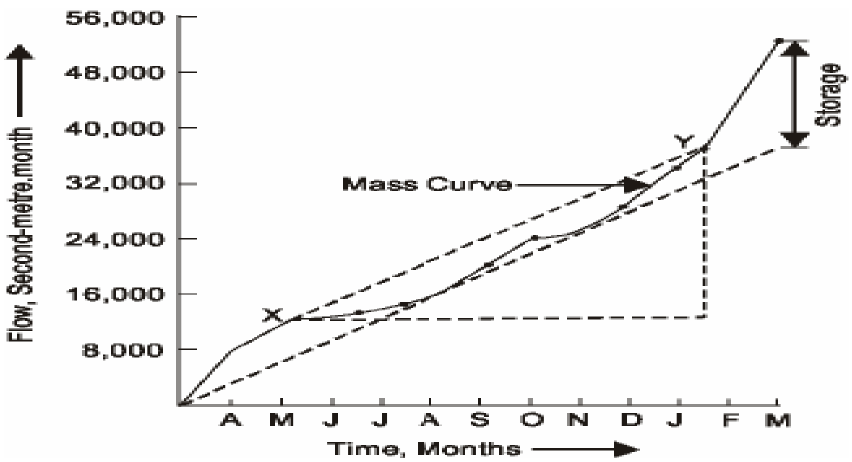
- A hydrograph indicates the variation of discharge or flow with time. It is plotted with flows as ordinates and time intervals as abscissas. The flow is in m^3/sec and the time may be in hours, days, weeks or months.

- A flow duration curve shows the relation between flows and lengths of time during which they are available. The flows are plotted as the ordinates and lengths of time as abscissas. The flow duration curve can be plotted from a hydrograph.

THE MASS CURVE:-

The use of the mass curve is to compute the capacity of the reservoir for a hydro site. The mass curve indicates the total volume of run-off in second meter-months or other convenient units, during a given period. The mass curve is obtained by plotting cumulative volume of flow as ordinate and time (days, weeks by months) as abscissa. Fig. 11.2 shows a mass curve for a typical river for which flow data is given in Table 11.2. The monthly flow is only the mean flow and is correct only at the beginning and end of the months. The variation of flow during each month is not considered. Cumulative daily flows, instead of monthly flows, will give a more accurate mass curve, but this involves an excessive amount of work. The slope of the curve at any point gives the flow rate in second- meter. Let us join two points X and Y on the curve. The slope of this line gives the average rate of flow during the period between X and Y. This will be = (Flow at Y-Flow at X)/Time Span Let the flow demand be, 3000 sec-meter. Then the line X-Y may be called as `demand line' or „Use line‟. If during a particular period, the slope of the mass Curve is greater than that of the demand line, it means more water is flowing into the reservoir than is being utilized, so the level of water in the reservoir will be increasing during that period and vice versa. Upto point X and beyond point Y the reservoir will be overflowing. Being full at both X and Y.

The capacity of the reservoir is given by the maximum ordinate between the mass curve and the demand line. For the portion of mass curve between point X and Y, the storage capacity is about 4600 sec-meter-month. However, considering the entire mass curve, storage capacity will be about 15,400 sec-meter-months.



UNIT III
TRANSMISSION LINE PARAMETERS

Parameters of single and three phase transmission lines with single and double circuits - Resistance, inductance and capacitance of solid, stranded and bundled conductors, Symmetrical and unsymmetrical spacing and transposition - application of self and mutual GMD; skin and proximity effects - interference with neighboring communication circuits - Typical configurations, conductor types and electrical parameters of EHV lines, corona discharges.

TYPES OF CONDUCTORS

Conductors used for electrical system are those having less resistance, low weight, high tensile strength, low cost and low coefficient of expansion. Normally aluminum and copper are used as conductors. The main advantages of aluminum conductors over copper conductors are:

- Low weight
- Low conductivity (less resistance) and less corona loss
- Low cost

The main problems with aluminum conductors are:

- Low tensile strength
- High coefficient of expansion
- Large area

TYPES OF CONDUCTOR

1. Copper

Copper is an ideal material for overhead lines owing to its high electrical conductivity and greater tensile strength. It is always used in the hard drawn form as stranded conductor. Although hard drawing decreases the electrical conductivity slightly yet it increases the tensile strength considerably. Copper has high current density *i.e.*, the current carrying capacity of copper per unit of X sectional area is quite large. This leads to two advantages. Firstly, smaller X- sectional area of conductor is required and secondly, the area offered by the conductor to wind loads is reduced. Moreover, this metal is quite homogeneous, durable and has high scrap value. There is hardly any doubt that copper is an ideal material for transmission and distribution of electric power. However, due to its higher cost and non-availability, it is rarely used for these purposes. Now a days the trend is to use aluminum in place of copper.

2. Aluminum

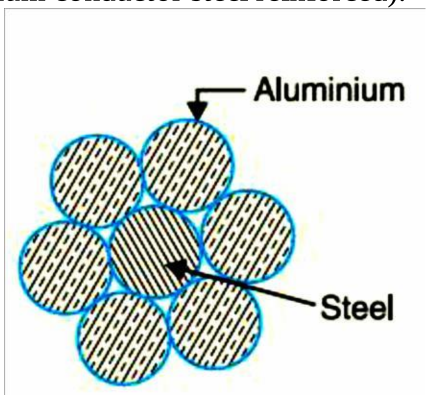
Aluminum is cheap and light as compared to copper but it has much smaller conductivity and tensile strength. The relative comparison of the two materials is briefed below:

(i) The conductivity of aluminum is 60% that of copper. The smaller conductivity of aluminum means that for any particular transmission efficiency, the X-sectional area of conductor must be larger in aluminum than in copper. For the same resistance, the diameter of aluminum conductor is about 1·26 times the diameter of copper conductor. The increased X-section of aluminum exposes a greater surface to wind pressure and, therefore, supporting towers must be designed for greater transverse strength. This often requires the use of higher towers with consequence of greater sag.

(ii) The specific gravity of aluminum (2·71 gm/cc) is lower than that of copper (8·9 gm/cc).Therefore, an aluminum conductor has almost one-half the weight of equivalent copper conductor. For this reason, the supporting structures for aluminum need not be made so strong as that of copper conductor.
(iii) Aluminum conductor being light is liable to greater swings and hence larger cross-arms are required.
(iv) Due to lower tensile strength and higher co-efficient of linear expansion of aluminum, the sag is greater in aluminum conductors. Considering the combined properties of cost, conductivity, tensile strength, weight etc., aluminum has an edge over copper. Therefore, it is being widely used as a conductor material. It is particularly profitable to use aluminum for heavy-current transmission where the conductor size is large and its cost forms a major proportion of the total cost of complete installation.

3. Steel cored aluminum

Due to low tensile strength, aluminum conductors produce greater sag. This prohibits their use for larger spans and makes them unsuitable for long distance transmission. In order to increase the tensile strength, the aluminum conductor is reinforced with a core of galvanized steel wires. The composite conductor thus obtained is known as *steel cored aluminum* and is abbreviated as A.C.S.R. (aluminum conductor steel reinforced).



Steel-cored aluminum conductor consists of central core of galvanized steel wires surrounded by a number of aluminum strands. Usually, diameter of both steel and aluminum wires is the same. The X-section of the two metals are generally in the ratio of 1 : 6 but can be modified to 1 : 4 in order to get more tensile strength for the conductor. Fig. shows steel cored aluminum conductor having one steel wire surrounded by six wires of aluminum. The result of this composite conductor is that steel core takes greater percentage of mechanical strength while aluminum strands carry the bulk of current. The steel cored aluminum conductors have the following

Advantages:

(i) The reinforcement with steel increases the tensile strength but at the same time keeps the composite conductor light. Therefore, steel cored aluminum conductors will produce smaller sag and hence longer spans can be used.

(ii) Due to smaller sag with steel cored aluminum conductors, towers of smaller heights can be used.

4. Galvanised steel

Steel has very high tensile strength. Therefore, galvanised steel conductors can be used for extremely long spans or for short line sections exposed to abnormally high stresses due to climatic conditions. They have been found very suitable in rural areas where cheapness is the main consideration. Due to poor conductivity and high resistance of steel, such conductors are not suitable for transmitting large power over a long distance. However, they can be used to advantage for transmitting a small power over a small distance where the size of the copper conductor desirable from economic considerations would be too small and thus unsuitable for use because of poor mechanical strength.

5. Cadmium copper

The conductor material now being employed in certain cases is copper alloyed with cadmium. An addition of 1% or 2% cadmium to copper increases the tensile strength by about 50% and the conductivity is only reduced by 15% below that of pure copper. Therefore, cadmium copper conductor can be useful for exceptionally long spans. However, due to high cost of cadmium, such conductors will be economical only for lines of small X-section i.e., where the cost of conductor material is comparatively small compared with the cost of supports.

STRANDED CONDUCTORS

For transmission lines operating at high voltages normally stranded conductors are used. These conductors are known as composite conductors as they compose of two or more elements or strands electrically in parallel. The conductors used for transmission lines are stranded copper conductors, hollow copper conductors, ACSR conductors and copper weld conductors.

In modern overhead transmission systems bare aluminum conductors are used which are classified as:

AAC : all-aluminum conductor
AAAC : all-aluminum alloy conductor
ACSR : aluminum conductor steel reinforced
ACAR : aluminum conductor alloy reinforced

In order to increase the tensile strength aluminum conductor is reinforced with a core of galvanized steel wire, which is aluminum conductor steel reinforced. ACSR composite conductors are widely used for long distance transmission due to

- Steel cored aluminum conductors are cheaper than copper conductors of equal resistance and this economy is obtained without sacrificing efficiency.
- These conductors are corrosion resistant and are useful under unfavorable conditions.
- The superior mechanical strength of ACSR can be utilized by using spans of larger length results in smaller number of supports.
- Corona losses are reduced because of larger diameter of the conductors.

BUNDLED CONDUCTORS

For voltages in excess of 230KV it is in fact not possible to use a round single conductor. Instead of going in for a hollow conductor it is preferable to use more than one conductor per phase which is known as bundling of conductors. A bundle conductor is a conductor made up of two or more sub conductors and is used as one phase conductor.

ADVANTAGES IN USING BUNDLE CONDUCTORS

- Reduced reactance
- Reduced voltage gradient
- Reduced corona loss
- Reduced radio interference
- Reduced surge impedance

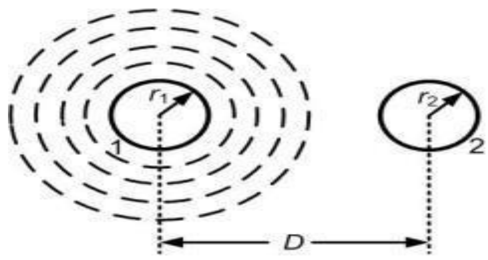
The basic difference between a stranded conductor and bundled conductor is that the sub conductors of bundled conductors are separated from each other by a distance of almost 30cms or more and the wires of composite conductors touch each other.

LINE PARAMETERS

An AC transmission line has resistance, inductance and capacitance uniformly distributed along its length. These are known as constants or parameters of a line. The performance of a transmission line depends upon these constants.

INDUCTANCE OF A SINGLE-PHASE LINE

Consider two solid round conductors with radii of r_1 and r_2 as shown in Fig. 1. One conductor is the return circuit for the other. This implies that if the current in conductor 1 is I then the current in conductor 2 is $-I$. First let us consider conductor 1. The current flowing in the conductor will set up flux lines. However, the flux beyond a distance $D + r_2$ from the center of the conductor links a net current of zero and therefore does not contribute to the flux linkage of the circuit. Also at a distance less than $D - r_2$ from the center of conductor 1 the current flowing through this conductor links the flux. Moreover since $D >> r_2$ we can make the following approximations



A single-phase line with two conductors.

$$D + r_1 \approx D \ and \ D - r_1 \approx D$$

We can specify the inductance of conductor 1 due to internal and external flux as

$$L_{int} = \frac{1}{2} \times 10^{-7} \text{ H/m}$$

$$L_{ext} = 2 \times 10^{-7} \ln \frac{D_2}{D_1} \text{ H/m}$$

$$L_1 = \left(\frac{1}{2} + 2 \ln \frac{D}{r_1} \right) \times 10^{-7} \text{ H/m} \qquad (1)$$

We can rearrange L_1 given in (1) as follows

$$L_1 = 2 \times 10^{-7} \left(\frac{1}{4} + \ln \frac{D}{r_1} \right) = 2 \times 10^{-7} \left(\ln e^{1/4} + \ln \frac{D}{r_1} \right) = 2 \times 10^{-7} \left(\ln \frac{D}{r_1 e^{-1/4}} \right)$$

Substituting $r_1' = r_1 e^{-1/4}$ in the above expression we get

$$L_1 = 2 \times 10^{-7} \left(\ln \frac{D}{r_1'} \right) \text{ H/m} \qquad (2)$$

The radius r_1' can be assumed to be that of a fictitious conductor that has no internal flux but with the same inductance as that of a conductor with radius r_1 .

In a similar way the inductance due current in the conductor 2 is given by

$$L_2 = 2 \times 10^{-7} \left(\ln \frac{D}{r_2'} \right) \text{ H/m} \qquad (3)$$

Therefore the inductance of the complete circuit is

$$L = L_1 + L_2 = 2 \times 10^{-7} \left(\ln \frac{D}{r_1'} \right) + 2 \times 10^{-7} \left(\ln \frac{D}{r_2'} \right)$$
$$= 2 \times 10^{-7} \left(\ln \frac{D^2}{r_1' r_2'} \right) = 4 \times 10^{-7} \left(\ln \frac{D}{\sqrt{r_1' r_2'}} \right) \text{ H/m} \qquad (4)$$

If we assume $r_1' = r_2' = r'$, then the total inductance becomes

$$L = 4\times10^{-7}\left(\ln\frac{D}{r'}\right) \text{ H/m} \quad (5)$$

Where $r' = re^{-1/4}$.

INDUCTANCE OF THREE-PHASE LINES WITH SYMMETRICAL SPACING

Consider the three-phase line shown in Fig.2. Each of the conductors has a radius of r and their centers form an equilateral triangle with a distance D between them. Assuming that the currents are balanced, we have

$$I_a + I_b + I_c = 0 \quad (1)$$

Consider a point P external to the conductors. The distance of the point from the phases a, b and c are denoted by D_{pa}, D_{pb} and D_{pc} respectively.

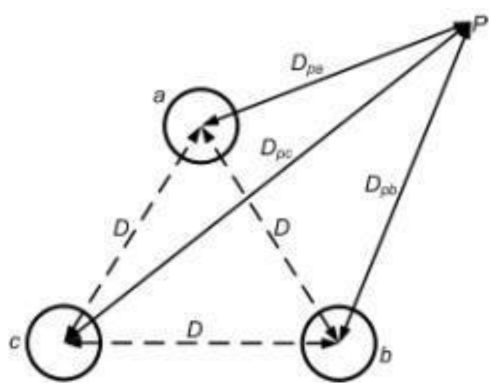


Fig.2 Three-phase symmetrically spaced conductors and an external point P.

Let us assume that the flux linked by the conductor of phase-a due to a current I_a includes the internal flux linkages but excludes the flux linkages beyond the point P . Then from

$$L_1 = 2\times10^{-7}\left(\ln\frac{D}{r_1'}\right)$$

We get

$$\lambda_{apa} = \left(\frac{1}{2} + 2\ln\frac{D_{pa}}{r}\right)I_a = 2\times10^{-7} I_a \ln\frac{D_{pa}}{r'} \quad (2)$$

The flux linkage with the conductor of phase-a due to the current I_b , excluding all flux beyond the point P , is given by as

$$\lambda_{apb} = 2\times10^{-7} I_b \ln\frac{D_{pb}}{D} \quad (3)$$

Similarly the flux due to the current I_c is

$$\lambda_{apc} = 2\times10^{-7} I_c \ln\frac{D_{pc}}{D} \quad (4)$$

Therefore the total flux in the phase-a conductor is

$$\lambda_a = \lambda_{apa} + \lambda_{apb} + \lambda_{apc} = 2\times10^{-7}\left(I_a\ln\frac{D_{pa}}{r'} + I_b\ln\frac{D_{pb}}{D} + I_c\ln\frac{D_{pc}}{D}\right)$$

The above expression can be expanded as

$$\lambda_a = 2\times10^{-7}\left(I_a \ln\frac{1}{r'} + I_b \ln\frac{1}{D} + I_c \ln\frac{1}{D} + I_a \ln D_{pa} + I_b \ln D_{pb} + I_c \ln D_{pc}\right) \quad (5)$$

We know

$$I_b + I_c = -I_a$$

Substituting the above expression in (5) we get

$$\lambda_a = 2\times10^{-7}\left(I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D} + I_b \ln\frac{D_{pb}}{D_{pa}} + I_c \ln\frac{D_{pc}}{D_{pa}}\right) \quad (6)$$

Now if we move the point *P* far away, then we can approximate $D_{pa} \approx D_{pb} \approx D_{pc}$.. Therefore their logarithmic ratios will vanish and we can write (6) as

$$\lambda_a = 2\times10^{-7}\left(I_a \ln\frac{1}{r'} - I_a \ln\frac{1}{D}\right) = 2\times10^{-7} I_a \ln\frac{D}{r'} \quad (7)$$

Hence the inductance of phase-a is given as

$$L_a = 2\times10^{-7} \ln\frac{D}{r'} \quad (8)$$

Note that due to symmetry, the inductances of phases b and c will be the same as that of phase-a given above, i.e., $L_b = L_c = L_a$.

