MALLA REDDY COLLEGE OF ENGINEERING & TECHNOLOGY

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DEPARTMENT OF ELECTRICAL & ELECTRONICS ENGINEERING

DIGITAL NOTES for ELECTRICAL POWER GENERATION, TRANSMISSION AND DISTRIBUTION - 1 (R17A0207)

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 tonnes), 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.

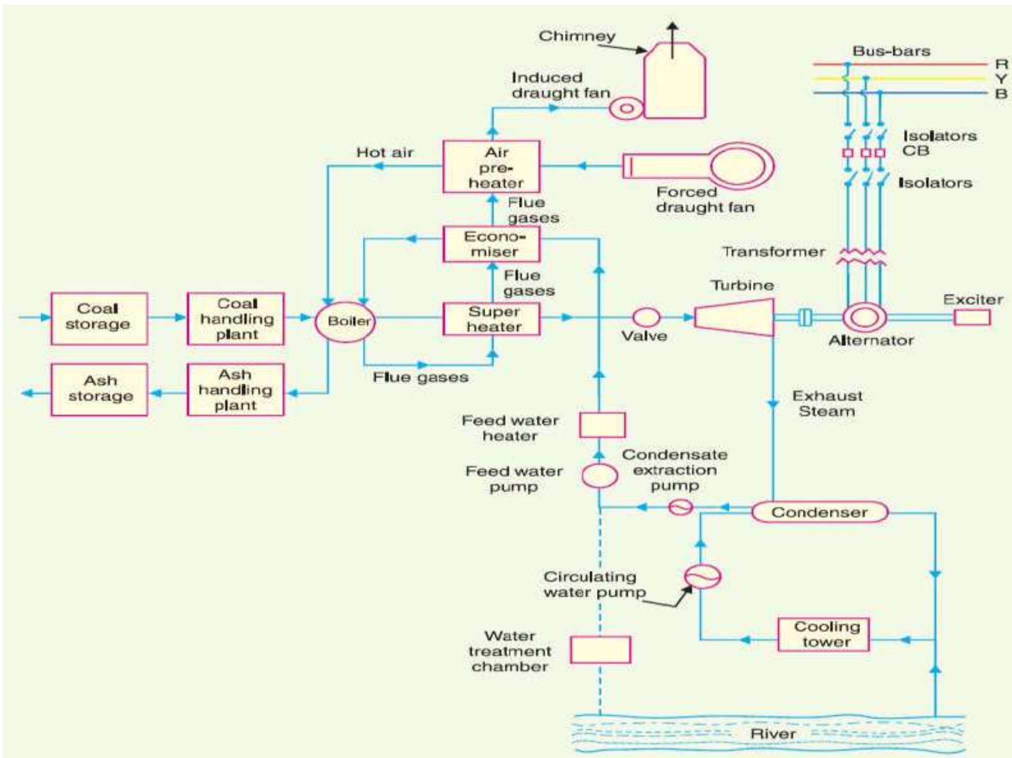
- **Eg:** For 2000MW plant, the land requirement may be of the order of 200-250 acres. As the cost of the land adds up to the final cost of the plant, it should be available at a reasonable price. Land should be available for future extension.

- **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

BOILER

- 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.

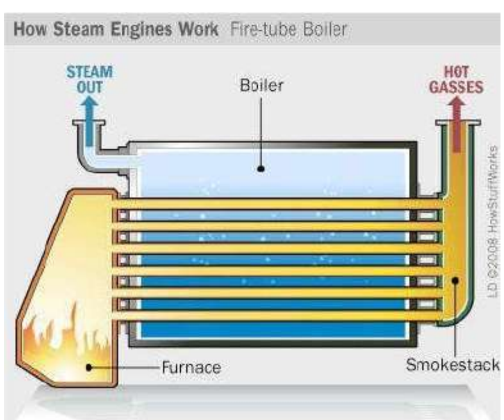


Figure : Fire Tube Boiler

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.

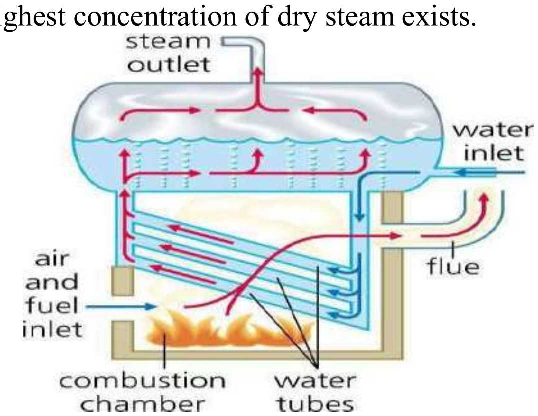


Figure :Water tube bolier

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 provide more energy to the turbine hence power out put is more.
- Superheated steam causes lesser erosion of the turbine blades and can be transmitted for longer distance with little heat loss

- A superheater may be convention type, radiant type or combination. However ,convention superheaters are more commonly used.

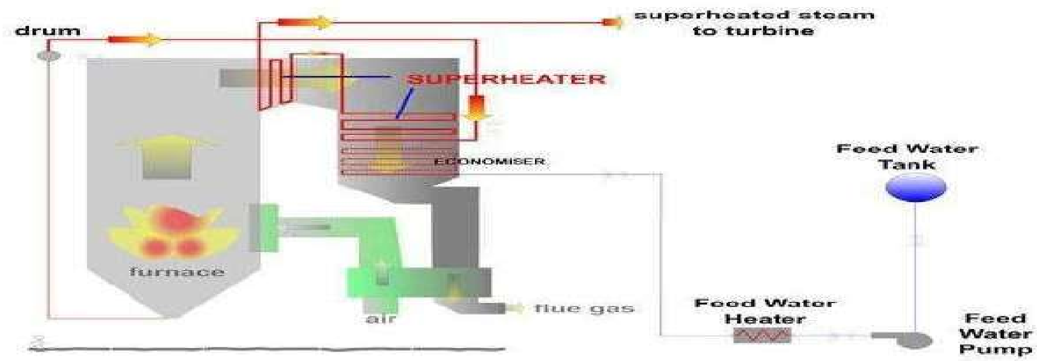


Figure : Functions of superheater

Figure: Superheaters

REHEATER

- In addition to super heater modern boiler has reheater also. The function of the reaheater 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 waterbefore 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.

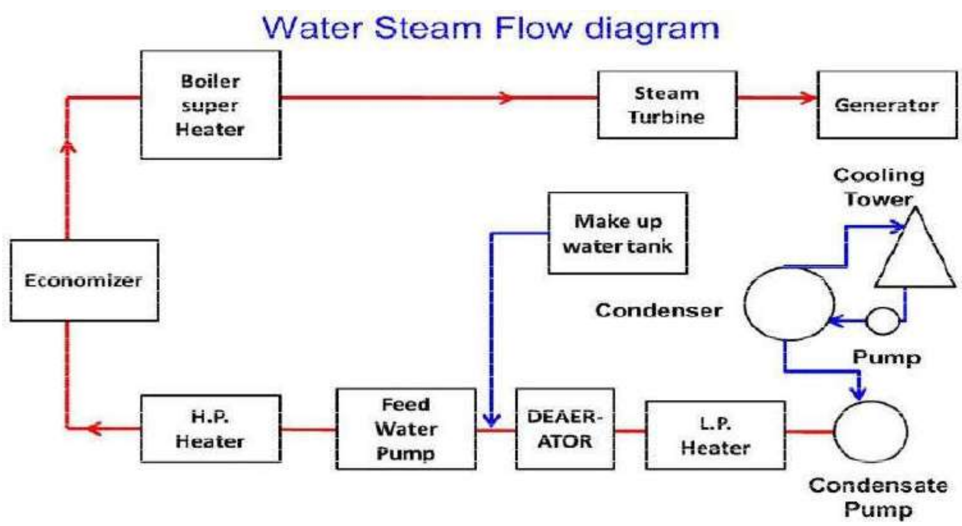


Figure: Water steam flow diagram

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 20^0increase 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 maintance 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.

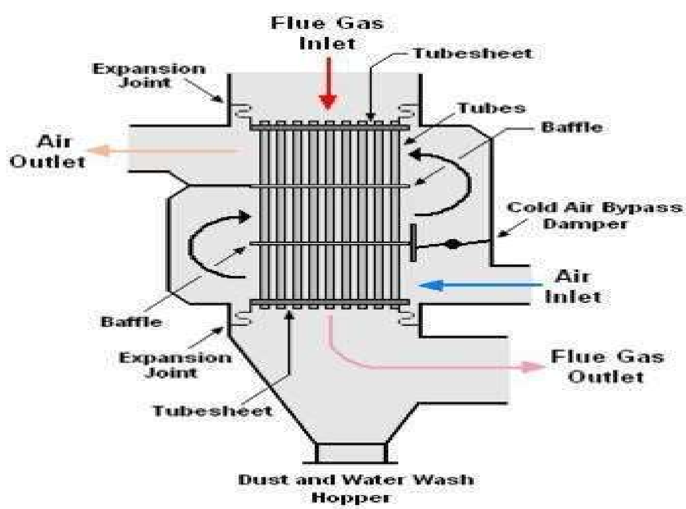


Figure : Air Preheater

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.

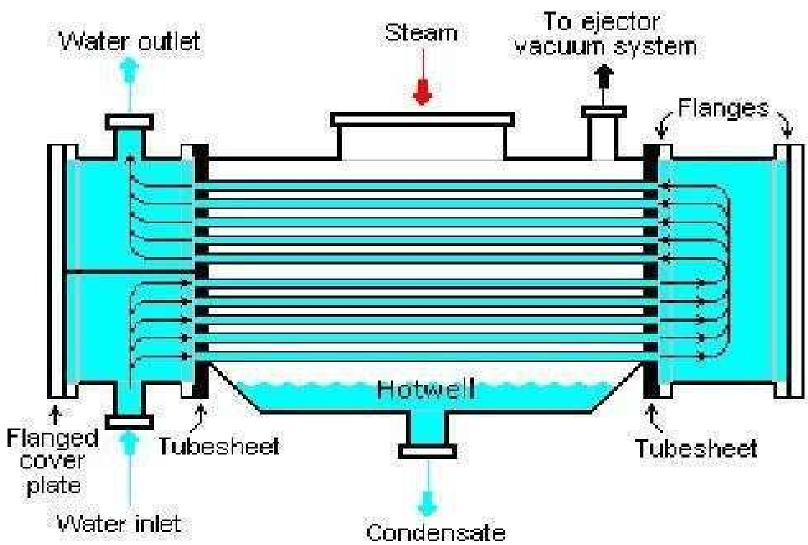


Figure: Surface Condenser

Figure: Surface Condenser

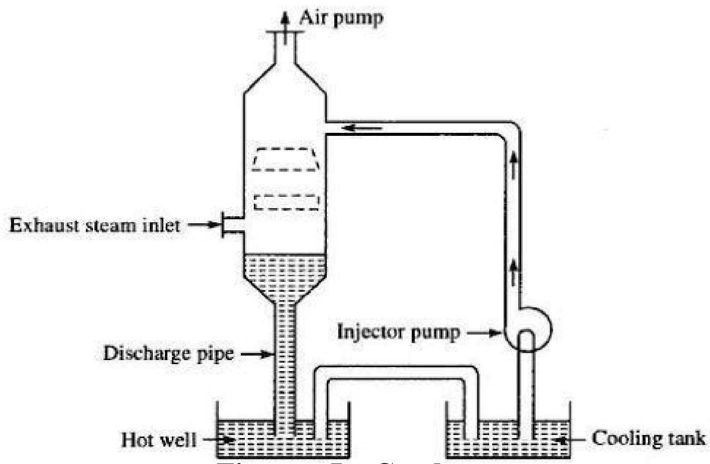


Figure : Jet Condenser

DEAERATORS

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

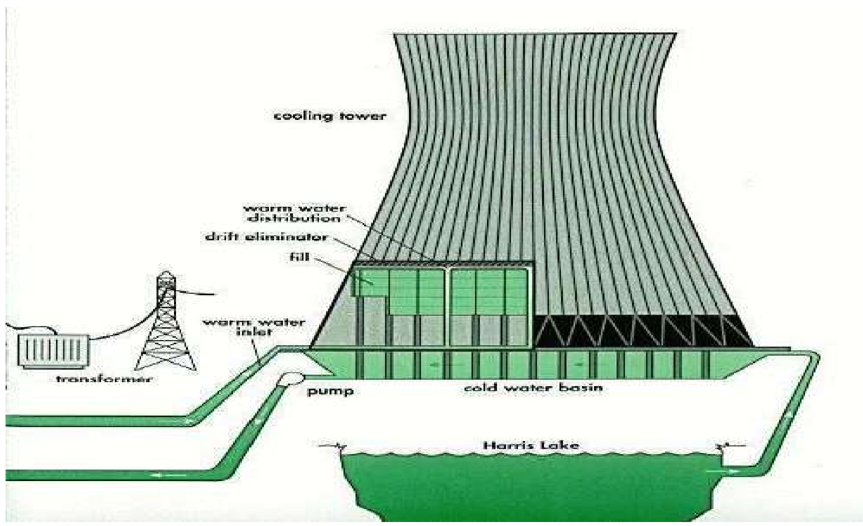
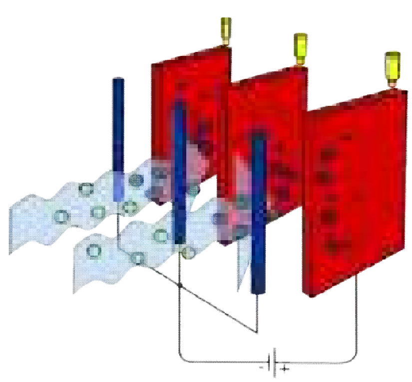


Figure : Cooling Tower

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

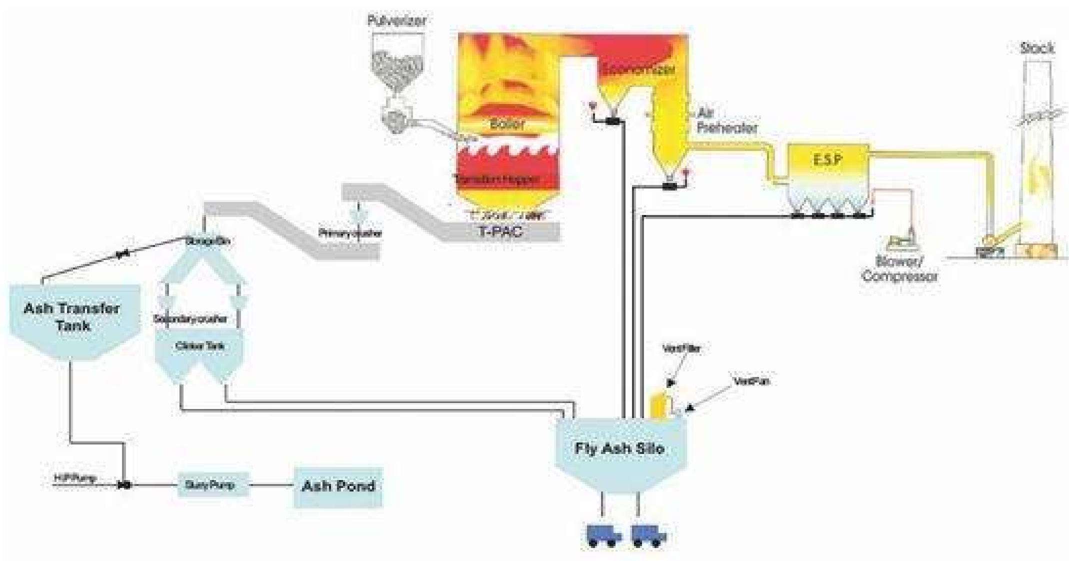
- Ash generated below furnace of the steam generator is called the bottom ash.