INDUCTANCE OF THREE-PHASE LINES WITH ASYMMETRICAL SPACING BUT TRANSPOSED

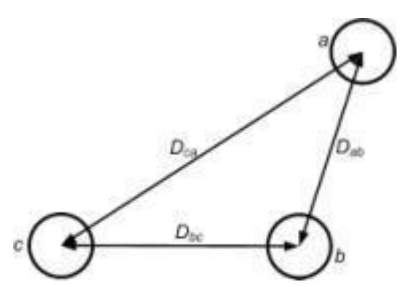


Fig. 3 Three-phase asymmetrically spaced line.

$$L_a = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2 \ln\frac{1}{D_{ab}} + a \ln\frac{1}{D_{ca}}\right) \quad (1)$$

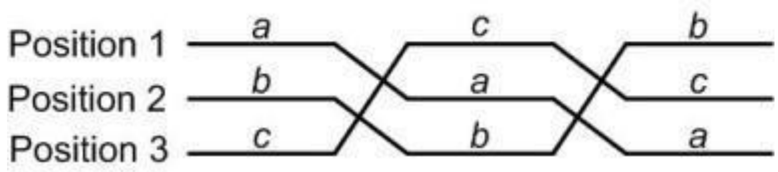
$$L_b = 2\times10^{-7}\left(\ln\frac{1}{r'} + a \ln\frac{1}{D_{ab}} + a^2 \ln\frac{1}{D_{bc}}\right) \quad (2)$$

$$L_c = 2\times10^{-7}\left(\ln\frac{1}{r'} + a^2 \ln\frac{1}{D_{ca}} + a \ln\frac{1}{D_{bc}}\right) \quad (3)$$

The inductances that are given in (1) to (3) are undesirable as they result in an unbalanced circuit configuration. One way of restoring the balanced nature of the circuit is to exchange the positions of the conductors at regular intervals. This is called transposition of line and is shown.

In this each segment of the line is divided into three equal sub-segments. The conductors of each of the phases a, b and c are exchanged after every sub-segment such that each of them is placed in each of the three positions once in the entire segment.

For example, the conductor of the phase-a occupies positions in the sequence 1, 2 and 3 in the three sub-segments while that of the phase-b occupies 2, 3 and 1. The transmission line consists of several such segments.



A segment of a transposed line**.**

In a transposed line, each phase takes all the three positions. The per phase inductance is the average value of the three inductances calculated in (1) to (3). We therefore have

$$L = \frac{L_a + L_b + L_c}{3} \quad (4)$$

This implies

$$L = \frac{2\times 10^{-7}}{3}\left[\ln\frac{3}{r'} + (a + a^2)\left(\ln\frac{1}{D_{ab}} + \ln\frac{1}{D_{bc}} + \ln\frac{1}{D_{bc}}\right)\right]$$

We know

$$a^2 = e^{j240^0} = -\frac{1}{2} + j\frac{\sqrt{3}}{2} \text{ and } 1 + a + a^2 = 0$$

we have $a + a^2 = -1$. Substituting this in the above equation we get

$$L = \frac{2\times 10^{-7}}{3}\left(3\ln\frac{1}{r'} - \ln\frac{1}{D_{ab}} - \ln\frac{1}{D_{bc}} - \frac{1}{D_{ca}}\right) \quad (5)$$

The above equation can be simplified as

$$L = 2\times 10^{-7}\left(\ln\frac{1}{r'} - \ln\frac{1}{(D_{ab}D_{bc}D_{ca})^{1/3}}\right) = 2\times 10^{-7}\ln\frac{(D_{ab}D_{bc}D_{ca})^{1/3}}{r'} \quad (6)$$

Defining the geometric mean distance (GMD) as

$$GMD = \sqrt[3]{D_{ab}D_{bc}D_{ca}} \qquad (7)$$

equation (7) can be rewritten as

$$L = 2\times10^{-7}\ln\frac{GMD}{r'} \text{ H/m} \qquad (8)$$

Notice that (8) is of the same form as for symmetrically spaced conductors. Comparing these two equations we can conclude that *GMD* can be construed as the equivalent conductor spacing. The *GMD* is the cube root of the product of conductor spacing.

CAPACITANCE OF A SINGLE-PHASE LINE

Consider the single-phase line consisting of two round conductors as shown in Fig.5. The separation between the conductors is *D*. Let us assume that conductor 1 carries a charge of q_1 C/m while conductor 2 carries a charge q_2 C/m. The presence of the second conductor and the ground will disturb field of the first conductor.

However we assume that the distance of separation between the conductors is much larger compared to the radius of the conductor and the height of the conductor is much larger than *D* for the ground to disturb the flux. Therefore the distortion is small and the charge is uniformly distributed on the surface of the conductor.

Assuming that the conductor 1 alone has the charge q_1 , the voltage between the conductors is

$$V_{12}(q_1) = \frac{q_1}{2\pi\varepsilon_0}\ln\frac{D_2}{r_1} \text{ V} \qquad (1)$$

Similarly if the conductor 2 alone has the charge q_2 , the voltage between the conductors is

$$V_{21}(q_2) = \frac{q_2}{2\pi\varepsilon_0}\ln\frac{D}{r_2}$$

The above equation implies that

$$V_{12}(q_2) = \frac{q_2}{2\pi\varepsilon_0}\ln\frac{r_2}{D} \text{ V} \qquad (2)$$

From the principle of superposition we can write

$$V_{12} = V_{12}(q_1) + V_{12}(q_2) = \frac{q_1}{2\pi\varepsilon_0}\ln\frac{D}{r_1} + \frac{q_2}{2\pi\varepsilon_0}\ln\frac{r_2}{D} \text{ V} \qquad (3)$$

For a single-phase line let us assume that q_1 (= $-q_2$) is equal to q. We therefore have

$$V_{12} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D}{r_1} - \frac{q}{2\pi\varepsilon_0}\ln\frac{r_2}{D} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D^2}{r_1r_2} \text{ V}$$

Assuming $r_1 = r_2 = r_3$, we can rewrite (4) as

(4)

$$V_{12} = \frac{q}{\pi \varepsilon_0} \ln \frac{D}{r} \quad \text{V}$$

(5)

The capacitance between the conductors is given by

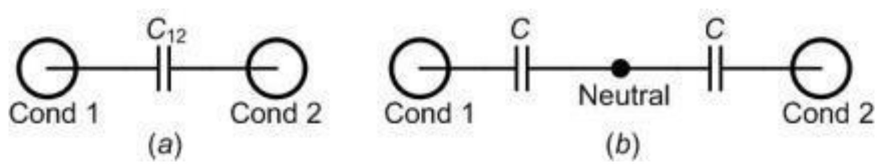
$$C_{12} = \frac{\pi \varepsilon_0}{\ln(D/r)} \quad \text{F/m}$$

(6)

The above equation gives the capacitance between two conductors. For the purpose of transmission line modeling, the capacitance is defined between the conductor and neutral.

Therefore the value of the capacitance is given from Fig. 5 as

$$C = 2C_{12} = \frac{2\pi \varepsilon_0}{\ln(D/r)}$$



Capacitance between two conductors and (b) equivalent capacitance to ground.

CAPACITANCE OF A THREE-PHASE TRANSPOSED LINE

Consider the three-phase transposed line shown in Fig. 6. In this the charges on conductors of phases a, b and c are q_a, $q_b$and q_c espectively. Since the system is assumed to be balanced we have

$$q_a + q_b + q_c = 0 \qquad (1)$$

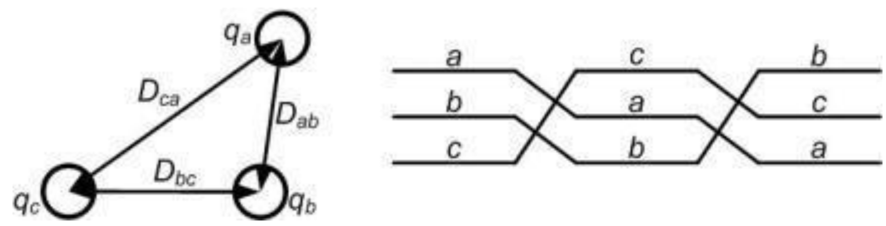


Fig. 6 Charge on a three-phase transposed line.

Using superposition, the voltage V_{ab} for the first, second and third sections of the transposition are given respectively as

$$V_{ab}(1) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ab}}{r} + q_b \ln\frac{r}{D_{ab}} + q_c \ln\frac{D_{bc}}{D_{ca}}\right) \text{V} \qquad (2)$$

$$V_{ab}(2) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{bc}}{r} + q_b \ln\frac{r}{D_{bc}} + q_c \ln\frac{D_{ca}}{D_{ca}}\right) \text{V} \qquad (3)$$

$$V_{ab}(3) = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ca}}{r} + q_b \ln\frac{r}{D_{ca}} + q_c \ln\frac{D_{ab}}{D_{bc}}\right) \text{V} \qquad (4)$$

Then the average value of the voltage is

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{D_{ab}D_{bc}D_{ca}}{r^3} + q_b \ln\frac{r^3}{D_{ab}D_{bc}D_{ca}} + q_c \ln\frac{D_{ab}D_{bc}D_{ca}}{D_{ab}D_{bc}D_{ca}}\right) \text{V} \qquad (5)$$

This implies

$$V_{ab} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln\frac{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}{r} + q_b \ln\frac{r}{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}\right) \text{V} \qquad (6)$$

From *GMD* of the conductors. We can therefore write

$$V_{ab} = \frac{1}{2\pi \varepsilon_0}\left(q_a \ln\frac{GMD}{r} + q_b \ln\frac{r}{GMD}\right) \text{ V} \qquad (7)$$

Similarly the voltage V_{ac} is given as

$$V_{ac} = \frac{1}{2\pi \varepsilon_0}\left(q_a \ln\frac{GMD}{r} + q_c \ln\frac{r}{GMD}\right) \qquad (8)$$

Adding (7) and (8) and using (1) we get

$$\begin{aligned} V_{ab} + V_{ac} &= \frac{1}{2\pi \varepsilon_0}\left[2q_a \ln\frac{GMD}{r} + (q_b + q_c)\ln\frac{r}{GMD}\right] \\ &= \frac{1}{2\pi \varepsilon_0}\left[2q_a \ln\frac{GMD}{r} - q_a \ln\frac{r}{GMD}\right] = \frac{3}{2\pi \varepsilon_0} q_a \ln\frac{GMD}{r} \end{aligned} \qquad (9)$$

For a set of balanced three-phase voltages

$$\begin{aligned} V_{ab} &= V_{an}\angle 0° - V_{an}\angle -120° \\ V_{ac} &= V_{an}\angle 0° - V_{an}\angle -240° \end{aligned}$$

Therefore we can write

$$V_{ab} + V_{ac} = 2V_{an}\angle 0° - V_{an}\angle -120° - V_{an}\angle -240° = 2V_{an}\angle 0° \text{ V} \qquad (10)$$

Combining (9) and (10) we get

$$V_{an} = \frac{1}{2\pi \varepsilon_0} q_a \ln\frac{GMD}{r} \text{ V} \qquad (11)$$

Therefore the capacitance to neutral is given by

$$C = \frac{q_a}{V_{an}} = \frac{2\pi \varepsilon_0}{\ln(GMD/r)} \text{ F/m} \qquad (12)$$

For bundles conductor

$$C = \frac{2\pi \varepsilon_0}{\ln(GMD/r)}$$

where

$$\begin{aligned} D_b &= \sqrt{\pi d} \quad \text{for 2 bundle} \\ &= \sqrt[3]{\pi d^2} \quad \text{for 3 bundle} \\ &= 1.094\sqrt[4]{\pi d^3} \quad \text{for 4 bundle conductors} \end{aligned}$$

EFFECT OF EARTH ON CAPACITANCE

In calculating the capacitance of transmission lines, the presence of earth was ignored, so far. The effect of earth on capacitance can be conveniently taken into account by the method of images.

METHOD OF IMAGES

- The electric field of transmission line conductors must conform to the presence of the earth below.
- The earth for this purpose may be assumed to be a perfectly conducting horizontal sheet of infinite extent which therefore acts like an equipotential surface.
- The electric field of two long, parallel conductors charged +q and –q per unit is such that it has a zero potential plane midway between the conductors as shown in Fig. 7.

- If a conducting sheet of infinite dimensions is placed at the zero potential plane, the electric field remains undisturbed.
- Further, if the conductor carrying charge -q is now removed, the electric field above the conducting sheet stays intact, while that below it vanishes.
- Using these well-known results in reverse, we may equivalently replace the presence of ground below a charged conductor by a fictitious conductor having equal and opposite charge and located as far below the surface of ground as the overhead conductor above it-such a fictitious conductor is the mirror image of the overhead conductor.
- This method of creating the same electric field as in the presence of earth is known as the method of images originally suggested by Lord Kelvin.

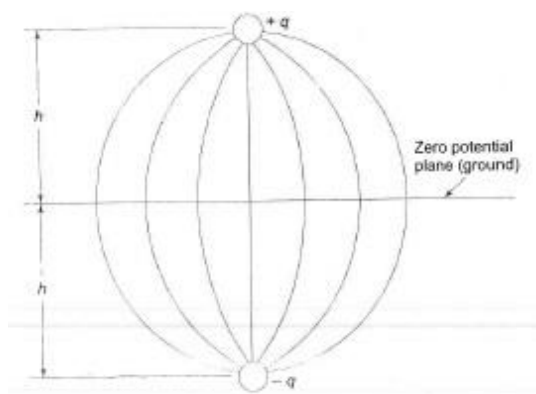
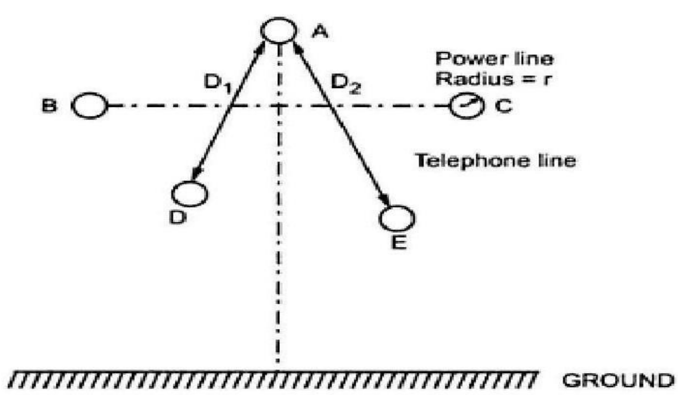


Fig. 7 Electric field of two long, parallel, oppositely charged conductors

EXPRESSION FOR THE VOLTAGE INDUCED IN COMMUNICATION LINESDUE TO THE CURRENT IN POWER LINES



The inductance of this loop is given by,

$$L_{AD} = 2 \times 10^{-7} \ln [D_1/r] \text{ H/m.}$$

The inductance of the loop AE is given by,

$$L_{AE} = 2 \times 10^{-7} \ln [D_2/r] \text{ H/m}$$

The mutual inductance between conductor A and the loop DE is given by,

$$M_A = L_{AE} - L_{AD} = 2 \times 10^{-7} [\ln [D_2/r] \ln [D_1/r]]$$

The net effect of the magnetic field will be,

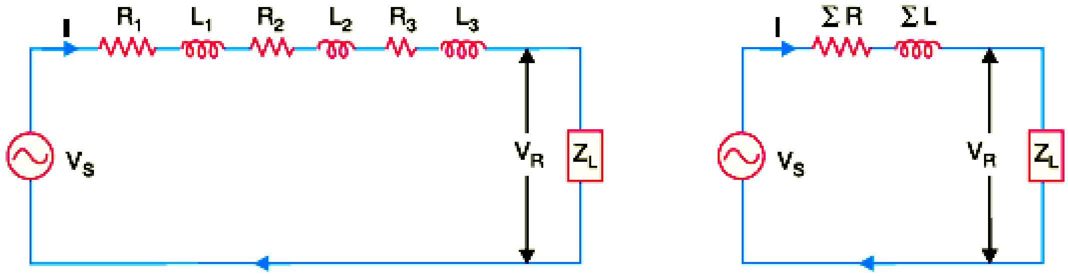
$$M = M_A + M_B + M_C$$

$$V = 2\Pi f I M \text{ volts /m.}$$

PARAMETERS OF SINGLE AND THREE PHASE TRANSMISSION LINES WITH SINGLE AND DOUBLE CIRCUITS

CONSTANTS OF A TRANSMISSION LINE

A transmission line has resistance, inductance and capacitance uniformly distributed along the whole length of the line. Before we pass on to the methods of finding these constants for a transmission line, it is profitable to understand them thoroughly.



(*i*) Resistance. It is the opposition of line conductors to current flow. The resistance is distributed uniformly along the whole length of the line as shown in Fig. However, the performance of a transmission line can be analysed conveniently if distributed resistance is considered as lumped as shown in Fig.

(*ii*) Inductance. When an alternating current flows through a conductor, a changing flux is set up which links the conductor. Due to these flux linkages, the conductor possesses inductance. Mathematically, inductance is defined as the flux linkages per ampere *i.e.*,

Inductance, $L = \frac{\psi}{I}$ henry

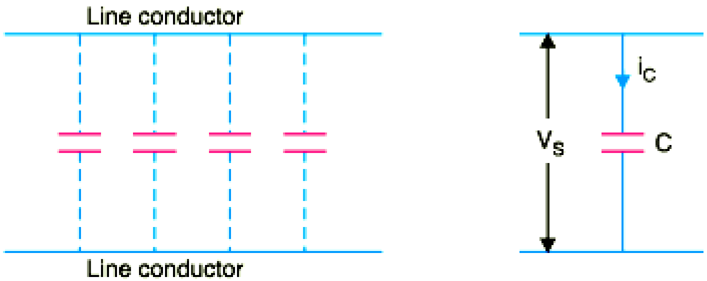
where ψ = flux linkages in weber-turns

I = current in amperes

The inductance is also uniformly distributed along the length of the * line as show in Fig. Again for the convenience of analysis, it can be taken to be lumped as shown in Fig

(*iii*) Capacitance. We know that any two conductors separated by an insulating material consti-tute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance between the conductors is the charge per unit potential difference

(*iii*) Capacitance. We know that any two conductors separated by an insulating material constitute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance between the conductors is the charge per unit potential difference *i.e.*, Capacitance, $C = \frac{q}{v}$ farad



where

q = charge on the line in coulomb

v = p.d. between the conductors in volts

The capacitance is uniformly distributed along the whole length of the line and may be regarded as a uniform series of capacitors connected between the conductors as shown in Fig. 9.2(*i*). When an alternating voltage is impressed on a transmission line, the charge on the conductors at any point increases and decreases with the increase and decrease of the instantaneous value of the voltage between conductors at that point. The result is that a current (known as *charging current*) flows between the conductors [See Fig. 9.2(*ii*)]. This charging current flows in the line even when it is open-circuited *i.e.*, supplying no load. It affects the voltage drop along the line as well as the efficiency and power factor of the line.