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.



Ash Handling System Flow Diagram

Figure 59: Ash handling Plant flow diagram

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 ${}_{92}U^{234}$
- ${}_{92}U^{235}$ is used as fuel in nuclear power plants.

Energy from Nuclear Reactions

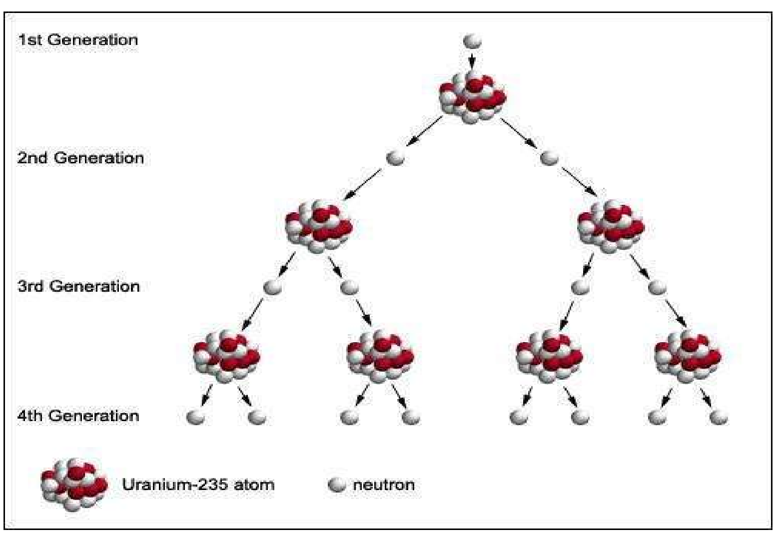
- The sum of masses of protons and neutrons exceeds the mass of the atomic nucleus and this difference is called mass defect Δm.
- In a nuclear reaction the mass defect is converted into energy known as binding energy according to Einstein's equation ($E=\Delta m\ c^2$).
- Fissioning one amu of mass 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.

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

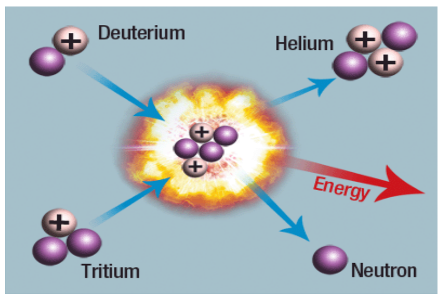


Figure 72: Nuclear Fusion

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.

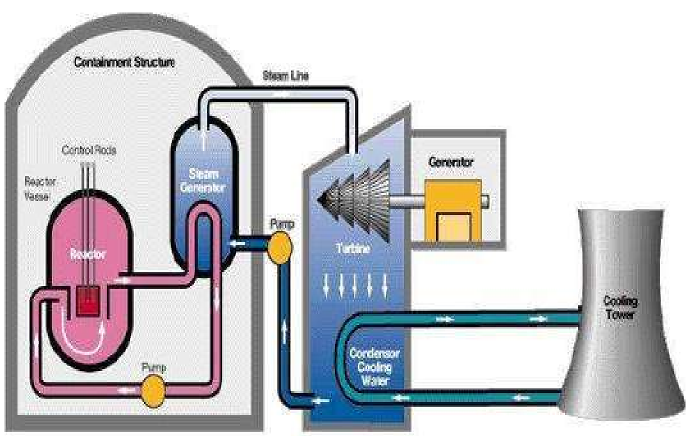


Figure 73: Schematic of a Nuclear Power Plant

Nuclear power plants are usually considered to be base load stations, which are best suited to constant power output.

Nuclear Power Reactors

Magnox Reactors

- The six main commercial reactor types, two (Magnox and AGR) owe much to the very earliest reactor designs in that they are graphite moderated and gas cooled. Magnox reactors were built in the UK from 1956 to 1971 but have now been superseded.
- The Magnox reactor is named after the magnesium alloy used to encase the fuel, which is natural uranium metal. Fuel elements consisting of fuel rods encased in Magnox cans are loaded into vertical channels in a core constructed of graphite blocks.

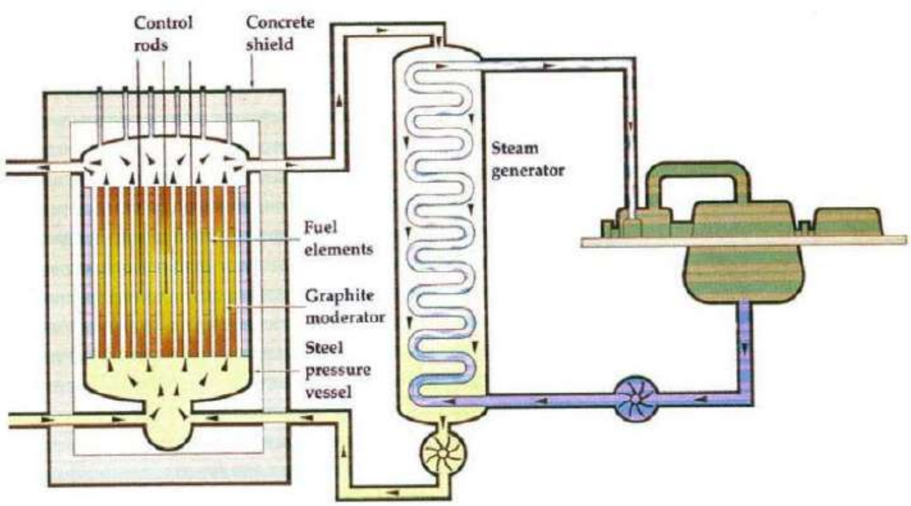


Figure 74: Magnox Reactor

Advanced Gas cooled Reactors

- In order to improve the cost effectiveness of this type of reactor, it was necessary to go to higher temperatures to achieve higher thermal efficiencies and higher power densities to reduce capital costs.
- This entailed increases in cooling gas pressure and changing from Magnox to stainless steel cladding and from uranium metal to uranium dioxide fuel. This in turn led to the need for an increase in the proportion of U^{235} in the fuel. The resulting design, known as the **Advanced Gas-Cooled Reactor, or AGR**

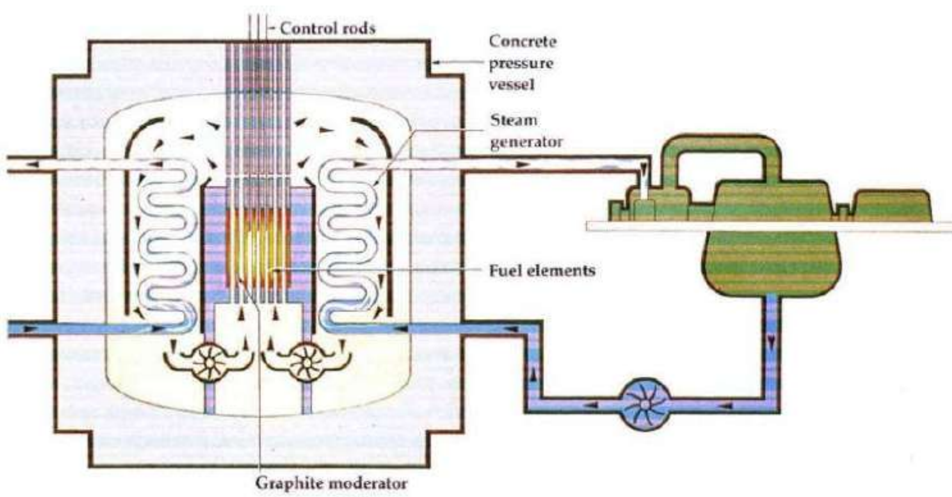


Figure 75: Advanced Gas Cooled Reactor

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.