Resistance of a Transmission Line

The resistance of transmission line conductors is the most important cause of power loss in a transmission line. The resistance R of a line conductor having resistivity ρ, length l and area of cross-section a is given by ;

$R = \rho\, l/a$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation. Suppose R_1 and R_2 are the resistances of a conductor at t_1 °C and t_2 °C

($t_2 > t_1$) respectively. If α_1 is the temperature coefficient at t_1 °C, then,

$$R_2 = R_1\,[1 + \alpha_1\,(t_2 - t_1)]$$

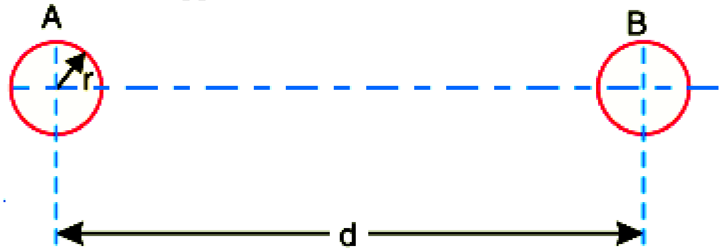
where $$\alpha_1 = \frac{\alpha_0}{1+\alpha_0\, t_1}$$

α_0 = temperature coefficient at 0° C

INDUCTANCE OF A SINGLE PHASE TWO-WIRE LINE

A single phase line consists of two parallel conductors which form a rectangular loop of one turn.

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



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

$$I_A+I_B = 0$$

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

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

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_d^\infty \frac{dx}{x}$$

Total flux linkages with conductor A is

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

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

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

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

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

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

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

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

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

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

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

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

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

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

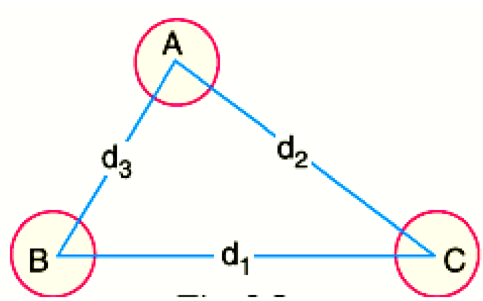
$$\text{Loop inductance} = 2 L_A \text{ H/m} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m}$$

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

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

INDUCTANCE OF A 3-PHASE OVERHEAD LINE

shows the three conductors A, B and C of a 3-phase line carrying currents I_A , I_B and I_C respectively. Let d_1 , d_2 and d_3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced i.e. $I_A + I_B + I_C = 0$. Consider the flux linkages with conductor There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of I_B and I_C



Flux linkages with conductor A due to its own current

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

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x}$$

Flux linkages with conductor A due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x}$$

Total flux linkages with conductor A is

$$\begin{aligned}
\psi_A &= (i)+(ii)+(iii)\\
&= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4}+\int_r^\infty \frac{dx}{x}\right)+\frac{\mu_0 I_B}{2\pi}\int_{d_3}^\infty \frac{dx}{x}+\frac{\mu_0 I_C}{2\pi}\int_{d_2}^\infty \frac{dx}{x}\\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}+\int_r^\infty \frac{dx}{x}\right)I_A + I_B\int_{d_3}^\infty \frac{dx}{x}+I_C\int_{d_2}^\infty \frac{dx}{x}\right]\\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I_A - I_B\log_e d_3 - I_C\log_e d_2 + \log_e \infty\left(I_A+I_B+I_C\right)\right]
\end{aligned}$$

As $I_A+I_B+I_C = 0,$

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

SYMMETRICAL SPACING

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d, then, d1 = d2 = d3 = d. Under such conditions, the flux Derived in a similar way, the expressions for inductance are the same for conductors B and C**.**

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

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

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

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

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

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

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

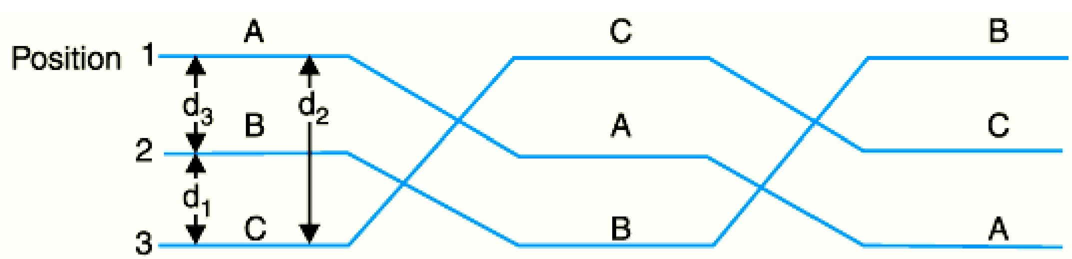
UNSYMMETRICAL SPACING

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

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

$$I_A + I_B + I_C = 0$$

Let the line currents be :



$$I_A = I(1 + j\,0)$$
$$I_B = I(-0{\cdot}5 - j\,0{\cdot}866)$$
$$I_C = I(-0{\cdot}5 + j\,0{\cdot}866)$$

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

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

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

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\log_e r\right)I - I(-0\cdot5 - j\,0\cdot866)\log_e d_3 - I(-0\cdot5 + j\,0\cdot866)\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + 0\cdot5\,I\log_e d_3 + j\,0\cdot866\log_e d_3 + 0\cdot5\,I\log_e d_2 - j\,0\cdot866\,I\log_e d_2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + 0\cdot5\,I\left(\log_e d_3 + \log_e d_2\right) + j\,0\cdot866\,I\left(\log_e d_3 - \log_e d_2\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I - I\log_e r + I^*\log_e\sqrt{d_2 d_3} + j\,0\cdot866\,I\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4}I + I\log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\,I\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0\,I}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2 d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]$$

∴ Inductance of conductor A is

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

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]$$

$$= \frac{4\pi\times10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,0\cdot866\log_e\frac{d_3}{d_2}\right]\text{ H/m}$$

$$= 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_2\,d_3}}{r} + j\,1\cdot732\log_e\frac{d_3}{d_2}\right]\text{ H/m}$$

Similarly inductance of conductors B and C will be :

$$L_B = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_3\,d_1}}{r} + j\,1\cdot732\log_e\frac{d_1}{d_3}\right]\text{ H/m}$$

$$L_C = 10^{-7}\left[\frac{1}{2} + 2\log_e\frac{\sqrt{d_1\,d_2}}{r} + j\,1\cdot732\log_e\frac{d_2}{d_1}\right]\text{ H/m}$$

Inductance of each line conductor

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

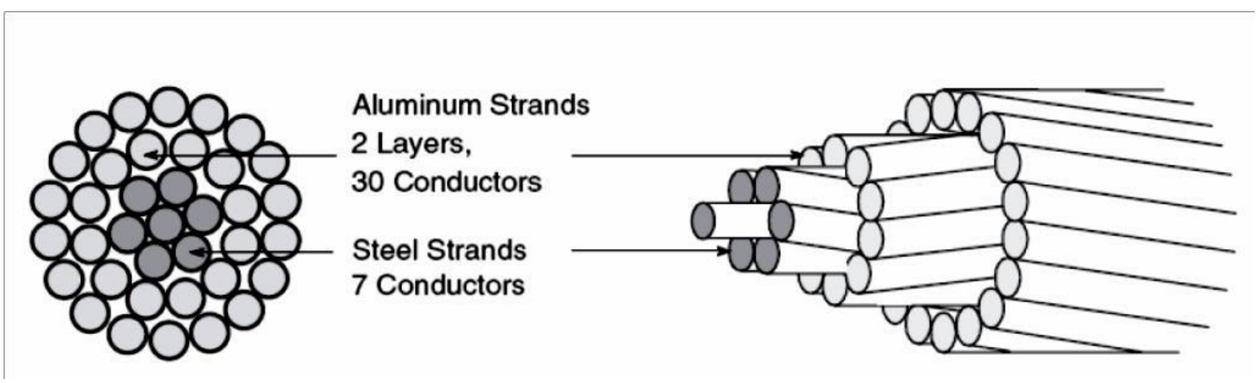
$$= * \left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

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

If we compare the formula of inductance of an un symmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$ The distance d is known as equivalent equilateral spacing for un symmetrically transposed line

SPIRALING AND BUNDLE CONDUCTOR EFFECT

There are two types of transmission line conductors: overhead and underground. Overhead conductors, made of naked metal and suspended on insulators, are preferred over underground conductors because of the lower cost and easy maintenance. Also, overhead transmission lines use aluminum conductors, because of the lower cost and lighter weight compared to copper conductors, although more cross-section area is needed to conduct the same amount of current. There are different types of commercially available aluminum conductors: aluminum-conductor-steel-reinforced (ACSR), aluminum-conductor-alloy-reinforced (ACAR), all-aluminum-conductor (AAC), and all-aluminumalloy- conductor (AAAC).



ACSR is one of the most used conductors in transmission lines. It consists of alternate layers of stranded conductors, spiraled in opposite directions to hold the strands together, surrounding a core of steel strands. Figure 13.4 shows an example of aluminum and steel strands combination. The purpose of introducing a steel core inside the stranded aluminum conductors is to obtain a high strength-to-weight ratio. A stranded conductor offers more flexibility and easier to manufacture than a solid large conductor. However, the total resistance is increased because the outside strands are larger than the inside strands on account of the spiraling. The resistance of each wound conductor at any layer, per unit length, is based on its total length as follows:

$$R_{cond} = \frac{\rho}{A}\sqrt{1+\left(\pi\frac{1}{P}\right)^2}\ \ \Omega/m$$

CONCEPT OF SELF-GMD AND MUTUAL-GMD

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

(i) Self-GMD (Ds)

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

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

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

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

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

Where

Ds = GMR or self-GMD = 0·7788 r

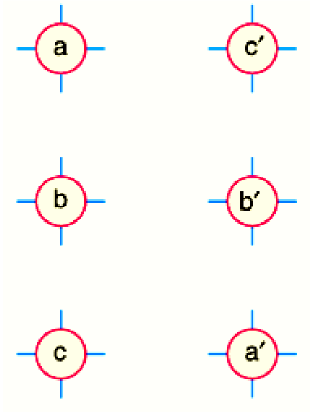
It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(ii) Mutual-GMD

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

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

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



(c) The principle of geometrical mean distances can be most profitably employed to 3-φ double circuit lines. Consider the conductor arrangement of the double circuit shown in Fig. Suppose the radius of each conductor is r.

Self-GMD of conductor = 0·7788 r

Self-GMD of combination aa' is

$$D_{s1} = (**D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$$

Self-GMD of combination bb' is

$$D_{s2} = (D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b})^{1/4}$$

Self-GMD of combination cc' is

$$D_{s3} = (D_{cc} \times D_{cc'} \times D_{c'c'} \times D_{c'c})^{1/4}$$

Equivalent self-GMD of one phase

$$D_s = (D_{s1} \times D_{s2} \times D_{s3})^{1/3}$$

The value of Ds is the same for all the phases as each conductor has the same radius.

Mutual-GMD between phases A and B is

$$D_{AB} = (D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'})^{1/4}$$

Mutual-GMD between phases B and C is

$$D_{BC} = (D_{bc} \times D_{bc'} \times D_{b'c} \times D_{b'c'})^{1/4}$$

Mutual-GMD between phases C and A is

$$D_{CA} = (D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'})^{1/4}$$

Equivalent mutual-GMD, $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

It is worthwhile to note that mutual GMD depends only upon the spacing and is substantially independent of the exact size, shape and orientation of the conductor.

Inductance Formulas in Terms of GMD

The inductance formulas developed in the previous articles can be conveniently expressed in terms of geometrical mean distances.

(i) Single phase line

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

where $D_s = 0{\cdot}7788\, r$ and D_m = Spacing between conductors = d

(ii) Single circuit 3-φ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

where $D_s = 0{\cdot}7788\, r$ and $D_m = (d_1\, d_2\, d_3)^{1/3}$

(iii) Double circuit 3-φ line

$$\text{Inductance/phase/m} = 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

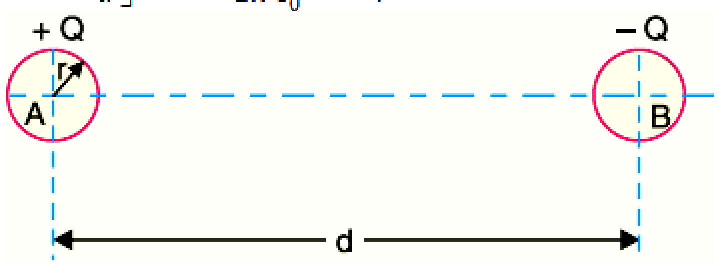
where $D_s = (D_{s1}\, D_{s2}\, D_{s3})^{1/3}$ and $D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$

CAPACITANCE OF A SINGLE PHASE TWO-WIRE LINE

Consider a single phase overhead transmission line consisting of two parallel conductors A and B spaced d metres apart in air. Suppose that radius of each conductor is r metres. Let their respective charge be + Q and − Q coulombs per metre length. The total p.d. between conductor A and neutral "infinite" plane is

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

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



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

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

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

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

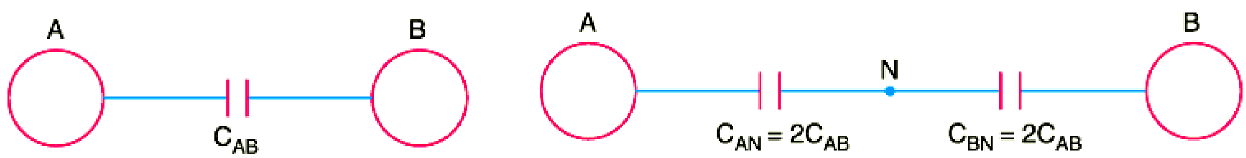
$$V_{AB} = 2V_A = \frac{2Q}{2\pi \varepsilon_0} \log_e \frac{d}{r} \text{ volts}$$

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

$$C_{AB} = \frac{\pi \varepsilon_0}{\log_e \frac{d}{r}} \text{ F / m}$$

Capacitance to neutral

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



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

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

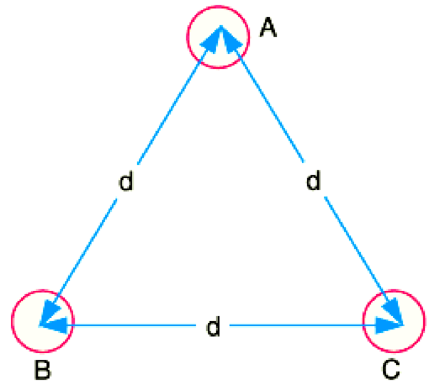
The reader may compare eq. (ii) to the one for inductance. One difference between the equations for capacitance and inductance should be noted carefully. The radius in the equation for capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula.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

2.7.1 CAPACITANCE OF A 3-PHASE OVERHEAD LINE

In a 3-phase transmission line, the capacitance of each conductor is considered instead of capacitance from conductor to conductor. Here, again two cases arise viz., symmetrical spacing and unsymmetrical spacing.

(i) Symmetrical Spacing

Fig shows the three conductors A, B and C of the 3-phase overhead transmission line having charges Q_A , Q_B and Q_C per meter length respectively. Let the conductors be equidistant (d meters) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line. Referring to Fig,



Overall potential difference between conductor A and infinite neutral plane is given by

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

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

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

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

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

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

∴ Capacitance of conductor A w.r.t neutral,

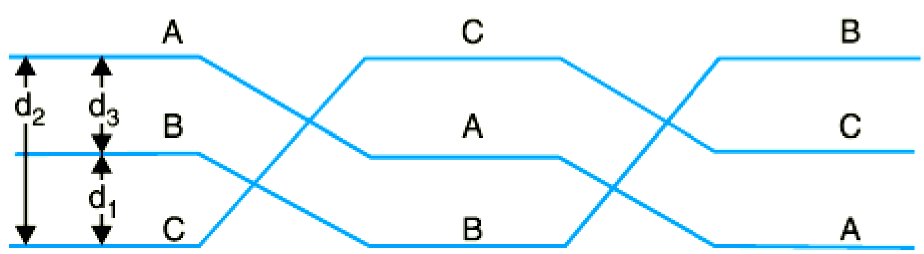
$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi\varepsilon_0}\log_e \frac{d}{r}} \text{ F/m} = \frac{2\pi\varepsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

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

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

(ii) Unsymmetrical spacing.

Fig. shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions i.e. $Q_A + Q_B + Q_C = 0$.



Considering all the three sections of the transposed line for phase A,

Potential of 1st position, $V_1 = \frac{1}{2\pi\varepsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right)$

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

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

Average voltage on conductor A is

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

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

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

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

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

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

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

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

Capacitance from conductor to neutral is

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

INDUCTIVE INTERFERENCE WITH NEIGHBOURING COMMUNICATION CIRCUITS

It is usual practice to run telephone lines along the same route as the power lines. The transmission lines transmit bulk power at relatively high voltages and, therefore, these lines give rise to electro-magnetic and electrostatic fields of sufficient magnitude which induce are superposed on the true speech currents in the neighboring telephone wires and set up distortion while the voltage so induced raise the potential of the communication circuit as a whole. In extreme cases the effect of these may make it impossible to transmit any message faithfully and may raise the potential of the telephone receiver above the ground to such an extent to render the handling of the telephone receiver extremely dangerous and in such cases elaborate precautions are required to be observed to avoid this danger.

In practice it is observed that the power lines and the communication lines run along the same path. Sometimes it can also be seen that both these lines run on same supports along the same route. The transmission lines transmit bulk power with relatively high voltage. Electromagnetic and electrostatic fields are produced by these lines having sufficient magnitude. Because of these fields, voltages and currents are induced in the neighbouring communication lines. Thus it gives rise to interference of power line with communication circuit.

Due to electromagnetic effect, currents are induced which is superimposed on speech current of the neighbouring communication line which results into distortion. The potential of the communication circuit as a whole is raised because of electrostatic effect and the communication apparatus and the equipments may get damaged due to extraneous voltages. In the worst situation, the faithful transmission of message becomes impossible due to effect of these fields. Also the potential of the apparatus is raised above the ground to such an extent that the handling of telephone receiver becomes extremely dangerous.

The electromagnetic and the electrostatic effects mainly depend on what is the distance between power and communication circuits and the length of the route over which they are parallel. Thus it can be noted that if the distortion effect and potential rise effect are within permissible limits then the communication will be proper. The unacceptable disturbance which is produced in the telephone communication because of power lines is called Telephone Interference.

There are various factors influencing the telephone interference. These factors are as follows

1) Because of harmonics in power circuit, their frequency range and magnitudes.
2) Electromagnetic coupling between power and telephone conductor.