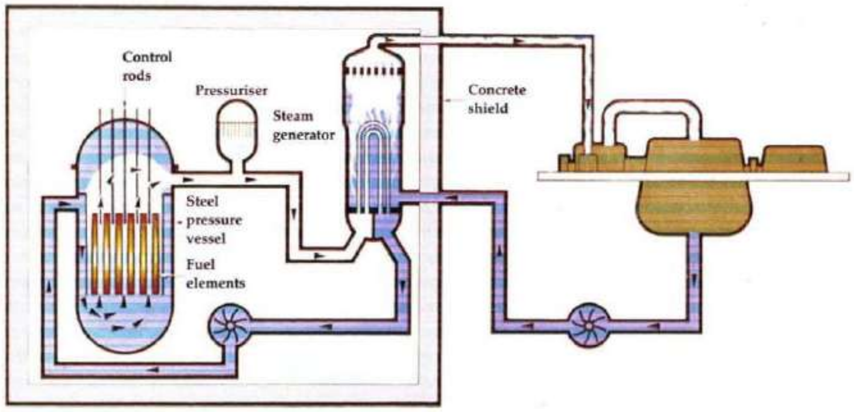


Figure 76: Pressurized Water Reactor

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.
- 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.

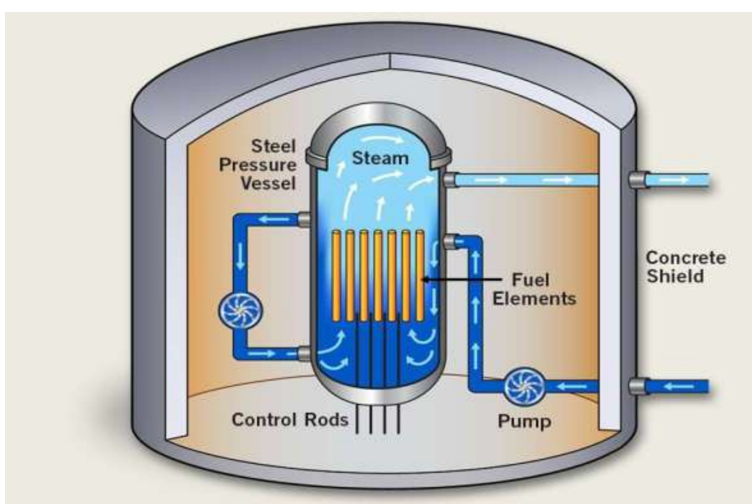


Figure 77: Boiling Water Reactor

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

design and fabrication • Thermal efficient is very low; around 20%	

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 fissileconcentration, 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 utilise the existing stocks of depleted uranium, which would otherwise have no value.

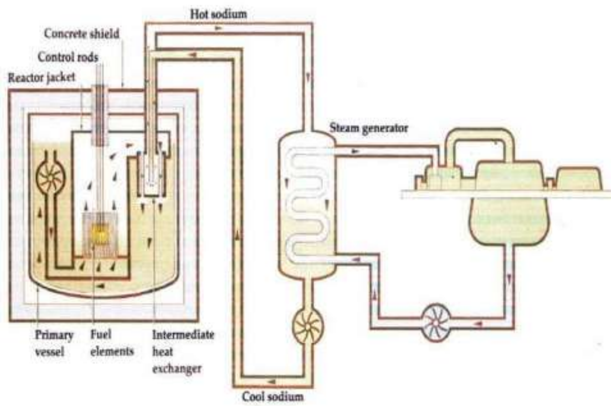


Figure 78: Fast Breeder Reactors

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**

GAS TURBINE POWER PLANT:

A gas turbine, also called a combustion turbine, is a type of internal combustion engine. It has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in-between.

Energy is added to the gas stream in the combustor, where fuel is mixed with air and ignited. In the high pressure environment of the combustor, combustion of the fuel increases the temperature. The products of the combustion are forced into the turbine section. There, the high velocity and volume of the gas flow is directed through a nozzle over the turbine's blades, spinning the turbine which powers the compressor and, for some turbines, drives their mechanical output. The energy given up to the turbine comes from the reduction in the temperature and pressure of the exhaust gas.

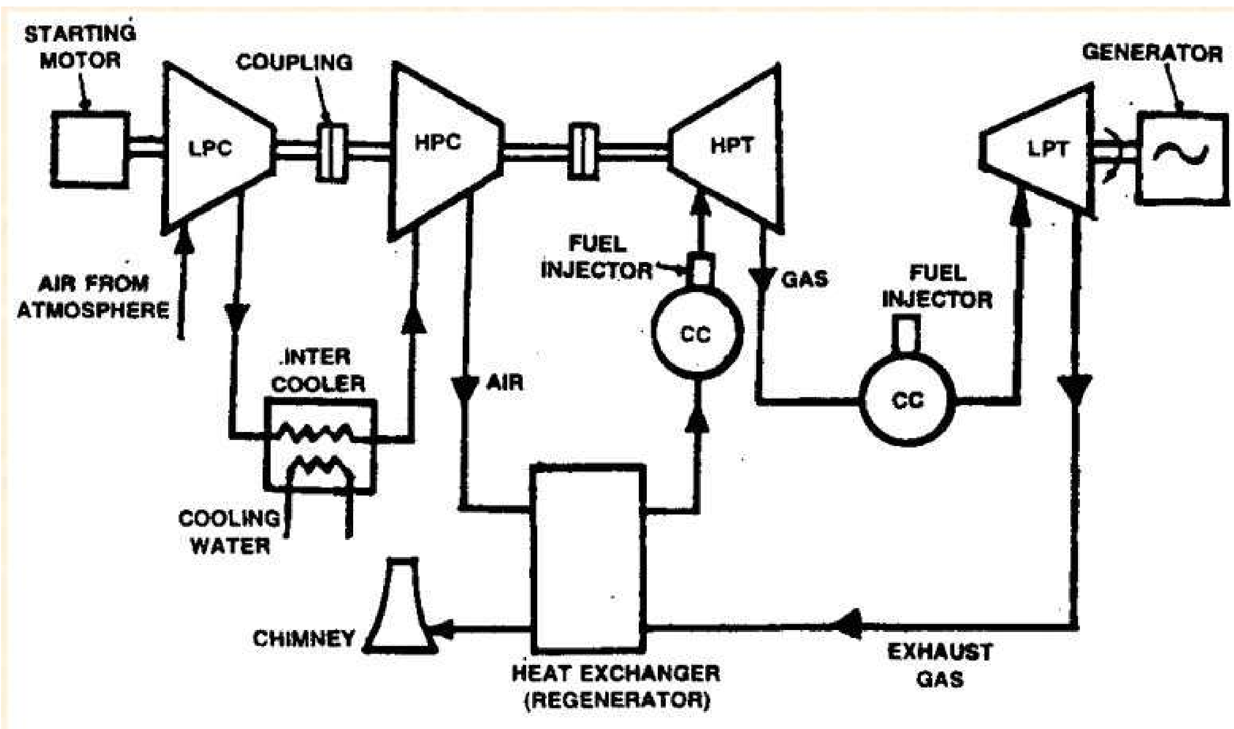


Fig. 3.12: OPEN CYCLE GAS TURBINE POWER PLANT

COMBINED POWER CYCLES:

In electric power generation a combined cycle is an assembly of heat engines that work in tandem off the same source of heat, converting it into mechanical energy, which in turn usually drives electrical generators. The principle is that the exhaust of one heat engine is used as the heat source for another, thus extracting more useful energy from the heat, increasing the system's overall efficiency. This works because heat engines are only able to use a portion of the energy their fuel generates (usually less than 50%).

The remaining heat (e.g., hot exhaust fumes) from combustion is generally wasted. Combining two or more thermodynamic cycles results in improved overall efficiency, reducing fuel costs. In stationary power plants, a successful, common combination is the Brayton cycle (in the form of a turbine burning natural gas or synthesis gas from coal) and the Rankine cycle (in the form of a steam power plant). Multiple stage turbine or steam cylinders are also common.

LOAD DURATION CURVE:

A **load duration curve** (LDC) is used in electric power generation to illustrate the relationship between generating capacity requirements and capacity utilization.

A LDC is similar to a load curve but the demand data is ordered in descending order of magnitude, rather than chronologically. The LDC curve shows the capacity utilization requirements for each increment of load. The height of each slice is a measure of capacity, and the width of each slice is a measure of the utilization rate or capacity factor. The product of the two is a measure of electrical energy (e.g. kilowatthours).

HIGH PRESSURE BOILERS:

A boiler is a closed vessel in which water or other fluid is heated. The heated or vaporized fluid exits the boiler for use in various processes or heating applications.

Most boilers produce steam to be used at saturation temperature; that is, saturated steam.

Superheated steam boilers vaporize the water and then further heat the steam in a superheater. This provides steam at much higher temperature, but can decrease the overall thermal efficiency of the steam generating plant because the higher steam temperature requires a higher flue gas exhaust temperature. There are several ways to circumvent this problem, typically by providing an *economizer* that heats the feed water, a combustion air heater in the hot flue gas exhaust path, or both. There are advantages to superheated steam that may, and often will, increase overall efficiency of both steam generation and its utilisation: gains in input temperature to a turbine should outweigh any cost in additional boiler complication and expense. There may also be practical limitations in using *wet* steam, as entrained condensation droplets will damage turbine blades.

Superheated steam presents unique safety concerns because, if any system component fails and allows steam to escape, the high pressure and temperature can cause serious, instantaneous harm to anyone in its path. Since the escaping steam will initially be completely superheated vapor, detection can be difficult, although the intense heat and sound from such a leak clearly indicates its presence.

Superheater operation is similar to that of the coils on an air conditioning unit, although for a different purpose. The steam piping is directed through the flue gas path in the boiler furnace. The temperature in this area is typically between 1,300–1,600 degrees Celsius. Some superheaters are radiant type; that is, they absorb heat by radiation. Others are convection type, absorbing heat from a fluid. Some are a combination of the two types. Through either method, the extreme heat in the flue gas path will also heat the superheater steam piping and the steam within. While the temperature of the steam in the superheater rises, the pressure of the steam does not: the turbine or moving pistons offer a continuously expanding space and the pressure remains the same as that of the boiler. Almost all steam superheater system designs remove droplets entrained in the steam to prevent damage to the turbine blading and associated piping.

SUPERCRITICAL BOILER:

Supercritical steam generators (also known as Benson boilers) are frequently used for the production of electric power. They operate at "supercritical pressure". In contrast to a "subcritical boiler", a supercritical steam generator operates at such a high pressure (over 3,200 psi/22.06 MPa or 220.6 bar) that actual boiling ceases to occur, and the boiler has no water - steam separation. There is no generation of steam bubbles within the water, because the pressure is above the "critical pressure" at which steam bubbles can form. It passes below the critical point as it does work in the high pressure turbine and enters the generator's condenser. This is more efficient, resulting in slightly less fuel use. The term "boiler" should not be used for a supercritical pressure steam generator, as no "boiling" actually occurs in this device.

FLUIDIZED BED BOILERS:

The major portion of the coal available in India is of low quality, high ash content and low calorific value. The traditional grate fuel firing systems have got limitations and are techno-economically unviable to meet the challenges of future. Fluidized bed combustion has emerged as a viable alternative and has significant advantages over conventional firing system and offers multiple benefits – compact boiler design, fuel flexibility, higher combustion efficiency and reduced emission of noxious pollutants such as SOx and NOx. The fuels burnt in these boilers include coal, washery rejects, rice husk, bagasse & other agricultural wastes. The fluidized bed boilers have a wide capacity range- 0.5 T/hr to over 100 T/hr.

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 hydroenergy into mechanical energy, the latter again drives a connected generator transforming the mechanical energy into electric energy. As hydroenergy 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.

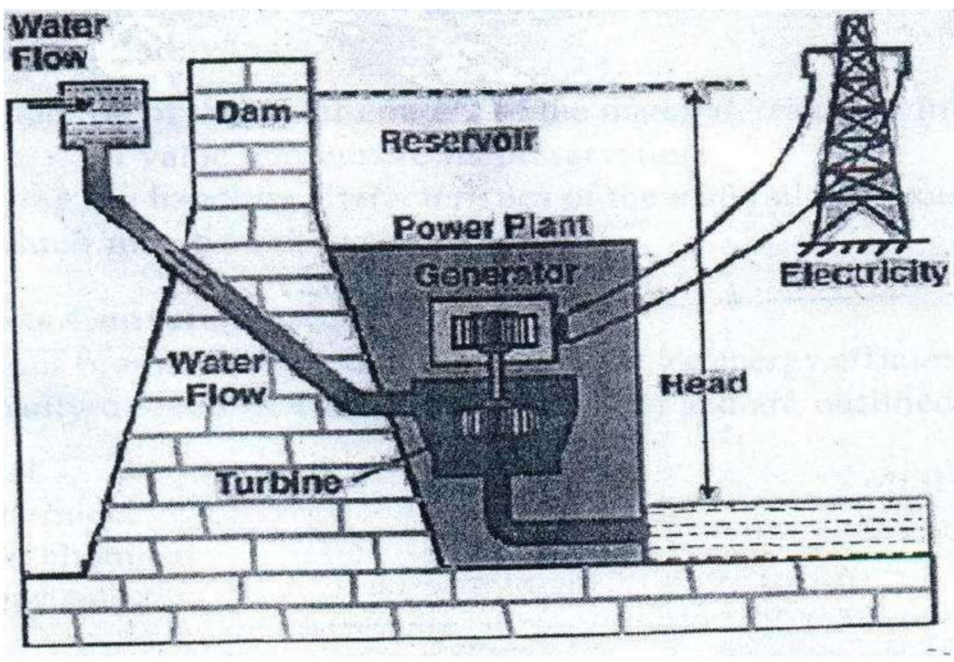


Fig. 1.5.1 General Layout of a dam based hydroelectric plant

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 depends upon type of hydroelectric development and classification with respect to head and size. There are three main types of hydropower schemes that can be cateigorized 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 remain 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 are 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 a 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:

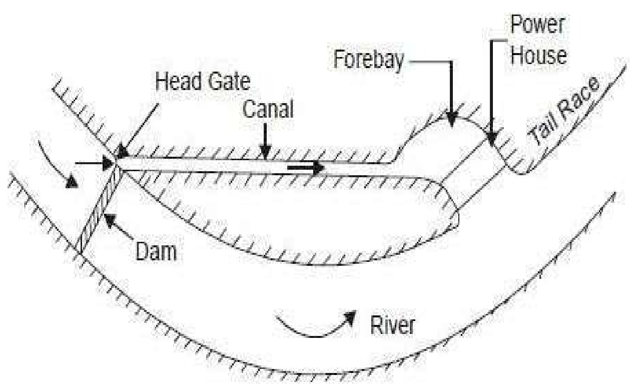
1. Base load plants
2. Peak load plants
3. Pumped storage plants