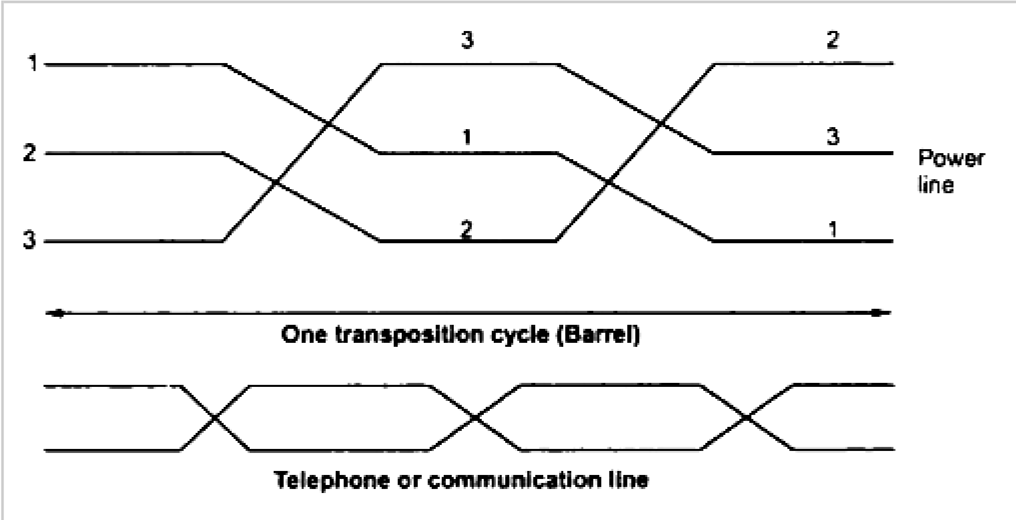
The electric coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms of mutual inductance at harmonic frequencies.

3) Due to unbalance in power circuits and in telephone circuits.
4) Type of return telephone circuit i.e. either metallic or ground return.
5) Screening effects.

Steps for Reducing Telephone Interference

There are various ways that can reduce the telephone interference. Some of them are as listed below

i) The harmonics at the source can be reduced with the use of A.C. harmonic filters, D.C. harmonic filters and smoothing rectors.
ii) Use greater spacing between power and telephone lines.
iii) The parallel run between telephone line and power line is avoided.
iv) Instead of using overhead telephone wires, underground telephone cables may be used.
v) If the telephone circuit is ground return then replace it with metallic return.
vi) Use microwave or carrier communication instead of telephone communication.
vii) The balance of AC power line is improved by using transposition. Transposition of lines reduces the induced voltages to a considerable extent. The capacitance of the lines is balanced by transposition leading to balance in electro statically induced voltages. Using transposition the fluxes due to positive and negative phase sequence currents cancel out so the electromagnetically induced e.m.f 's are diminished. For zero sequence currents the telephone lines are also transposed which is shown in the Fig.



INDUCTIVE INTERFERENCE WITH NEIGHBOURING CIRCUITS

The factors influencing the telephone interference are:

- Because of harmonics in power circuit, their frequency range and magnitudes
- Electromagnetic coupling
- Due to unbalance in power circuits and in telephone circuits
- Type of return telephone circuit
- Screening effects

STEPS FOR REDUCING TELEPHONE INTERFERENCE

- Harmonics can be reduced with the use of AC harmonic filters, DC harmonic filters and smoothening reactors
- Use greater spacing between power and telephone lines
- Parallel run between telephone and power line is avoided
- If telephone circuit is ground return, replace with metallic return.

UNIT IV

PERFORMANCE OF SHORT, MEDIUM AND LONG TRANSMISSION LINES

CLASSIFICATION OF LINES - INTRODUCTION

The important considerations in the design and operation of a transmission line are the determination of voltage drop, line losses and efficiency of transmission. These values are greatly influenced by the line constants *R*, *L* and *C* of the transmission line. For instance the voltage drop in the line depends upon the values of above three line constants. Similarly, the resistance of transmission line conductors is the most important cause of power loss in the line and determines the transmission efficiency. In this chapter, we shall develop formulas by which we can calculate voltage regulation, line losses and efficiency of transmission lines. These formulas are important for two principal reasons. Firstly, they provide an opportunity to understand the effects of the parameters of the line on bus voltages and the flow of power. Secondly, they help in developing an overall understanding of what is occurring on electric power system.

CLASSIFICATION OF OVERHEAD TRANSMISSION LINES

A transmission line has *three constants *R*, *L* and *C* distributed uniformly along the whole length of the line. The resistance and inductance form the series impedance. The capacitance existing between conductors for 1-phase line or from a conductor to neutral for a 3-phase line forms a shunt path throughout the length of the line. Therefore, capacitance effects introduce complications in transmission line calculations. Depending upon the manner in which capacitance is taken into account, the overhead transmission lines are classified as :

(i) Short transmission lines. When the length of an overhead transmission line is up to about 50 km and the line voltage is comparatively low (< 20 kV), it is usually considered as a short transmission line. Due to smaller length and lower voltage, the capacitance effects are small and hence can be neglected. Therefore, while studying the performance of a short transmission line, only resistance and inductance of the line are taken into account.

(ii) Medium transmission lines. When the length of an overhead transmission line is about 50-150 km and the line voltage is moderately high (>20 kV < 100 kV), it is considered as a medium transmission line. Due to sufficient length and voltage of the line, the capacitance effects are taken into account. For purposes of calculations, the distributed capacitance of the line is divided and lumped in the form of condensers shunted across the line at one or more points.

(iii) Long transmission lines. When the length of an overhead transmission line is more than 150 km and line voltage is very high (> 100 kV), it is considered as a long transmission line. For the treatment of such a line, the line constants are considered uniformly distributed over the whole length of the line and rigorous methods are employed for solution.

It may be emphasized here that exact solution of any transmission line must consider the fact that the constants of the line are not lumped but are distributed uniformly throughout the length of the line.

However, reasonable accuracy can be obtained by considering these constants as lumped for short and medium transmission lines.

Important Terms

While studying the performance of a transmission line, it is desirable to determine its voltage regulation and transmission efficiency. We shall explain these two terms in turn.

(i) Voltage regulation. When a transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. The result is that receiving end voltage (V_R) of the line is generally less than the sending end voltage (V_S). This voltage drop ($V_s - V_R$) in the line is expressed as a percentage of receiving end voltage V and is called voltage regulation. The difference in voltage at the receiving end of a transmission line **between conditions of no load and full load is called **voltage regulation** and is expressed as a percentage of the receiving end voltage.

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

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

PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

As stated earlier, the effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in Fig.

Here, the total line resistance and inductance are shown as concentrated or lumped instead of being distributed. The circuit is a simple a.c. series circuit.

Let

I = load current

R = loop resistance i.e., resistance of both conductors

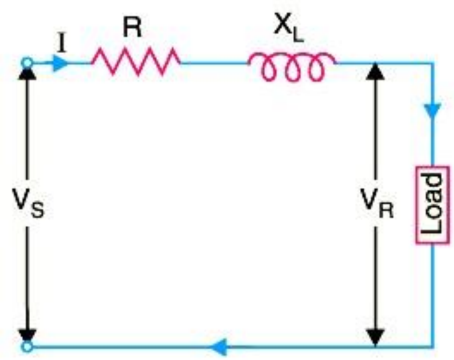
X_L= loop reactance

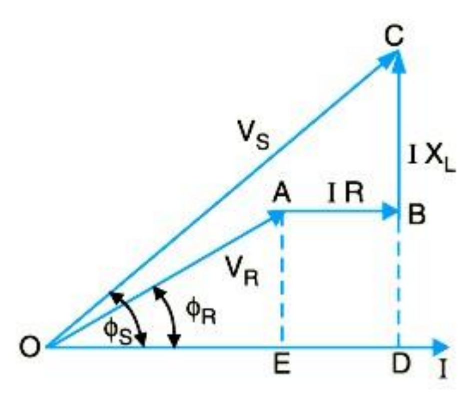
V_R = receiving end voltage

cos φ_R = receiving end power factor (lagging)

V_S= sending end voltage

cos φ_S= sending end power factor





The *phasor diagram of the line for lagging load power factor is shown in Fig. From the right angled traingle ODC, we get,

$$(OC)^2 = (OD)^2 + (DC)^2$$

or
$$V_S^2 = (OE + ED)^2 + (DB + BC)^2$$
$$= (V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2$$

$$\therefore \quad V_S = \sqrt{(V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2}$$

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

(ii) $\text{Sending end } p.f., \cos \phi_S = \dfrac{OD}{OC} = \dfrac{V_R \cos \phi_R + IR}{V_S}$

(iii) $\text{Power delivered} = V_R I_R \cos \phi_R$

$\text{Line losses} = I^2 R$

$\text{Power sent out} = V_R I_R \cos \phi_R + I^2 R$

$$\%\text{age Transmission efficiency} = \frac{\text{Power delivered}}{\text{Power sent out}} \times 100$$
$$= \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I^2 R} \times 100$$

An approximate expression for the sending end voltage Vs can be obtained as follows. Draw S perpendicular from B and C on OA produced as shown in Fig. Then OC is nearly equal to OF

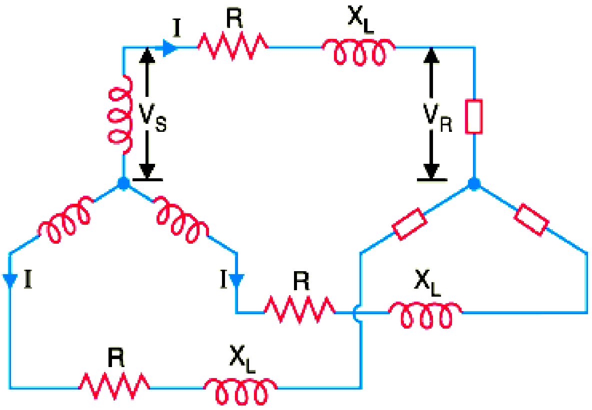
OC = OF = OA + AF = OA + AG + GF

= OA + AG + BH

$$V_s = V_R + IR \cos \varphi_R + I X_L \sin \varphi_R$$

THREE-PHASE SHORT TRANSMISSION LINES

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally analyze 3-phase system by considering one phase only. Therefore, expression for regulation, efficiency etc. derived for a single phase line can also be applied to a 3-phase system. Since only one phase is considered, phase values of 3-phase system should be taken. Thus, Vs and V_R are the phase voltages, whereas R and X_L are the resistance S and inductive reactance per phase respectively.



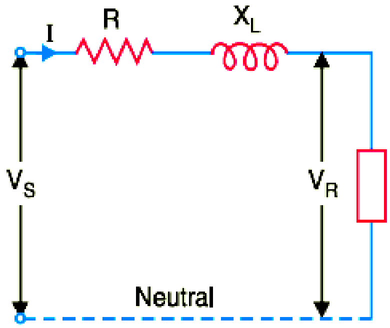


Fig (*i*) shows a *Y*-connected generator supplying a balanced *Y*-connected load through a transmission line. Each conductor has a resistance of *R* Ω and inductive reactance of *X* Ω. Fig. (ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

Effect of Load p.f. On Regulation and Efficiency

The regulation and efficiency of a transmission line depend to a considerable extent upon the power factor of the load.

1. **Effect on regulation.**
   The expression for voltage regulation of a short transmission line is given by :

$$\%\text{age Voltage regulation} = \frac{I R \cos \phi_R + I X_L \sin \phi_R}{V_R} \times 100 \qquad (\textit{for lagging p.f.})$$

$$\%\text{age Voltage regulation} = \frac{I R \cos \phi_R - I X_L \sin \phi_R}{V_R} \times 100 \qquad (\textit{for leading p.f.})$$

The following conclusions can be drawn from the above expressions:

(*i*) When the load p.f. is lagging or unity or such leading that $I R \cos \varphi_R > I X_L \sin \varphi_R$, then voltage regulation is positive *i.e.* , receiving end voltage V_R will be less than the sending end voltage V_S .
(*ii*) For a given V_R and *I*, the voltage regulation of the line increases with the decrease in p.f. for lagging loads.
(*iii*) When the load p.f. is leading to this extent that $I X_L \sin \varphi_R > I \cos \varphi_R$, then voltage regulation is negative *i.e.* the receiving end voltage V_R *is* more than the sending end voltage V_S .
(*iv*) For a given V_R and *I*, the voltage regulation of the line decreases with the decrease in p.f. for leading loads.

2. Effect on transmission efficiency.

The power delivered to the load depends upon the power factor.

$$P = V_R * I \cos \phi_R \quad \text{(For 1-phase line)}$$

$$I = \frac{P}{V_R \cos \phi_R}$$

$$P = 3\, V_R I \cos \phi_R \quad \text{(For 3-phase line)}$$

$$I = \frac{P}{3V_R \cos \phi_R}$$

It is clear that in each case, for a given amount of power to be transmitted (P) and receiving end voltage Power Factor Meter (V_R), the load current I is inversely proportional to the load p.f. cos φ_R. Consequently, with the decrease in load p.f., the load current and hence the line losses are increased. This leads to the conclusion that transmission efficiency of a line decreases with the decrease in load Power Factor Regulator p.f. and vice-versa,

ABCD PARAMETERS

A major section of power system engineering deals in the transmission of electrical power from one particular place (eg. Generating station) to another like substations or distribution units with maximum efficiency. So its of substantial importance for power system engineers to be thorough with its mathematical modeling. Thus the entire transmission system can be simplified to a **two port network** for the sake of easier calculations.

The circuit of a 2 port network is shown in the diagram below. As the name suggests, a 2 port network consists of an input port PQ and an output port RS. Each port has 2 terminals to

Connect itself to the external circuit. Thus it is essentially a 2 port or a 4 terminal circuit, having

Supply end voltage = VS and Supply end current = IS given to the input port P Q.

And there is the Receiving end Voltage = VR and Receiving end current = IR

Given to the output port R S. As shown in the diagram below.

Now the **ABCD parameters** or the transmission line parameters provide the link between the supply and receiving end voltages and currents, considering the circuit elements to be linear in nature.

Thus the relation between the sending and receiving end specifications are given using

ABCD parameters by the equations below.

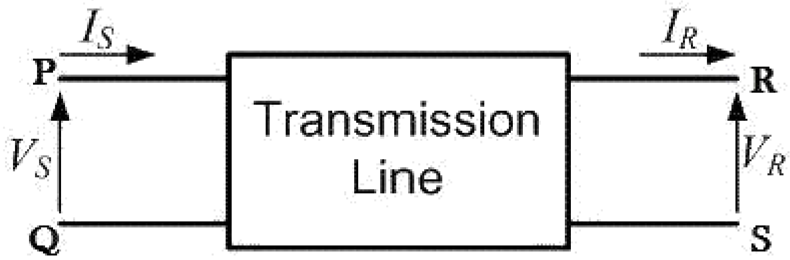
VS = A VR + B IR ———————-(1)

IS = C VR + D IR ———————-(2)

Now in order to determine the ABCD parameters of transmission line let us impose the required circuit conditions in different cases.

ABCD parameters, when receiving end is open circuited

The receiving end is open circuited meaning receiving end current IR = 0. Applying this condition to



equation (1) we get.

$$V_S = A\,V_R + B\,0 \Rightarrow V_S = A\,V_R + 0$$

$$A = \left.\frac{V_S}{V_R}\right|_{I_R = 0}$$

Thus its implies that on applying open circuit condition to ABCD parameters, we get parameter A as the ratio of sending end voltage to the open circuit receiving end voltage. Since dimension wise A is a ratio of voltage to voltage, A is a dimension less parameter.

Applying the same open circuit condition i.e IR = 0 to equation (2)

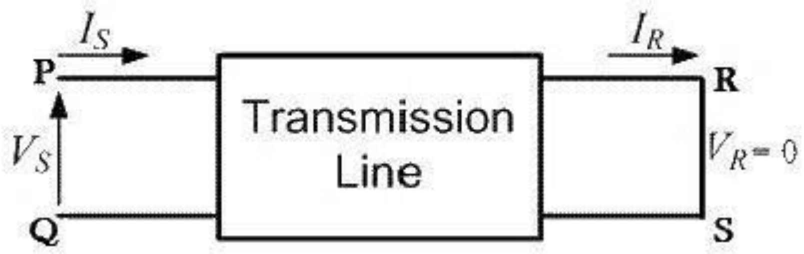
$$I_S = C\,V_R + D\,0 \Rightarrow I_S = C\,V_R + 0$$

$$C = \left.\frac{I_S}{V_R}\right|_{I_R = 0}$$

Thus its implies that on applying open circuit condition to ABCD parameters of transmission line, we get parameter C as the ratio of sending end current to the open circuit receiving end voltage. Since dimension wise C is a ratio of current to voltage, its unit is mho.

Thus C is the open circuit conductance and is given by C = IS ⁄ VR mho.

ABCD parameters when receiving end is short circuited



Receiving end is short circuited meaning receiving end voltage VR = 0 Applying this condition to equation (1) we get

$$V_S = A\,0 + B\,I_R \Rightarrow V_S = 0 + B\,I_R$$
$$B = \frac{V_S}{I_R}\bigg|_{V_R = 0}$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter B as the ratio of sending end voltage to the short circuit receiving end current. Since dimension wise B is a ratio of voltage to current, its unit is Ω. Thus B is the short circuit resistance and is

given by

B = VS / IR Ω.

Applying the same short circuit condition i.e VR = 0 to equation (2) we get

$$I_S = C\,0 + D\,I_R \Rightarrow I_S = 0 + D\,I_R$$
$$D = \frac{I_S}{I_R}\bigg|_{V_R = 0}$$

Thus its implies that on applying short circuit condition to ABCD parameters, we get parameter D as the ratio of sending end current to the short circuit receiving end current. Since dimension wise D is a ratio of current to current, it's a dimension less parameter. ∴ the ABCD parameters of transmission line can be tabulated as:-

Parameter Specification

Unit A = VS / VR Voltage ratio

Unit less B = VS / IR

Short circuit resistance Ω

C = IS / VR Open circuit conductance mho

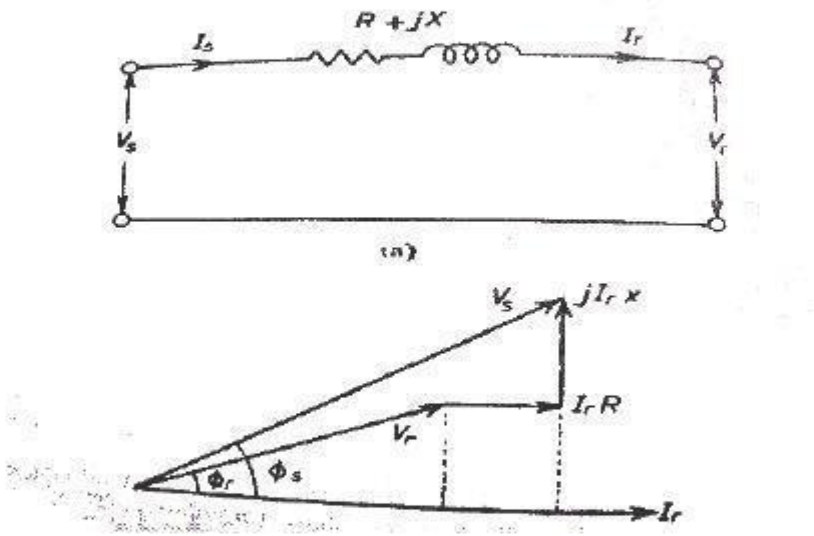
D = IS / IR Current ratio Unit less

SHORT TRANSMISSION LINE

The transmission lines which have length less than 80 km are generally referred as short transmission lines.

For short length, the shunt capacitance of this type of line is neglected and other parameters like resistance and inductance of these short lines are lumped, hence the equivalent circuit is represented as given below,

Let's draw the vector diagram for this equivalent circuit, taking receiving end current Ir as reference. The sending end and receiving end voltages make angle with that reference receiving end current, of φs and φr, respectively.



As the shunt capacitance of the line is neglected, hence sending end current and receiving end current is same, i.e. Is = Ir.

Now if we observe the vector diagram carefully, we will get, Vs is approximately equal to

Vr + Ir.R.cosφr + Ir.X.sinφr that means,

Vs ≅ Vr + Ir.R.cosφr + Ir.X.sinφr as the it is assumed that φs ≅ φr

As there is no capacitance, during no load condition the current through the line is considered as zero, hence at no load condition, receiving end voltage is the same as sending end voltage As per dentition of voltage regulation,

$$\% \text{ regulation} = \frac{V_s - V_r}{V_r} X \, 100\ \%$$

$$= \frac{I_r.R.\cos\varphi_r + I_r.X.\sin\varphi_r}{V_r} X \, 100\ \%$$

$$\text{per unit regulation} = \frac{I_r.R}{V_r}\cos\varphi_r + \frac{I_r.X}{V_r}\sin\varphi_r = v_r\cos\varphi_r + v_x\sin\varphi_r$$

$$A = \left.\frac{V_s}{V_r}\right| I_r = 0$$

Here, vr and vx are the per unit resistance and reactance of the short transmission line.

Any electrical network generally has two input terminals and two output terminals. If we consider any complex electrical network in a black box, it will have two input terminals and output terminals. This network is called two – port network. Two port model of a network simplifies the network solving technique. Mathematically a two port network can be solved by 2 by 2 matrixes.

A transmission as it is also an electrical network; line can be represented as two port network. Hence two port network of transmission line can be represented as 2 by 2 matrixes. Here the concept of ABCD parameters comes. Voltage and currents of the network can represented as ,

Vs= AVr + BIr… (1)

Is= CVr + DIr… (2)

Where A, B, C and D are different constant of the network. If we put Ir = 0 at equation (1), we get

Hence, A is the voltage impressed at the sending end per volt at the receiving end when receiving end is open. It is dimension less.

If we put Vr = 0 at equation (1), we get

$$B = \left.\frac{V_s}{I_r}\right| V_r = 0$$

That indicates it is impedance of the transmission line when the receiving terminals are short circuited. This parameter is referred as transfer impedance.

$$C = \left.\frac{I_s}{V_r}\right| I_r = 0$$

C is the current in amperes into the sending end per volt on open circuited receiving end. It has the dimension of admittance.

$$D = \left.\frac{I_s}{I_r}\right| V_r = 0$$

D is the current in amperes into the sending end per amp on short circuited receiving end. It is dimensionless.

Now from equivalent circuit, it is found that,

Vs = Vr + IrZ and Is = Ir Comparing these equations with equation 1 and 2 we get,

A = 1, B = Z, C = 0 and D = 1. As we know that the constant A, B, C and D are related for passive network as

Here, A = 1, B = Z, C = 0 and D = 1

$$AD - BC = 1.$$

$$\Rightarrow 1.1 - Z.0 = 1$$

So the values calculated are correct for short transmission line. From above equation (1),

$$V_s = AV_r + BI_r$$

When Ir = 0 that means receiving end terminals is open circuited and then from the equation 1, we get receiving end voltage at no load

$$V_r' = \frac{V_s}{A}$$

and as per definition of voltage regulation,

$$\%\text{ voltage regulation} = \frac{V_s / A - V_r}{V_r} X100\ \%$$

Efficiency of Short Transmission Line

The efficiency of short line as simple as efficiency equation of any other electrical equipment, that means

$$\%\text{ efficiency } (\mu) = \frac{\text{Power received at receiving end}}{\text{Power delivered at sending end}} X\ 100\ \%$$

$$\%\ \mu = \frac{\text{Power received at receiving end}}{\text{Power received at receiving end} + 3I_r^2.R} X\ 100\ \%$$

MEDIUM TRANSMISSION LINES

In short transmission line calculations, the effects of the line capacitance are neglected because such lines have smaller lengths and transmit power at relatively low voltages (< 20 kV). However, as the length and voltage of the line increase, the capacitance gradually becomes of greater importance.

Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20 kV, the effects of capacitance cannot be neglected. Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration.

The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localising the line capacitance gives reasonably accurate results. The most commonly used methods (known as localised capacitance methods) for the solution of medium transmissions lines are:

(i) End condenser method

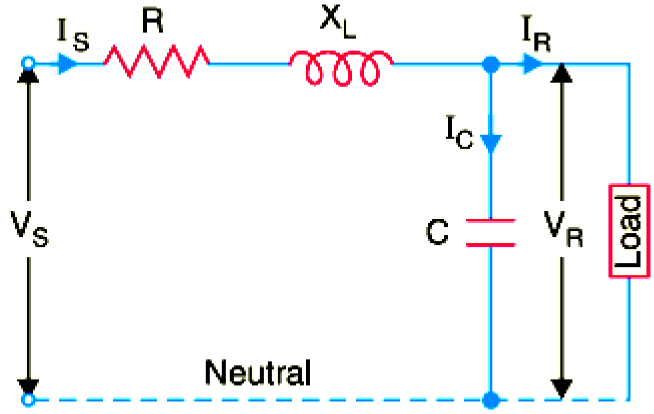
(ii) Nominal T method

(iii) Nominal π method.

Although the above methods are used for obtaining the performance calculations of medium lines, they can also be used for short lines if their line capacitance is given in a particular problem.

i) End Condenser Method

In this method, the capacitance of the line is lumped or concentrated at the receiving or load end as shown in Fig. This method of localising the line capacitance at the load end overestimates the effects of capacitance. In Fig, one phase of the 3-phase transmission line is shown as it is more convenient to work in phase instead of line-to-line values.



Let

I_R= load current per phase
R = resistance per phase
X_L= inductive reactance per phase
C = capacitance per phase
cos φ_R= receiving end power factor (lagging)
V_S= sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig Taking the receiving end voltage VR as the reference phasor,

$$\text{we have, } \vec{V_R} = V_R + j\,0$$

$$\text{Load current, } \vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$$

$$\text{Capacitive current, } \vec{I_C} = j\,\vec{V_R}\,\omega C = j\,2\pi f C\,\vec{V_R}$$

The sending end current I_s is the phasor sum of load current I_R and capacitive current I_C i.e.

$$\begin{aligned}\vec{I_S} &= \vec{I_R} + \vec{I_C} \\ &= I_R(\cos\phi_R - j\sin\phi_R) + j\,2\pi f C\,V_R \\ &= I_R\cos\phi_R + j\,(-I_R\sin\phi_R + 2\pi f C V_R) \\ &= \vec{I_S}\,\vec{Z} = \vec{I_S}\,(R + jX_L) \\ \vec{V_S} &= \vec{V_R} + \vec{I_S}\,\vec{Z} = \vec{V_R} + \vec{I_S}\,(R + j\,X_L)\end{aligned}$$

Thus, the magnitude of sending end voltage V_S can be calculated.

$$\%\text{ Voltage regulation } = \frac{V_S - V_R}{V_R} \times 100$$

$$\%\text{ Voltage transmission efficiency} = \frac{\text{Power delivered / phase}}{\text{Power delivered / phase + losses / phase}} \times 100$$

$$= \frac{V_R I_R \cos\phi_R}{V_R I_R \cos\phi_R + I_S^2 R} \times 100$$

Limitations

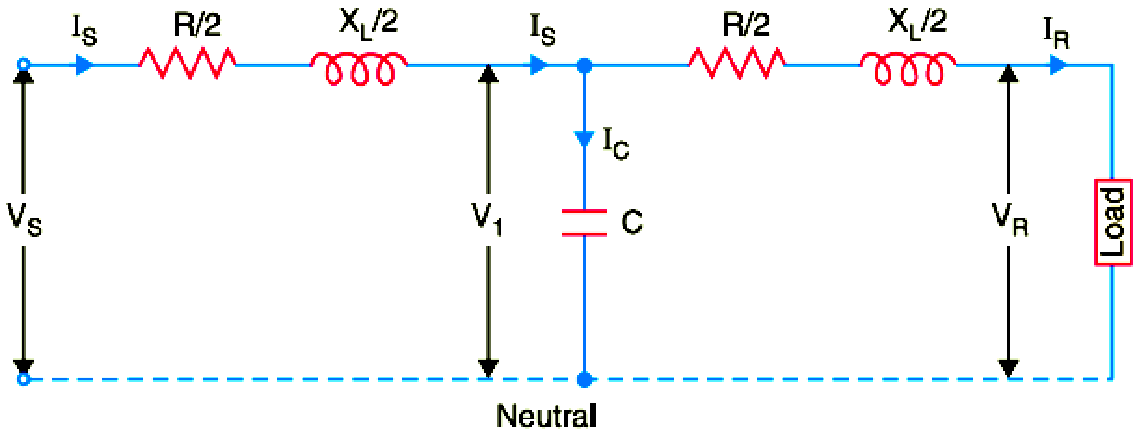
Although end condenser method for the solution of medium lines is simple to work out calculations, yet it has the following drawbacks:

(i) There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.

(ii) This method overestimates the effects of line capacitance.

ii) Nominal T Method

In this method, the whole line capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on its either side as shown in Fig. Therefore, in this arrangement, full charging current flows over half the line. In Fig. one phase of 3-phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.



Let

I_R = load current per phase; R = resistance per phase

X_L = inductive reactance per phase;

C = capacitance per phase

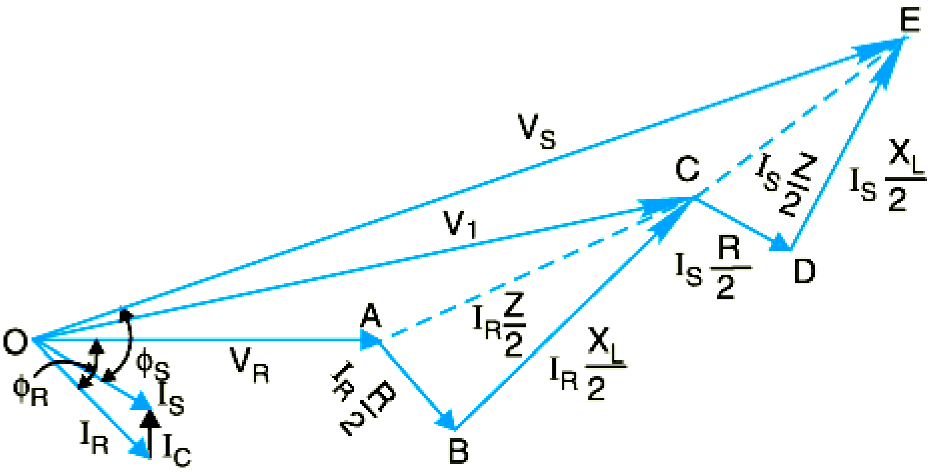
cos φ_R = receiving end power factor (lagging) ; V_S= sending end voltage/phase

V_1 = voltage across capacitor C

The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage V_R as the reference phasor, we have,

Receiving end voltage, $\vec{V_R} = V_R + j\,0$

Load current, $\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$



Voltage across C, $\vec{V_1} = \vec{V_R} + \vec{I_R}\,\vec{Z}/2$

$$= V_R + I_R(\cos\phi_R - j\sin\phi_R)\left(\frac{R}{2} + j\,\frac{X_L}{2}\right)$$

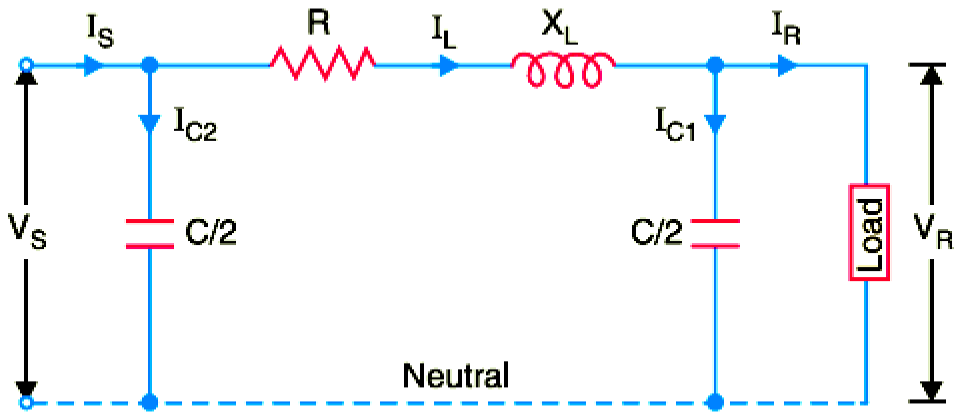
Capacitive current, $\vec{I_C} = j\,\omega\,C\,\vec{V_1} = j\,2\pi f\,C\,\vec{V_1}$

Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C}$

Sending end voltage, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\frac{\vec{Z}}{2} = \vec{V_1} + \vec{I_S}\left(\frac{R}{2} + j\,\frac{X_L}{2}\right)$

iii) Nominal π Method

In this method, capacitance of each conductor (i.e., line to neutral) is divided into two halves; one half being lumped at the sending end and the other half at the receiving end as shown in Fig. It is obvious that capacitance at the sending end has no effect on the line drop. However, its charging current must be added to line current in order to obtain the total sending end current.



Let

I_R = load current per phase R = resistance per phase

X_L = inductive reactance per phase C = capacitance per phase

cos φ_R = receiving end power factor (lagging) V_S= sending end voltage per phase

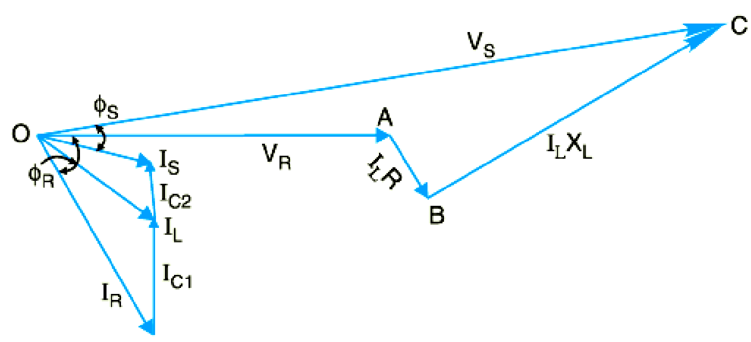
The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage as the reference phasor, we have,

$$\vec{V_R} = V_R + j\,0$$

Load current, $$\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$$

Charging current at load end is

$$\vec{I_{C1}} = j\,\omega\,(C/2)\,\vec{V_R} = j\,\pi\,f\,C\,\vec{V_R}$$



Line current, $\overrightarrow{I_L} = \overrightarrow{I_R} + \overrightarrow{I_{C1}}$

Sending end voltage, $\overrightarrow{V_S} = \overrightarrow{V_R} + \overrightarrow{I_L}\,\overrightarrow{Z} = \overrightarrow{V_R} + \overrightarrow{I_L}\,(R + jX_L)$

Charging current at the sending end is

$$\overrightarrow{I_{C2}} = j\,\omega\,(C/2)\,\overrightarrow{V_S} = j\,\pi\,f\,C\,\overrightarrow{V_S}$$

∴ Sending end current, $\overrightarrow{I_S} = \overrightarrow{I_L} + \overrightarrow{I_{C2}}$

MEDIUM TRANSMISSION LINE

The transmission line having its effective length more than 80 km but less than 250 km is generally referred to as a **medium transmission line**. Due to the line length being considerably high, admittance Y of the network does play a role in calculating the effective circuit parameters, unlike in the case of short transmission lines. For this reason the modelling of a **medium length transmission line** is done using lumped shunt admittance along with the lumped impedance in series to the circuit.

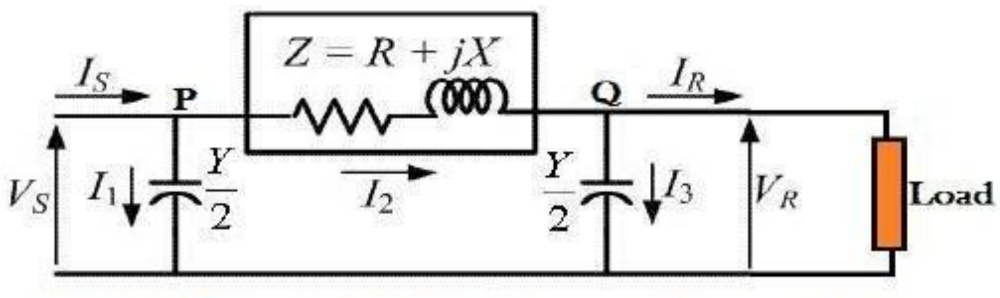
These lumped parameters of a medium length transmission line can be represented using two different models, namely.

1) Nominal **Π** representation.
2) Nominal **T** representation.

Let's now go into the detailed discussion of these above mentioned models.

Nominal Π representation of a medium transmission line

In case of a nominal **Π** representation, the lumped series impedance is placed at the middle of the circuit where as the shunt admittances are at the ends. As we can see from the diagram of the Π network below, the total lumped shunt admittance is divided into 2 equal halves, and each half with value Y ⁄ 2 is placed at both the sending and the receiving end while the entire circuit impedance is between the two. The shape of the circuit so formed resembles that of a symbol **Π**, and for this reason it is known as the nominal Π representation of a medium transmission line. It is mainly used for determining the general circuit parameters and performing load flow analysis.