According to head:

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

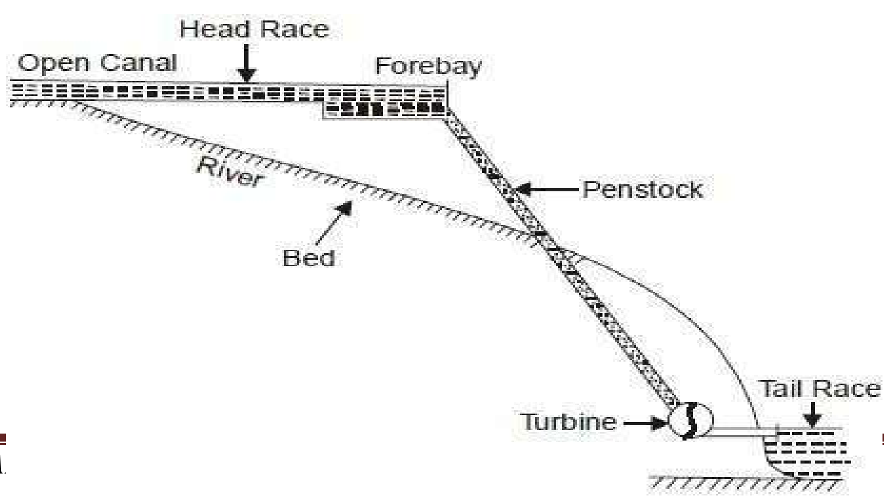
Low head plant

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



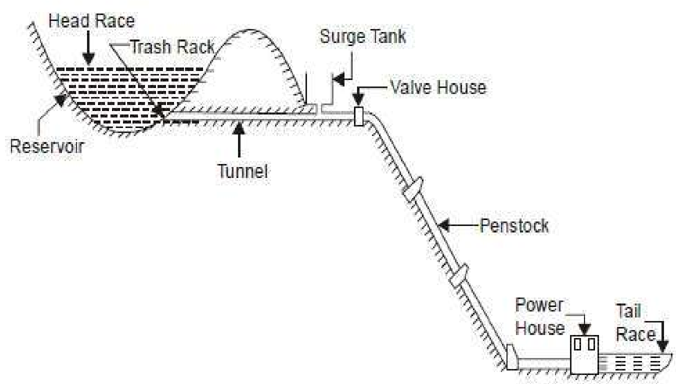
Medium head plant

- 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 on the penstock.



Components of a HPP

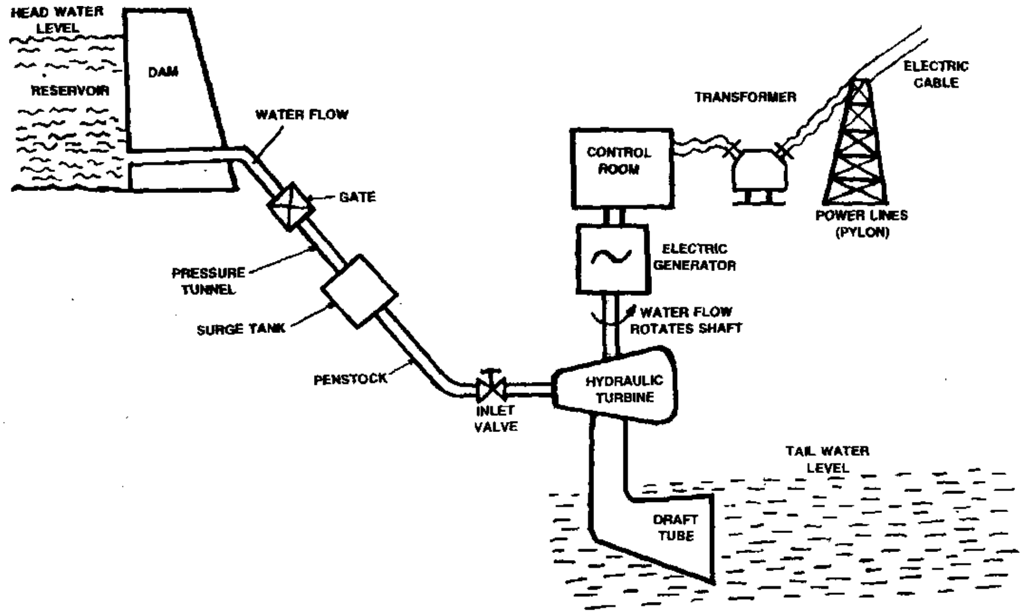


FIG. 3.6: LAYOUT OF HYDRO-ELECTRIC POWER PLANT

Figure 4: 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

Figure 5: 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.

Figure 8: 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:

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.

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.

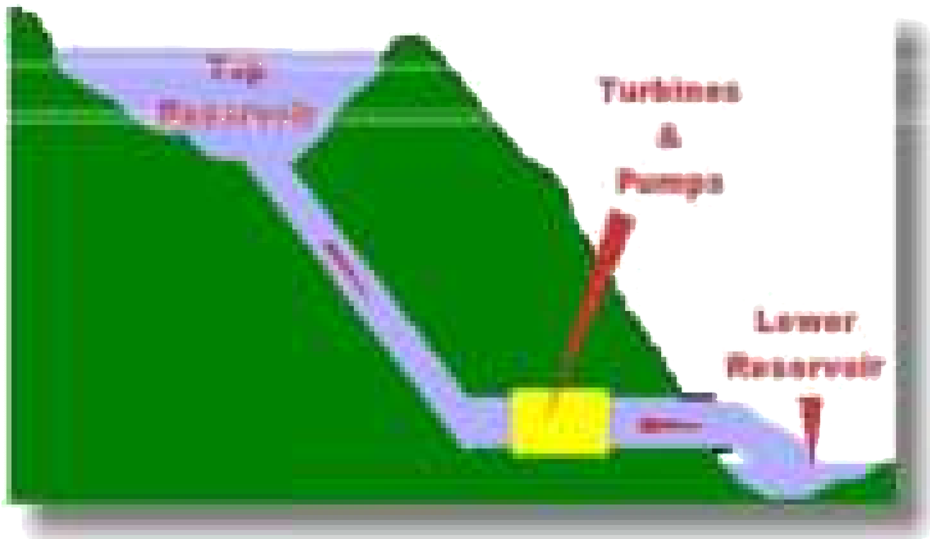
If turbine is reversible, it can be used as a pump to supply water back to reservoir, otherwise separate pump can be used.

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 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.