Nominal Π network of medium transmission line.

As we can see here, VS and VR is the supply and receiving end voltages respectively, and Is is the current flowing through the supply end.

IR is the current flowing through the receiving end of the circuit.

I1 and I3 are the values of currents flowing through the admittances. And I2 is the current through the impedance Z.

Now applying KCL, at node P, we get. IS = I1 + I2 ——————(1)

Similarly applying KCL, to node Q. I2 = I3 + IR ——————(2)

Now substituting equation (2) to equation(1)

IS = I1 + I3 + IR

$$= \frac{Y}{2}V_S + \frac{Y}{2}V_R + I_R \text{--------(3)}$$

Now by applying KVL to the circuit, VS = VR + Z I2

$$= V_R + Z(V_R\frac{Y}{2} + I_R)$$

$$= (Z\frac{Y}{2} + 1)\, V_R + ZI_R \text{ ---------(4)}$$

Now substituting equation (4) to equation (3), we get.

$$I_s = \frac{Y}{2}[(\frac{Y}{2}Z + 1)V_R + ZI_R] + \frac{Y}{2}V_R + I_R$$

$$= Y(\frac{Y}{4}Z + 1)V_R + (\frac{Y}{2}Z + 1)I_R \text{ -----------(5)}$$

Comparing equation (4) and (5) with the standard ABCD parameter equations

VS = A VR + B IR

IS = C VR + D IR

We derive the parameters of a medium transmission line as:

$$A = (\frac{Y}{2}Z + 1)$$

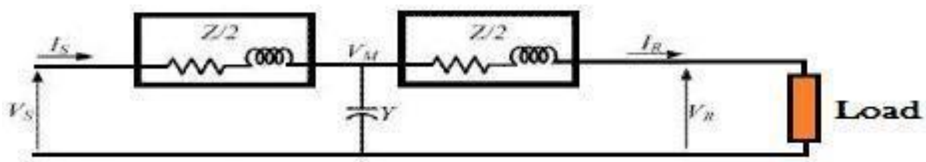
$$B = Z\ \Omega$$

$$C = Y(\frac{Y}{4}Z + 1)$$

$$D = (\frac{Y}{2}Z + 1)$$

NOMINAL T REPRESENTATION OF A MEDIUM TRANSMISSION LINE

In the **nominal T** model of a medium transmission line the lumped shunt admittance is placed in the middle, while the net series impedance is divided into two equal halves and and placed on either side of the shunt admittance. The circuit so formed resembles the symbol of a capital **T**, and hence is known as the nominal T network of a medium length transmission line and is shown in the diagram below.



Nominal T representation of a medium transmission line.

Here also Vs and Vr is the supply and receiving end voltages respectively, andIs is the current flowing through the supply end. Ir is the current flowing through the receiving end of the circuit. Let M be a node at the midpoint of the circuit, and the drop at M, be given by
Vm. Applying KVL to the above network we get

$$\frac{V_S - V_M}{Z/2} = Y V_M + \frac{V_m - V_R}{Z/2}$$

$$\text{Or } V_M = \frac{2(V_S + V_R)}{YZ + 4} \text{------------------(6)}$$

And the receiving end current

$$\text{Or } I_R = \frac{2(V_M - V_R)}{Z/2} \text{------------------(7)}$$

Now substituting V_M from equation (6) to (7) we get,

$$\text{Or } I_R = \frac{[(2V_S + V_R)/YZ+4] - V_R}{Z/2}$$

Rearranging the above equation:

$$V_S = (\frac{Y}{2}Z + 1)V_R + Z(\frac{Y}{4}Z + 1)I_R \text{------------------(8)}$$

Now the sending end current is

Is = Y VM + IR ——————(9)

Substituting the value of VM to equation (9) we get,

$$\text{Or } I_S = Y V_R + (\frac{Y}{2}Z + 1)I_R \text{------------------(10)}$$

Again comparing Comparing equation (8) and (10) with the standard ABCD parameter equations

VS = A VR + B IR

IS = C VR + D IR

The parameters of the **T** network of a medium transmission line are

$$A = (\frac{Y}{2}Z + 1)$$

$$B = Z(\frac{Y}{4}Z + 1)\ \Omega$$

$$C = Y \text{ mho}$$

$$D = (\frac{Y}{2}Z + 1)$$

LONG TRANSMISSION LINES

It is well known that line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped. If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are considered as uniformly distributed throughout the length of the line. Rigorous mathematical treatment is required for the solution of such lines. Fig shows the equivalent circuit of a 3-phase long transmission line on a phase-neutral basis. The whole line length is divided into n sections, each section having line constants 1 /n th of those for the whole line. The following points may by noted :

(i) The line constants are uniformly distributed over the entire length of line as is actually the case.

(ii) The resistance and inductive reactance are the series elements.

(ii) The leakage susceptance (B) and leakage conductance (G) are shunt elements.

(iii) The leakage susceptance is due to the fact that capacitance exists between line and neutral. The leakage conductance takes into account the energy losses occurring through leakage over the

$$= \sqrt{G^2 + B^2} .$$

insulators or due to corona effect between conductors. Admittance

(iv) The leakage current through shunt admittance is maximum at the sending end of the line and decreases continuously as the receiving end of the circuit is approached at which point its value is zero.

ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD)

Fig. shows one phase and neutral connection of a 3-phase line with impedance and shunt admittance of the line uniformly distributed.

Consider a small element in the line of length dx situated at a distance x from the receiving end.

Let

z = series impedance of the line per unit length y

= shunt admittance of the line per unit length

V = voltage at the end of element towards receiving end

V + dV = voltage at the end of element towards sending end I

+ dI = current entering the element dx

I = current leaving the element dx

Then for the small element dx,

z dx = series impedance y

dx = shunt admittance

Obviously, dV = I z dx

$$\frac{dV}{dx} = I z$$

Now, the current entering the element is I + dI whereas the current leaving the element is I. The difference in the currents flows through shunt admittance of the element i.e.,

dI = Current through shunt admittance of element = Vy dx

or $$\frac{dI}{dx} = V y \quad \ldots(ii)$$

Differentiating eq. (*i*) w.r.t. *x*, we get,

$$\frac{d^2V}{dx^2} = z\frac{dI}{dx} = z(V y) \qquad \left[\because \frac{dI}{dx} = V\ y\ from\ \exp.(ii)\right]$$

or $$\frac{d^2V}{dx^2} = y z V \quad \ldots(iii)$$

The solution of this differential equation is

$$V = k_1 \cosh\left(x\sqrt{y z}\right) + k_2 \sinh\left(x\sqrt{y z}\right) \quad \ldots(iv)$$

or $$\frac{dI}{dx} = V y \quad \ldots(ii)$$

Differentiating eq. (*i*) w.r.t. *x*, we get,

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or $$\frac{d^2V}{dx^2} = y z V \quad \ldots(iii)$$

The solution of this differential equation is

$$V = k_1 \cosh\left(x\sqrt{y z}\right) + k_2 \sinh\left(x\sqrt{y z}\right) \quad \ldots(iv)$$

Equations (iv) and (v) give the expressions for V and I in the form of unknown constants k_1 and K_2 . The values of k_1 and k_2 can be found by applying end conditions as under

At $x = 0, \quad V = V_R$ and $I = I_R$

Putting these values in eq. (*iv*), we have,

$$V_R = k_1 \cosh 0 + k_2 \sinh 0 = k_1 + 0$$

$$\therefore \quad V_R = k_1$$

Similarly, putting $x = 0, \quad V = V_R$ and $I = I_R$ in eq. (*v*), we have,

$$I_R = \sqrt{\frac{y}{z}}\left[k_1 \sinh 0 + k_2 \cosh 0\right] = \sqrt{\frac{y}{z}}\left[0 + k_2\right]$$

$$\therefore \quad k_2 = \sqrt{\frac{z}{y}}\, I_R$$

Substituting the values of k_1 and k_2 in eqs. (*iv*) and (*v*), we get,

$$V = V_R \cosh\left(x\sqrt{y\,z}\right) + \sqrt{\frac{z}{y}}\, I_R \sinh\left(x\sqrt{y\,z}\right)$$

and

$$I = \sqrt{\frac{y}{z}} V_R \sinh\left(x\sqrt{y\,z}\right) + I_R \cosh\left(x\sqrt{y\,z}\right)$$

The sending end voltage (V_S) and sending end current (I_S) are obtained by putting $x = l$ in the above equations *i.e.*,

$$V_S = V_R \cosh (l\sqrt{y\,z}) + \sqrt{\frac{z}{y}} I_R \sinh (l\sqrt{y\,z})$$

$$I_S = \sqrt{\frac{y}{z}} V_R \sinh (l\sqrt{y\,z}) + I_R \cosh (l\sqrt{y\,z})$$

Now, $l\sqrt{y\,z} = \sqrt{l\,y \cdot l\,z} = \sqrt{Y\,Z}$

and $\sqrt{\frac{y}{z}} = \sqrt{\frac{y\,l}{z\,l}} = \sqrt{\frac{Y}{Z}}$

where Y = total shunt admittance of the line

Z = total series impedance of the line

Therefore, expressions for V_S and I_S become :

$$\mathbf{V}_S = \mathbf{V}_R \cosh \sqrt{\mathbf{YZ}} + \mathbf{I}_R \sqrt{\frac{\mathbf{Z}}{\mathbf{Y}}} \sinh \sqrt{\mathbf{YZ}}$$

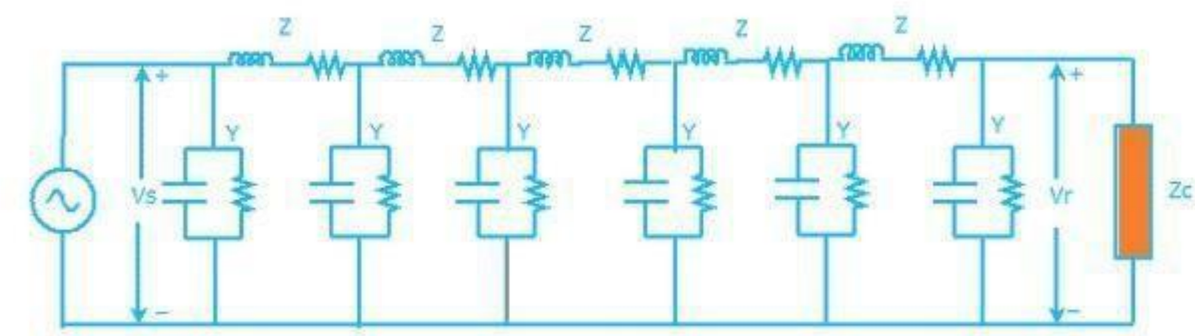
$$\mathbf{I}_S = \mathbf{V}_R \sqrt{\frac{\mathbf{Y}}{\mathbf{Z}}} \sinh \sqrt{\mathbf{YZ}} + \mathbf{I}_R \cosh \sqrt{\mathbf{YZ}}$$

It is helpful to expand hyperbolic sine and cosine in terms of their power series.

$$\cosh \sqrt{Y\,Z} = \left(1 + \frac{Z\,Y}{2} + \frac{Z^2 Y^2}{24} + \ldots\ldots\right)$$

$$\sinh \sqrt{Y\,Z} = \left(\sqrt{Y\,Z} + \frac{(Y\,Z)^{3/2}}{6} + \ldots\ldots\right)$$

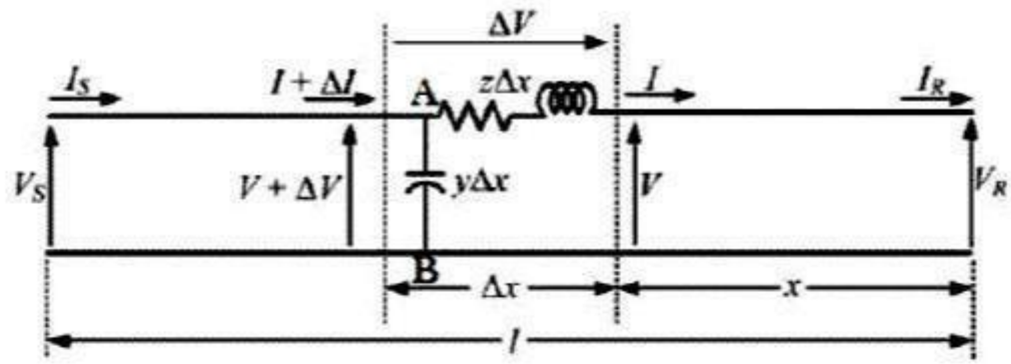
LONG TRANSMISSION LINE (ABCD PARAMETERS)



Long Transmission Line model

A power transmission line with its effective length of around 250 Kms or above is referred to as a **long transmission line**. Calculations related to circuit parameters (ABCD parameters) of such a power transmission is not that simple, as was the case for a short or medium transmission line. The reason being that, the effective circuit length in this case is much higher than what it was for the former models(long and medium line) and, thus ruling out the approximations considered there like.

a) Ignoring the shunt admittance of the network, like in a small transmission line model.
b) Considering the circuit impedance and admittance to be lumped and concentrated at a point as was the case for the medium line model.
Rather, for all practical reasons we should consider the circuit impedance and admittance to be distributed over the entire circuit length as shown in the figure below.
The calculations of circuit parameters for this reason is going to be slightly more rigorous as we will see here. For accurate modeling to determine circuit parameters let us consider the circuit of the **long transmission line** as shown in the diagram below.



Long Transmission Line.

Here a line of length l > 250km is supplied with a sending end voltage and current of VS and IS respectively, where as the VR and IR are the values of voltage and current obtained from the receiving end. Lets us now consider an element of infinitely small length Δx at a distance x from the receiving end as shown in the figure where.

V = value of voltage just before entering the element Δx. I = value of current just before entering the element Δx. V+ΔV = voltage leaving the element Δx.

I+ΔI = current leaving the element Δx. ΔV = voltage drop across element Δx. zΔx = series impedence of element Δx yΔx = shunt admittance of element Δx

Where Z = z l and Y = y l are the values of total impedance and admittance of the long transmission line.

∴ The voltage drop across the infinitely small element Δx is given by $\Delta V = I z \Delta x$

Or $I z = \Delta V / \Delta x$

Or $I z = dV / dx$ ——————————(1)

Now to determine the current ΔI, we apply KCL to node A. $\Delta I = (V+\Delta V) y\Delta x = V y\Delta x + \Delta V y\Delta x$

Since the term $\Delta V\, y\Delta x$ is the product of 2 infinitely small values, we can ignore it for the sake of easier calculation.

∴ We can write $dI/dx = V y$ ————

——(2) Now derevating both sides of eq (1) w.r.t x, $d^2 V/d x^2 = z\, dI/dx$

Now substituting $dI/dx = V y$ from equation (2) $d^2 V/d x^2 = zyV$

or $d^2 V/d x^2 - zyV = 0$ ————(3)

The solution of the above second orders differential equation is given by. $V = A1\, e^{x\sqrt{yz}} + A2\, e^{-x\sqrt{yz}}$ —————(4)

Derivating equation (4) w.r.to x.

$dV/dx = \sqrt{(yz)}\, A1\, e^{x\sqrt{yz}} - \sqrt{(yz)} A2\, e^{-x\sqrt{yz}}$ ————

(5) Now comparing equation (1) with equation (5)

$$I = \frac{dV}{dx} = \frac{zA_1 e^{x\sqrt{(yz)}}}{\sqrt{(z/y)}} - \frac{zA_1 e^{-x\sqrt{(yz)}}}{\sqrt{(z/y)}} \text{-----------------(6)}$$

Now to go further let us define the characteristic impedance Zc and propagation constant δ of a long transmission line as

$Zc = \sqrt{(z/y)}\ \Omega$ $\delta = \sqrt{(yz)}$

Then the voltage and current equation can be expressed in terms of characteristic impedance and propagation constant as

$V = A1\, e^{\delta x} + A2\, e^{-\delta x}$ ————(7)

$I = A1/ Zc\, e^{\delta x} + A2 / Zc\, e^{-\delta x}$ ——————(8)

Now at x=0, V= VR and I= Ir. Substituting these conditions to equation (7) and (8) respectively. $VR = A1 + A2$ ——————(9)

$IR = A1/ Zc + A2 / Zc$ ——————(10)

Solving equation (9) and (10), We get values of A1 and A2 as,

A1 = (VR + ZCIR)

⁄ 2 And A1 = (VR

− ZCIR)

Now applying another extreme condition at x=l, we have V = VS and I = IS.

Now to determine VS and IS we substitute x by l and put the values of A1 and A2 in equation (7) and (8) we get

$$VS = (VR + ZC\ IR)e^{\delta l}/2 + (VR - ZC\ IR)e^{-\delta l}/2 \quad (11)$$

$$IS = (VR/ZC + IR)e^{\delta l}/2 - (VR / ZC - IR)e^{-\delta l}/2 \quad (12)$$

By trigonometric and exponential operators we know $\sinh \delta l = (e^{\delta l} - e^{-\delta l})/2$

And $\cosh \delta l = (e^{\delta l} + e^{-\delta l})/2$

∴ equation (11) and (12) can be re-written as

VS = VRcosh δl + ZC IR sinh δl IS = (VR sinh δl)/ZC + IRcosh δl

Thus comparing with the general circuit parameters equation, we get the ABCD parameters of a long transmission line as,

C = sinh δl ⁄ ZC A = cosh δl D = cosh δl B = ZC sinh δl

CIRCLE DIAGRAMS

Transmission line problems often involve manipulations with complex numbers, making the time and effort required for a solution several times greater than that needed for a similar sequence of operations on real numbers. One means of reducing the labor without seriously affecting the accuracy is by using transmission-line charts. Probably the most widely used one is the Smith chart. Basically, this diagram shows curves of constant resistance and constant reactance; these may represent either input impedance or load impedance. The latter, of course, is the input impedance of a zero-length line. An indication of location along the line is also provided, usually in terms of the fraction of a wavelength from a voltage maximum or minimum. Although they are not specifically shown on the chart, the standing-wave ratio and the magnitude and angle of the reflection coefficient are very quickly determined. As a matter of fact, the diagram is constructed within a circle of unit radius, using polar co-ordinates, the basic relationship upon which the chart is constructed is

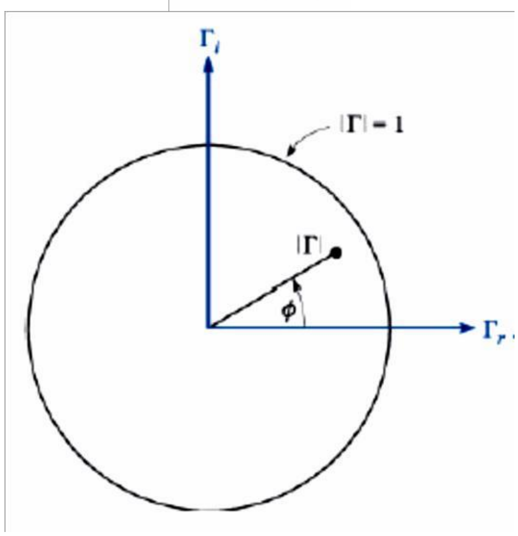
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

The impedances which we plot on the chart will be normalized with respect to the characteristic impedance. Let us identify the normalized load impedance as z_L

$$z_L = r + jx = \frac{Z_L}{Z_0} = \frac{R_L + jX_L}{Z_0}$$

$$\Gamma = \frac{z_L - 1}{z_L + 1}$$

$$z_L = \frac{1 + \Gamma}{1 - \Gamma}$$



UNIT – 5

FACTORS GOVERNING THE PERFORMANCE OF TRANSMISSION LINES

SURGE IMPEDANCE:

The characteristic impedance or surge impedance (usually written Z_0) of a uniform transmission line is the ratio of the amplitudes of voltage and current of a single wave propagating along the line; that is, a wave travelling in one direction in the absence of reflections in the other direction. Characteristic impedance is determined by the geometry and materials of the transmission line and, for a uniform line, is not dependent on its length. The SI unit of characteristic impedance is the ohm.

The characteristic impedance of a lossless transmission line is purely real, with no reactive component. Energy supplied by a source at one end of such a line is transmitted through the line without being dissipated in the line itself. A transmission line of finite length (lossless or lossy) that is terminated at one end with an impedance equal to the characteristic impedance appears to the source like an infinitely long transmission line and produces no reflections.

THE SURGE IMPEDANCE LOADING:

The surge impedance loading (SIL) of a line is the power load at which the net reactive power is zero. So, if your transmission line wants to "absorb" reactive power, the SIL is the amount of reactive power you would have to produce to balance it out to zero. You can calculate it by dividing the square of the line-to-line voltage by the line's characteristic impedance. Transmission lines can be considered as, a small inductance in series and a small capacitance to earth, - a very large number of this combinations, in series. Whatever voltage drop occurs due to inductance gets compensated by capacitance. If this compensation is exact, you have surge impedance loading and no voltage drop occurs for an infinite length or, a finite length terminated by impedance of this value (SIL load). (Loss-less line assumed!). Impedance of this line (Zs) can be proved to be sq. root (L/C). If capacitive compensation is more than required, which may happen on an unloaded EHV line, and then you have voltage rise at the other end, the Ferranti effect. Although given in many books, it continues to remain an interesting discussion always.

The capacitive reactive power associated with a transmission line increases directly as the square of the voltage and is proportional to line capacitance and length.

Capacitance has two effects:

1 Ferranti effect

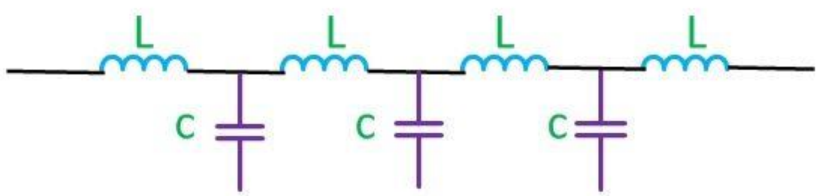
2 Rise in the voltage resulting from capacitive current of the line flowing through the source impedances at the terminations of the line.

SIL is Surge Impedance Loading and is calculated as (KV x KV) / Zs their units are megawatts.

Where Zs is the surge impedance....be aware...one thing is the surge impedance and other very different is the surge impedance loading.

SURGE IMPEDANCE LOADING

Capacitance and reactance are the main parameters of the transmission line. It is distributed uniformly along the line. These parameters are also called distributed parameters. When the voltage drops occur in transmission line due to inductance, it is compensated by the capacitance of the transmission line.

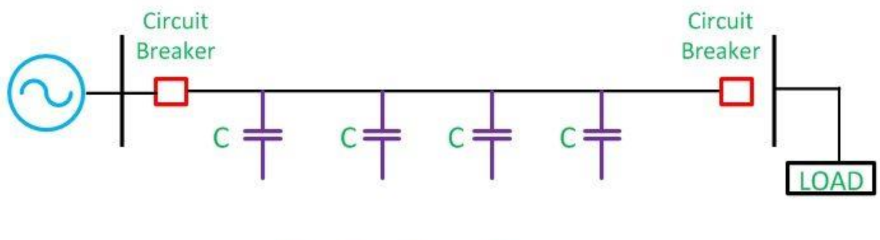


Distributed Parameters of transmission line

The transmission line generates capacitive reactive volt-amperes in its shunt capacitance and absorbing reactive volt-amperes in its series inductance. The load at which the inductive and capacitive reactive volt-amperes are equal and opposite, such load is called surge impedance load.

It is also called natural load of the transmission line because power is not dissipated in transmission. In surge impedance loading, the voltage and current are in the same phase at all the point of the line. When the surge impedance of the line has terminated the power delivered by it is called surge impedance loading.

Shunt capacitance charges the transmission line when the circuit breaker at the sending end of the line is close. As shown below

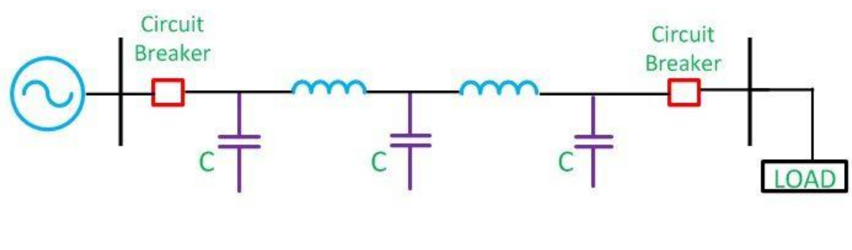


Shunt Capacitance Charges

Let V = phase voltage at the receiving end
L = series inductance per phase
X_L = series inductance reactance per phase
X_C = shunt capacitance reactance per phase
Z_o = surge impedance loading per phase
Capacitive volt-amperes (VAr) generated in the line

$$= \frac{V^2}{X_C} = V^2 wc \; per \; phase$$

The series inductance of the line consumes the electrical energy when the sending and receiving end terminals are closed.

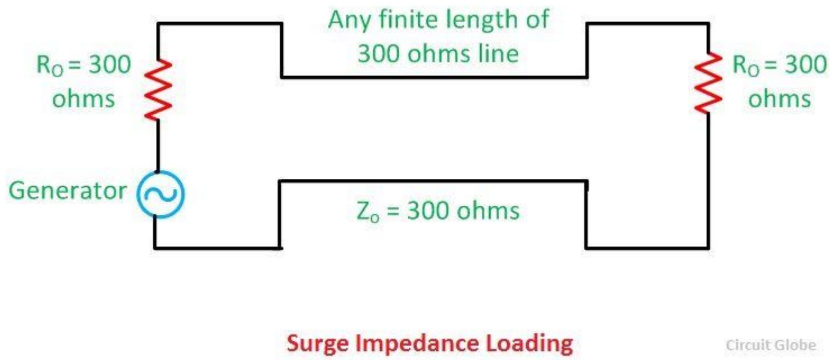


Series Inductance consume energy

Inductive reactive volt-amperes (VAr) absorbed by the line

$$= I^2 X_L = I^2 wL$$

Under natural load, the reactive power becomes terminated, and the load becomes purely resistive.



Surge Impedance Loading

And it is calculated by the formula given below

$$V^2wC = I^2wL$$

$$\frac{V}{I} = \frac{\sqrt{L}}{\sqrt{C}} = Z_0$$

Surge impedance loading is also defined as the power load in which the total reactive power of the lines becomes zero. The reactive power generated by the shunt capacitance is consumed by the series inductance of the line.

If Po is its natural load of the lines, $(SIL)_{1\emptyset}$ of the line per phase

$$(SIL)_{1\emptyset} = P_O = V_p I_p cos\emptyset$$

Since the load is purely resistive,

$$cos\emptyset = 1$$

$$P_O = V_P I_P = V_P \frac{V_P}{Z_O}$$

$$P_O = \frac{V_P^2}{Z_O} W/phase$$

Thus, per phase power transmitted under surge impedance loading is $(V_P^2)/Z_O$ watts, Where V_p is the phase voltage.

$$Line\ voltage\ V_L = \sqrt{3}V_P$$

$$(SIL)_{3\emptyset} = 3P_O = \frac{3V_P^2}{Z_O} = \frac{V_L^2}{Z_O}\ W$$

If kVL is the receiving end voltage in kV, then

$$(SIL)_{3\emptyset} = \frac{(kV_L)^2}{Z_O}\ \text{MW}$$

Surge impedance loading depends on the voltage of the transmission line. Practically surge impedance loading always less than the maximum loading capacity of the line.

If the load is less than the SIL, reactive volt-amperes are generated, and the voltage at the receiving end is greater than the sending end voltage. On the other hand, if the SIL is greater than the load, the voltage at receiving end is smaller because the line absorbs reactive power.

If the shunt conductance and resistance are neglected and SIL is equal to the load than the voltage at both the ends will be equal.

Surge impedance load is the ideal load because the current and voltage are uniform along the line. The wave of current and voltage is also in phase because the reactive power consumed are equal to the reactive power generated by the transmission line.

CORONA

Electric-power transmission practically deals in the bulk transfer of electrical energy, from generating stations situated many kilometers away from the main consumption centers or the cities. For this reason the long distance transmission cables are of utmost necessity for effective power transfer, which in-evidently results in huge losses across the system. Minimizing those has been a major challenge for power engineers of late and to do that one should have a clear understanding of the type and nature of losses. One of them being the **corona effect in power system**, which has a predominant role in reducing the efficiency of EHV(extra high voltage lines) which we are going to concentrate on, in this article.

What is corona effect in power system and why it occurs?

For corona effect to occur effectively, two factors here are of prime importance as mentioned below:-

1) Alternating potential difference must be supplied across the line.
2) The spacing of the conductors, must be large enough compared to the line diameter.

Corona Effect in Transmission Line

When an alternating current is made to flow across two conductors of the transmission line whose spacing is large compared to their diameters, then air surrounding the conductors (composed of ions) is subjected to di-electric stress. At low values of supply end voltage, nothing really occurs as the stress is too less to ionize the air outside. But when the potential difference is made to increase beyond some threshold value of around 30 kV known as the critical disruptive voltage, then the field strength increases and then the air surrounding it experiences stress high enough to be dissociated into ions making the atmosphere conducting. This results in electric discharge around the conductors due to the flow of these ions, giving rise to a faint luminescent glow, along with the hissing sound accompanied by the liberation of ozone, which is readily identified due to its characteristic odor. This phenomena of electrical discharge occurring in transmission line for high values of voltage is known as the corona effect in power system. If the voltage across the lines is still increased the glow becomes more and more intense along with hissing noise, inducing very high power loss into the system which must be accounted for.

Factors Affecting Corona

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

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

(ii) *Conductor size.* The corona effect depends upon the shape and conditions of the conductors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has irregular surface and hence gives rise to more corona that a solid conductor.

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

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

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

(i) Critical disruptive voltage. It is the minimum phase-neutral voltage at which corona *occurs.* Consider two conductors of radii *r* cm and spaced *d* cm apart. If *V* is the phase-

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

neutral potential, then potential gradient at the conductor surface is given by:

In order that corona is formed, the value of *g* must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*) and is denoted by *go*. If *Vc* is the phase-neutral potential required under these conditions, then,

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

where g_o = breakdown strength of air at 76 cm of mercury and 25°C
= 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

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

The above expression for disruptive voltage is under standard conditions *i.e.*, at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of *go*. The value of *go* is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of *b* cm of mercury and temperature of *t*ºC becomes

™ *go* where

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

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

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

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

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

where m_o = 1 for polished conductors
= 0·98 to 0·92 for dirty conductors
= 0·87 to 0·8 for stranded conductors

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

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

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

where m_v is another irregularity factor having a value of 1·0 for polished conductors and 0·72 to 0·82 for rough conductors.

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

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

where f = supply frequency in Hz
V = phase-neutral voltage (*r.m.s.*)
V_c = disruptive voltage (*r.m.s.*) per phase

Advantages and Disadvantages of Corona

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

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting andhence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.

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

Disadvantages

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

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

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

Methods of Reducing Corona Effect

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

(i) *By increasing conductor size.* By increasing conductor size, the voltage at which corona occurs is raised and hence corona effects are considerably reduced. This is one of the reasons that *ACSR* conductors which have a larger cross-sectional area are used in transmission lines.

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

DISRUPTIVE CRITICAL VOLTAGE:

- The critical disruptive voltage is defined as the minimum phase to neutral voltage at which Corona occurs. It is denoted as Vd.

VISUAL CRITICAL VOLTAGE:

- The critical visual disruptive voltage is the minimum phase to neutral voltage at which corona glow appears and visible along the conductors.
- In parallel conductors, the corona glow does not begin at the disruptive voltage Vc but a higher voltage Vv called visual critical voltage.

CORONA POWER LOSS:

The corona effect due to which several losses occur in transmission lines. These losses decrease the efficiency of transmission lines. Out of all the losses the corona power loss is the one which affects most, the proficiency of lines.

The power dissipated in the system due to corona discharges is called corona loss. Accurate estimation of corona loss is difficult because of its variable nature. It has been found that the corona loss under fair weather condition is less than under foul weather conditions. The corona loss under appropriate weather conditions is given below by the Peek's formula;

$$P_C = \frac{244}{\delta}(f+25)(E_n - E_O)^2 \frac{\sqrt{r}}{\sqrt{D}} 10^{-5}\, kW/km/phase$$

Where P_c – corona power loss
f – frequency of supply in Hz
δ – air density factor
E_n – r.m.s phase voltage in kV
E_o – disruptive critical voltage per phase in kV
r – radius of the conductor in meters
D – spacing between conductors in meters

It is also to be noticed that for a single –phase line,

E_n=1/2×line voltage

and for a three phase line,

$E_n = 1/(\sqrt{3})\times$line voltage

Peek's formula is applicable for decided visual corona. This formula the gives the inaccurate result when the losses are low, and En/Eo is less than 1.8. It is superseded by Peterson's formula given below;

$$P_C = 2.1 f F \frac{E_n^2}{\left(log_{10}\frac{D}{r}\right)^2} \times 10^{-5}$$

Where,
P_c – corona power loss
f – frequency of supply in Hz
E_n – voltage per phase
r – radius of the conductor
D – spacing between conductors in meters
Factor F is called the corona loss function. It varies with the ratio (En/Eo). Eo is calculated by the formula given below,

$$E_o = G_o m_o r \delta^{\frac{2}{3}} In \frac{Deq}{r} V/phase$$

Where,
G_o – maximum value of disruptive critical voltage gradient in V/m.
m_o= irregularity factor

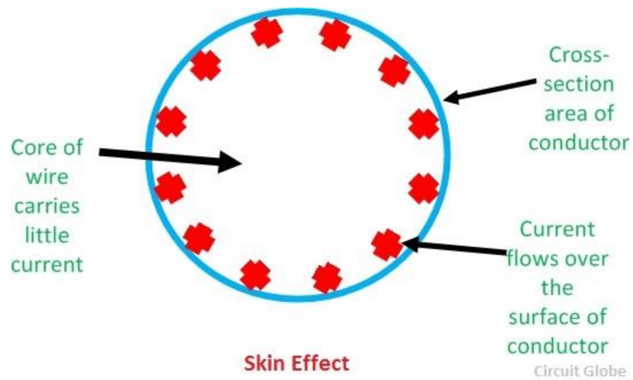
Factors Affecting Corona Loss
The following are the factors which affect the corona loss:

- **Effect of system voltage** – The electric field intensity around the conductor depends on the potential difference between the conductors. If the potential difference is high, electric field intensity is also high, and hence corona loss is also high.
- **Effect of Frequency** – The corona loss is directly proportional to system frequency.
- **Effect of Density of Air –** The corona loss is inversely proportional to air density factor. The corona loss increases with the decreases in density of air. The corona loss of the hilly area is more than that of the plains because plain have low density of air.
- **Effect of Conductor Radius** – If the wire area has high surface area, then their surface field intensity is low, and hence corona loss is less.

SKIN EFFECT

The non-uniform distribution of electric current over the surface or skin of the conductor carrying A.C is called the skin effect. In other words, the concentration of charge is more near the surface as compared to the core of the conductor. The ohmic resistance of the conductor is increased due to the concentration of current on the surface of the conductor.

Skin effect increases with the increase in frequency. At low frequency, such as 50Hz, there is a small increase in the current density near the surface of the conductor; but, at high frequencies, such as radio frequency, practically the whole of the currents flows on the surface of the conductor. If d.c current (frequency=0) is passed in a conductor, the current is uniformly distributed over the cross-section of the conductors



WHY SKIN EFFECT OCCURS?

Let us consider the conductor is made up of a number of concentric cylinders. When A.C is passed in a conductor, the magnetic flux induces in it. The magnetic flux linking a cylindrical element near the center is greater than that linking another cylindrical element near the surface of the conductor. This is due to the fact that the center cylindrical element is surrounded by both the internal as well as the external flux, while the external cylindrical element is surrounded by the external flux only.

The self-inductance in the inner cylindrical element is more and, therefore, will offer a greater inductive reactance than the outer cylindrical element. This difference in the inductive reactance gives a tendency to the current to concentrate towards the surface or skin of the conductor.

- A conductor carries a steady D.C current. This current is uniformly distributed over the whole cross- section of the conductor.
- The current distribution is non – uniform if conductor carries alternating current.
- The current density is higher at the surface than at the surface than at its centre
- This behavior of alternating current to concentrate near the surface of the conductor is known as skin effect.

Factors affecting skin effect

1. **Frequency** – Skin effect increases with the increase in frequency.
2. **Diameter** – It increases with the increase in diameter of the conductor.
3. **The shape of the conductor** – Skin effect is more in the solid conductor and less in the stranded conductor because the surface area of the solid conductor is more.
4. **Type of material** – Skin effect increase with the increase in the permeability of the material (Permeability is the ability of material to support the formation of the magnetic field).