HYDRAULIC TURBINES

Types of Hydraulic Turbines

1. According to the head and quantity of water available
   a. Low head (2-15m)
   b. Medium head (16-70m)
   c. High head (71-500m)
   d. Very high head (>500m)
2. According to the name of the originator
   a. Francis
   b. Kaplan
   c. Pelton
3. According to the nature of working of water on blades

Table 2: Impulse and Reaction Turbines

Impulse	Reaction
Available head of water converted into kinetic energy in a nozzle	Flow of water takes place in a closed conduit system
The free jet strikes a bucket which revolves around a shaft	Part of P.E. is converted into K.E. and part into pressure energy

Turbines are above ground	Water flows in a closed conduit system and turbines are submerged in water
After energy production, water falls freely through the passage into tail race	Water falls through a draft tube

4. According to the direction of flow of water
   a. Radial
   b. Axial
   c. Tangential (Deriaz)
5. According to the axis of the turbine shaft: vertical, horizontal Comparison of Turbines

Comparison of Turbines

Turbine	Head (m)	Specific Speed (metric)
Kaplan	30 to 70	300 to 1000
Francis	40 to 400	60 to 300
Pelton	>400 m	10 to 50

Specific Speed (Ns)

- It is defined as the speed of a geometrically similar turbine to produce 1 kW of power under 1 m head. Its units are 'rpm in (m-kW)' or 'rpm in (m-mhp)'.

$$N_s = \frac{N\sqrt{P}}{K5/\ 4}$$

Where N = rotational speed of the turbine in rpm
P = Power output of the turbine in kW or mhp H = Head of the turbine in meters

- Specific speed is the basis of comparison of the characteristics of hydraulic turbines.
- Higher the specific speed for a given head and power output, the lower the cost of installation as a whole.

Example:
Find out the specific speed of a turbine of 10 MW capacity working under a head of 500m and having the normal working speed of 300 RPM.
Solution:

N_s = 300x sqrt (10000) / 500^(1.25) = 12 rpm in (m-kW)

Runaway Speed
It is the maximum speed at which a turbine would run under the worst conditions of operation i.e. with all gates open so as to allow all possible water inflow under maximum head and corresponding to the condition of the load being suddenly thrown off from the generator.

Hydraulic turbines are generally classified as

Tangential Flow

Radial Flow

Axial Flow

Mixed Flow

Impulse and Reaction Turbines

- The flow energy to the impulse turbines is completely converted to kinetic energy before transformation in the runner.
- The impulse forces being transferred by the direction changes of the flow velocity vectors when passing the buckets create the energy converted to mechanical energy on the turbine shaft.
- The flow enters the runner from jets spaced around the rim of the runners. The jet hits momentarily only a part of the circumference of the runner.
- In the reaction turbines two effects cause the energy transfer from the flow to the mechanical energy on the turbine shaft:
  - Firstly, it follows from a drop in pressure from inlet to outlet of the runner. This is denoted as the *reaction part* of the energy conversion.
  - Secondly, the changes in the directions of the flow velocity vectors through the runner blade channels transfer impulse forces. This is denoted as the *impulse part* of the energy conversion.
- The pressure drop from inlet to outlet of the runners is obtained because the runners are completely filled with water.

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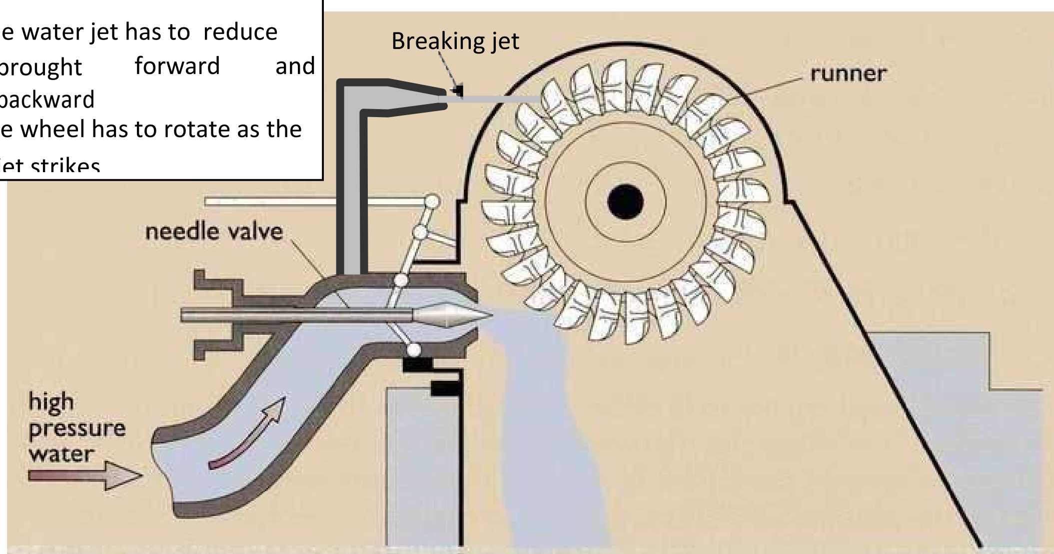
- The pressure drop from inlet to outlet of the runners is obtained because the runners are completely filled with water.

PELTON WHEEL OR TURBINE

Pelton wheel, named after an eminent engineer, is an impulse turbine wherein the flow is tangential to the runner and the available energy at the entrance is completely kinetic energy. Further, it is preferred at a very high head and low discharges with low specific speeds. The pressure available at the inlet and the outlet is atmospheric.

Animation:

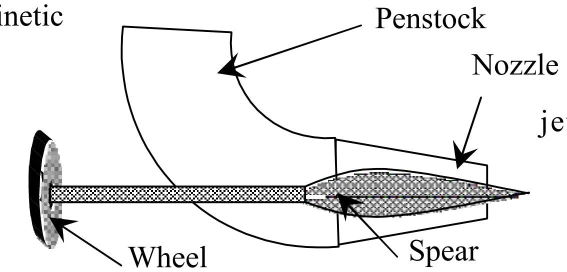
(i) The water jet has to reduce brought forward and backward
(ii) The wheel has to rotate as the jet strikes



The main components of a Pelton turbine are:

(i) *Nozzle and flow regulating arrangement:*

Water is brought to the hydroelectric plant site through large penstocks at the end of which there will be a nozzle, which converts the pressure energy completely into kinetic energy. This will convert the liquid flow into a high-speed jet, which strikes the buckets or vanes mounted on the runner, which in-turn rotates the runner of

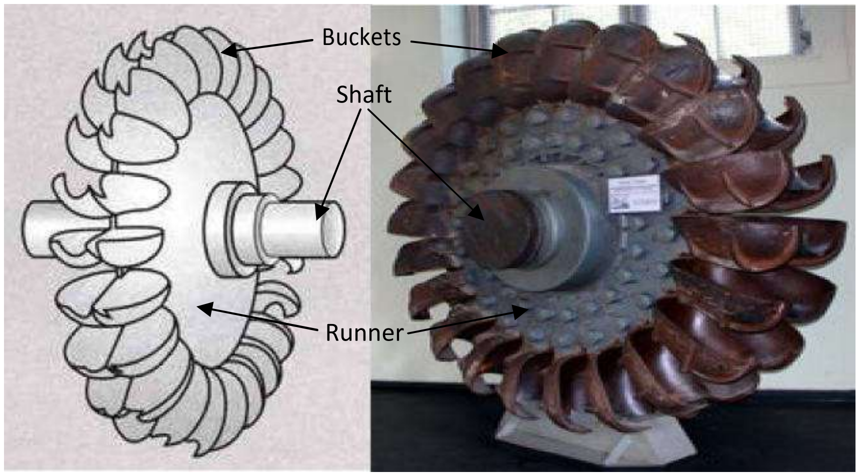


the turbine. The amount of water striking the vanes is controlled by the forward and backward motion of the spear. As the water is flowing in the annular area between the annular area between the

nozzle opening and the spear, the flow gets reduced as the spear moves forward and vice- versa.