Points-to-remember

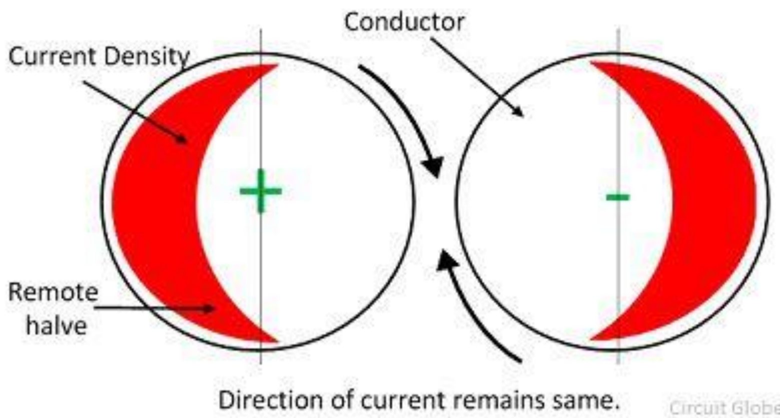
1. The Skin effect is negligible if the frequency is less than the 50Hz and the diameter of the conductor is less than the 1cm.
2. In the stranded conductors like ACSR (Aluminium Conductor Steel Reinforced) the current flows mostly in the outer layer made of aluminum, while the steel near the center carries no current and gives high tensile strength to the conductor. The concentration of current near the surface enabled the use of ACSR conductor.

PROXIMITY EFFECT

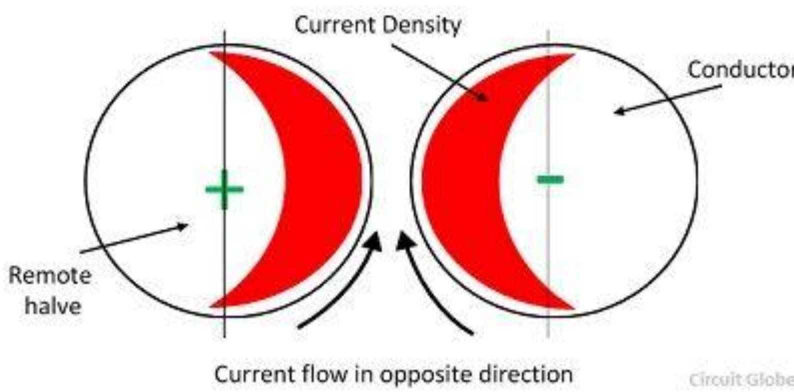
Definition: When the conductors carry the high alternating voltage then the currents are non-uniformly distributed on the cross-section area of the conductor. This effect is called proximity effect. The proximity effect results in the increment of the apparent resistance of the conductor due to the presence of the other conductors carrying current in its vicinity.

When two or more conductors are placed near to each other, then their electromagnetic fields interact with each other. Due to this interaction, the current in each of them is redistributed such that the greater current density is concentrated in that part of the strand most remote from the interfering conductor.

If the conductors carry the current in the same direction, then the magnetic field of the halves of the conductors which are close to each other is cancelling each other and hence no current flow through that halves portion of the conductor. The current is crowded in the remote half portion of the conductor.



When the conductors carry the current in the opposite direction, then the close part of the conductor carries, the more current and the magnetic field of the far off half of the conductor cancel each other. Thus, the current is zero in the remote half of the conductor and crowded at the nearer part of the conductor.



If DC flows on the surface of the conductor, then the current are uniformly distributed around the cross section area of the conductor. Hence, no proximity effect occurs on the surface of the conductor.

The proximity effect is important only for conductor sizes greater than 125 mm^2.Correction factors are to be applied to take this fact into account.

If R_{dc} – uncorrected DC level of the core
Y_s – skin effect factor, i.e., the fractional increment in resistance to allowing for skin effect.
y_p – proximity effect factor, i.e., the fractional increment in resistance to allowing for skin effect.
R_e – effective or corrected ohmic resistance of the core.
The allowance for proximity effect is made, the AC resistance of the conductor becomes

$$R_e = R_{dc}(1 + y_{dc} + y_p)$$

The resistance R_{dc} is known from stranded tables.

Factors Affecting the Proximity Effect

The proximity effect mainly depends on the factors like conductor's material, conductor diameter, frequency and conductor structure. The factors are explained below in details

1. **Frequency** – The proximity increases with the increases in the frequency.
2. **Diameter –** The proximity effect increases with the increase in the conductor.
3. **Structure –** This effect is more on the solid conductor as compared to the stranded conductor (i.e., ASCR) because the surface area of the stranded conductor is smaller than the solid conductor.
4. **Material –** If the material is made up of high ferromagnetic material then the proximity effect is more on their surface.

How to reduce Proximity Effect?

The proximity effect can be reduced by using the ACSR (Aluminum Core Steel Reinforced) conductor. In ACSR conductor the steel is placed at the centre of the conductor and the aluminium conductor is positioned around steel wire.

The steel increased the strength of the conductor but reduced the surface area of the conductor. Thus, the current flow mostly in the outer layer of the conductor and no current is carried in the centre of the conductor. Thus, reduced the proximity effect on the conductor.

- The current distribution may be non-uniform because of another effect known as proximity effect. Consider a two wire line as shown in fig. below

- Let each of the line conductor is assumed to be divided into 3 sections having equal Cross-sectional area. These parallel loops are formed by the pairs xx', yy' and zz'.
- The inductance of inter loop is less. Thus, the current density is highest at inner edges of the conductor.
- Due to this non uniform distribution of current, the effective conductor resistance increases.
- The proximity effect also depends on the same factors as that of skin effect.

FERRANTI EFFECT

Ferranti Effect in Transmission Lines and Its Calculation

Generally, we know that the flow of current in every electrical system will be from the higher potential area to lower potential area, to reimburse for the difference that lives in the system. In practical, the voltage at the transmitting end is superior to the voltage at the receiving end due to line losses, so the flow of current will be from the supply to the load. In the year 1989, Sir S.Z. Ferranti came up with a theory, namely astonishing theory. The main concept of this theory is all about "Medium Distance Transmission Line" or Long Distance Transmission Lines proposing that in case of no-load operation of the transmission system. The voltage at the receiving end frequently enhances beyond the transmitting end. This is the Ferranti Effect in power system

What is a Ferranti Effect?

The Ferranti effect definition is, the voltage effect on the collecting end of the transmission line is higher than the transmitting end is called as "Ferranti Effect". Generally, this sort of effect happens due to an open circuit, light load at the collecting end or charging-current of the transmission line. Here, charging current can be defined as, whenever an exchanging voltage is connected, the current will flows through the capacitor, and it is also called as "capacitive current". When the voltage at the collecting end of the line is superior to the transmitting end, then the charging current rises in the line.

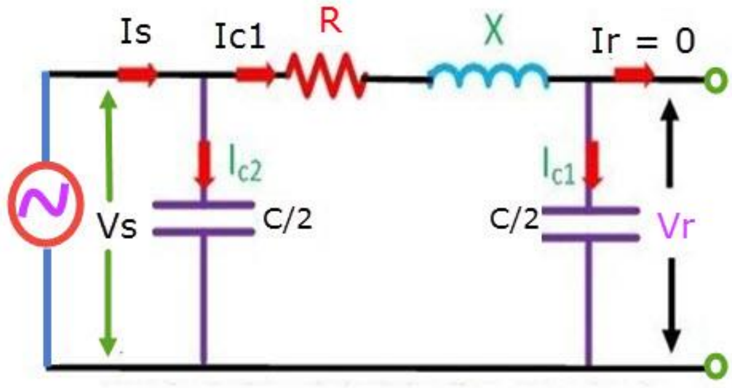
Parameters of Ferranti Effect

Ferranti effect mainly occurs due to the charging current, and couples with the line capacitance. In addition, the following parameters must be noticed.
Capacitance depends on composition and length of a line. In capacitance, cables have more capacitance than bare conductor per length. Whereas in line length, long lines have higher capacitance than short lines.

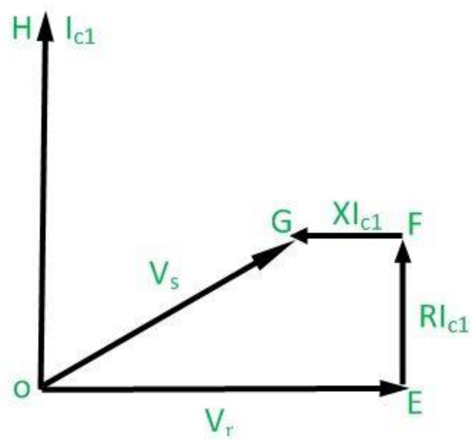
Charging current turns into more important as load current decreases, and it Increases with the voltage of the system given the similar capacitive charge. As a result, the Ferranti effect happens only for long lightly loaded or open-circuited energized lines. In addition, the fact becomes clearer with higher applied voltage and underground cables.

Ferranti Effect In Transmission Line, Calculation

Let us think the Ferrenki Effect in extensive transmission line where OE-signifies the collecting end voltage, OH-signifies the flow of current in the capacitor at the collecting end. The FE-phasor signifies a decrease in a voltage across the resistance R. FG-signifies a decrease in a voltage across the (X) inductance. The OG-phasor signifies the transmitting end voltage in a no-load state. The nominal Pi model of the transmission line at no load condition circuit is shown below.



In the following phasor graphical representation that OE is greater than OG (OE>OG). In other terms, the voltage at the receiving end is superior to the voltage at the transmitting end when the transmission line is at no load condition. Here the **Ferranti effect phasor diagram** is shown below.



Phasor Diagram Circuit Globe

For a nominal pi (п) model

$$V_s = \left(1 + \frac{ZY}{2}\right)V_r + ZI_r$$

At no load, Ir = 0

$$V_s = \left(1 + \frac{ZY}{2}\right) V_r$$

$$V_s - V_r = \left(1 + \frac{ZY}{2}\right) V_r - V_r$$

$$V_s - V_r = V_r \left[1 + \frac{YZ}{2} - 1\right]$$

$$V_S - V_r = \frac{YZ}{2} V_r$$

$$Z = (r + jwl)S, Y = (jwc)S$$

If the resistance of the line is neglected,

$$Z = jwlS$$

$$V_S - V_r = \frac{1}{2}(jwlS)(jwcS)V_r$$

$$V_S - V_r = -\frac{1}{2}(w^2 S^2) lcV_r$$

For overhead lines, 1/√lc = velocity of propagation of electromagnetic waves on the transmission lines = 3×10^8m/s.

$$\sqrt{lc} = \frac{1}{3 \times 10^8}$$

$$lc = \frac{1}{(3 \times 10^8)^2}$$

$$V_S - V_R = -\frac{1}{2}w^2S^2.\frac{1}{(3 \times 10^8)^2}V_r$$

$$w = 2\pi f$$

$$V_S - V_R = -\left(\frac{4\pi^2}{18} \times 10^{-16}\right)f^2S^2V_r$$

Above equation shows that (VS-Vr) is negative. That is Vr>VS. This equation also shows that Ferranti effect also depends on frequency and the electrical length of the lines.

In general, for any line

$$V_S = AV_r + BI_r$$

At no load

$$I_r = 0, V_{r=}V_{rnl}$$

$$V_S = AV_{rnl}$$

$$|V_{rnl}| = \frac{|V_s|}{|A|}$$

For a long line, A is less than unity, and it decrease with the increase in the length of the line. Hence, the voltage at no load is greater than the voltage at no load (Vrnl > Vs). As the line length increases the rise in the voltage at the receiving end at no load becomes more predominant.

How to reduce Ferranti effect:

Electrical devices are designed to work at some particular voltage. If the voltages are high at the user ends their equipment get damaged, and their windings burn because of high voltage. Ferranti effect on long transmission lines at low load or no load increases the receiving end voltage.This voltage can be controlled by placing the shunt reactors at the receiving end of the lines.

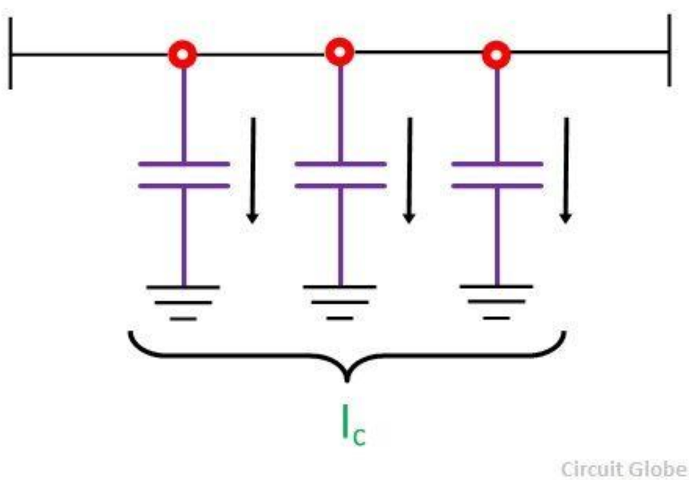
Shunt reactor is an inductive current element connected between line and neutral to compensate the capacitive current from transmission lines. When this effect occurs in long transmission lines, shunt reactors compensate the capacitive VAr of the lines and therefore the voltage is regulated within the prescribed limits.

Note:

- Voltage rise is directly proportional to the square of the length of a line.
- Ferranti effect is more occurs in short transmission cables because their capacitance is high.

CHARGING CURRENT IN TRANSMISSION LINE

In a transmission line, air acts as a dielectric medium between the conductors. When the voltage is applied across the sending end of the transmission line, current starts flowing between the conductors (due to imperfections of the dielectric medium). This current is called the **charging current in the transmission line**.



In other words, we can say, the current associated with the capacitance of a line is known as the charging current.The strength of the charging current depends on the voltage, frequency, and capacitance of the line. It is given by the equations shown below.

For a single-phase line, the charging current

$$I_c = \frac{V_n}{-jX_c} = \frac{V}{-j/wC} = j2\pi fCVA$$

Where,

C= line-to-line in farads
X_c= capacitive reactance in ohms
V= line voltage in volts

$$Charging\ voltamperes = VI_c = \frac{V.V}{X_C} = \frac{V^2}{X_c}\ VAr$$

Also, reactive volt-ampere generated by the line = charging volt-amperes of the lines

$$Q = VI_c = \frac{V^2}{X_c} VAr$$

For a three phase line, the charging current phase

$$I = \frac{V_n}{-jX_c} = \frac{V_n}{-j/wC} = jwC_nV_n\ A$$

where V_n =voltage to neutral in volts = phase voltages in volts
C_n = capacitance to neutral in farads

C_n = capacitance to neutral in farads

$$Charging\ voltamperes\ per\ phase = V_nI_c = V_n \times \frac{V_n}{X_c} = \frac{V_n^2}{X_c} VAr$$

$$Total\ three\ phase\ charging\ voltamperes = 3V_nI_c = \frac{V_n^2}{X_C}\mathrm{VAr}$$

Reactive volt-ampere generated by the line = charging volt-amperes of the lines

$$Q_c = \frac{3V_nI_n}{X_c} = \frac{3}{X_c}\left(\frac{V_t}{\sqrt{3}}\right)^2 = \frac{V_t^2}{X_c} VAr$$

where V_t = line-to-line voltage in volts.

Significance of charging current

1. It reduces the load current, due to which line losses decreases, and hence the efficiency of the line is increased.
2. It improves the power factor of the transmission line.
3. Charging current improves the load capacity of the line.
4. It improves the voltage regulation of the line because the voltage drop is quite small.

INDUCTIVE INTERFERENCE WITH NEIGHBOURING COMMUNICATION CIRCUITS

It is usual practice to run telephone lines along the same route as the power lines. The transmission lines transmit bulk power at relatively high voltages and, therefore, these lines give rise to electro-magnetic and electrostatic fields of sufficient magnitude which induce are superposed on the true speech currents in the neighboring telephone wires and set up distortion while the voltage so induced raise the potential of the communication circuit as a whole. In extreme cases the effect of these may make it impossible to transmit any message faithfully and may raise the potential of the telephone receiver above the ground to such an extent to render the handling of the telephone receiver extremely dangerous and in such cases elaborate precautions are required to be observed to avoid this danger.

In practice it is observed that the power lines and the communication lines run along the same path. Sometimes it can also be seen that both these lines run on same supports along the same route. The transmission lines transmit bulk power with relatively high voltage. Electromagnetic and electrostatic fields are produced by these lines having sufficient magnitude. Because of these fields, voltages and currents are induced in the neighboring communication lines. Thus it gives rise to interference of power line with communication circuit.

Due to electromagnetic effect, currents are induced which is superimposed on speech current of the neighboring communication line which results into distortion. The potential of the communication circuit as a whole is raised because of electrostatic effect and the communication apparatus and the equipments may get damaged due to extraneous voltages. In the worst situation, the faithful transmission of message becomes impossible due to effect of these fields. Also the potential of the apparatus is raised above the ground to such an extent that the handling of telephone receiver becomes extremely dangerous.

The electromagnetic and the electrostatic effects mainly depend on what is the distance between power and communication circuits and the length of the route over which they are parallel. Thus it can be noted that if the distortion effect and potential rise effect are within permissible limits then the communication will be proper. The unacceptable disturbance which is produced in the telephone communication because of power lines is called Telephone Interference.

There are various factors influencing the telephone interference. These factors are as follows

1) Because of harmonics in power circuit, their frequency range and magnitudes.

2) Electromagnetic coupling between power and telephone conductor.

The electric coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms of mutual inductance at harmonic frequencies.

3) Due to unbalance in power circuits and in telephone circuits.

4) Type of return telephone circuit i.e. either metallic or ground return.

5) Screening effects.

Steps for Reducing Telephone Interference

There are various ways that can reduce the telephone interference. Some of them are as listed below

i) The harmonics at the source can be reduced with the use of A.C. harmonic filters, D.C. harmonic filters and smoothing rectors.
ii) Use greater spacing between power and telephone lines.
iii) The parallel run between telephone line and power line is avoided.
iv) Instead of using overhead telephone wires, underground telephone cables may be used.
v) If the telephone circuit is ground return then replace it with metallic return.
vi) Use microwave or carrier communication instead of telephone communication.

The balance of AC power line is improved by using transposition. Transposition of lines reduces the induced voltages to a considerable extent. The capacitance of the lines is balanced by transposition leading to balance in electro statically induced voltages. Using transposition the fluxes due to positive and negative phase sequence currents cancel out so the electromagnetically induced e.m.f's is diminished. For zero sequence currents the telephone lines are also transposed