(ii) *Runner with buckets:*

Runner is a circular disk mounted on a shaft on the periphery of



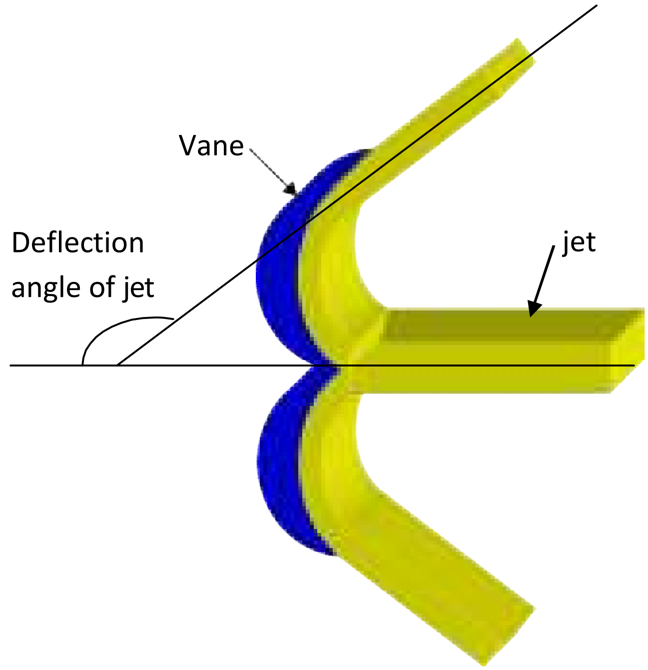
which a number of buckets are fixed equally spaced as shown in Fig. The buckets are made of cast-iron cast-steel, bronze or stainless steel depending upon the head at the inlet of the turbine. The water jet strikes the bucket on the splitter of the bucket and gets deflected through (α) 160-170^0.

(iii) *Casing:*

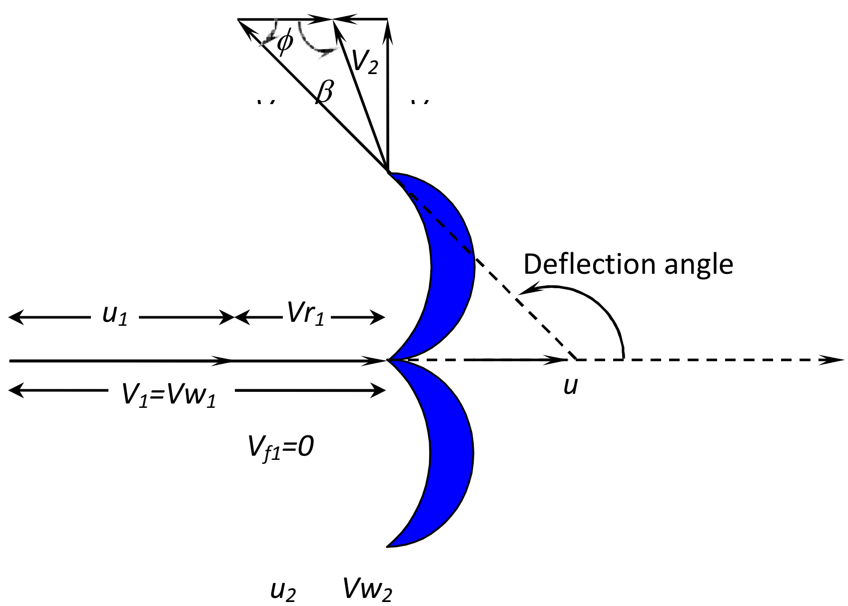
It is made of cast- iron or fabricated steel plates. The main function of the casing is to prevent splashing of water and to discharge the water into tailrace.

(iv) *Breaking jet:*

Even after the amount of water striking the buckets is completely stopped, the runner goes on rotating for a very long time due to inertia. To stop the runner in a short time, a small nozzle is provided which directs the jet of water on the back of bucket with which the rotation of the runner is reversed. This jet i s called as breaking jet.



2 D Picture of a jet striking the splitter and getting split in to two parts and deviating.



Velocity triangles for the jet striking the bucket

From the impulse-momentum theorem, the force with which the jet strikes tthe bucket along the direction of vane is given by

F_x = rate of change of momentum of the jet along the direction of vane motion

F_x = (Mass of water / second) x change in velocity along the x direction

$$= \rho a V_1 \left[V_{w1} - \left(- V_{w2} \right) \right]$$

$$= \rho a V_1 \left[V_{w1} + V_{w2} \right]$$

Work done per second by the jet on the vane is given by the product of Force exerted on the vane and the distance moved by the vane in one second

W.D./S = F_x x u

$$= \rho a V_1 [V_{w1} + V_{w2}] u$$

Input to the jet per second = Kinetic energy of the jet per second

$$= \frac{1}{2} \rho a V_1^3$$

Efficiency of the jet = $\frac{Output/second}{Input/second} = \frac{Workdone/second}{Input/second}$

$$\eta = \frac{\rho a V_1 [V_{w1} + V_{w2}] u}{\frac{1}{2} \rho a V_1^3}$$

$$\eta = \frac{2u [V_{w1} + V_{w2}]}{V_1^2}$$

From inlet velocity triangle, $V_{w1} = V_1$

Assuming no shock and ignoring frictional losses through the vane, we have $V_{r1} = V_{r2} = (V_1 - u_1)$

In case of Pelton wheel, the inlet and outlet are located at the same radial distance from the centre of runner and hence $u_1 = u_2 = u$

From outlet velocity triangle, we have $V_{w2} = V_{r2}\, Cos\phi - u_2$

$$= (V_1 - u) Cos\phi - u$$

$$F_x = \rho a V_1 [V_1 + (V_1 - u) Cos\phi - u]$$

$$F_x = \rho a V_1 (V_1 - u)[1 + Cos\phi]$$

Substituting these values in the above equation for efficiency, we have

$$\eta = \frac{2u [V_1 + (V_1 - u)\cos\phi - u]}{V_1^2}$$

$$\eta = \frac{2u}{V_1^2} [(V_1 - u) + (V_1 - u)\cos\phi]$$

$$\eta = \frac{2u}{V_1^2}(V_1 - u)[1 + \cos\phi]$$

The above equation gives the efficiency of the jet striking the vane in case of Pelton wheel.

To obtain the maximum efficiency for a given jet velocity and vane angle, from maxima-minima, we have

$$\frac{d\eta}{du} = 0$$

$$\Rightarrow \frac{d\eta}{du} = \frac{2}{V_1^2}[1 + \cos\phi]\frac{d}{du}\left(uV_1 - u^2\right) = 0$$

$$V_1 - 2u = 0$$

or $$u = \frac{V_1}{2}$$

i.e. When the bucket speed is maintained at half the velocity of the jet, the efficiency of a Pelton wheel will be maximum. Substituting we get,

$$\eta_{max} = \frac{2u}{(2u)^2}(2u - u)[1 + \cos\phi]$$

$$\eta_{max} = \frac{1}{2}[1 + \cos\phi]$$

From the above it can be seen that more the value of $\cos\phi$, more will be the efficiency. Form maximum efficiency, the value of $\cos\phi$ should be 1 and the value of ϕ should be 0^0. This condition makes the jet to completely deviate by 180^0 and this, forces the jet striking the bucket to strike the successive bucket on the back of it acting like a breaking jet. Hence to avoid this situation, at least a small angle of $\phi = 5^0$ should be provided.

Francis Turbine

Reaction Turbine: The principal feature of a reaction turbine that distinguishes it from an impulse turbine is that only a part of the total head available at the inlet to the turbine is converted to velocity head, before the runner is reached. Also in the reaction turbines the working fluid, instead of engaging only one or two blades, completely fills the passages in the runner. The pressure or static head of the fluid changes gradually as it passes through the runner along with the change in its kinetic energy based on absolute velocity due to the impulse action between the fluid and the runner. Therefore the cross-sectional area of flow through the passages of the fluid. A reaction turbine is usually well suited for low heads. A radial flow hydraulic turbine of reaction type was first developed by an American Engineer, James B. Francis (1815-92) and is named after him as the Francis turbine. The schematic diagram of a Francis turbine is shown in Fig. 28.1

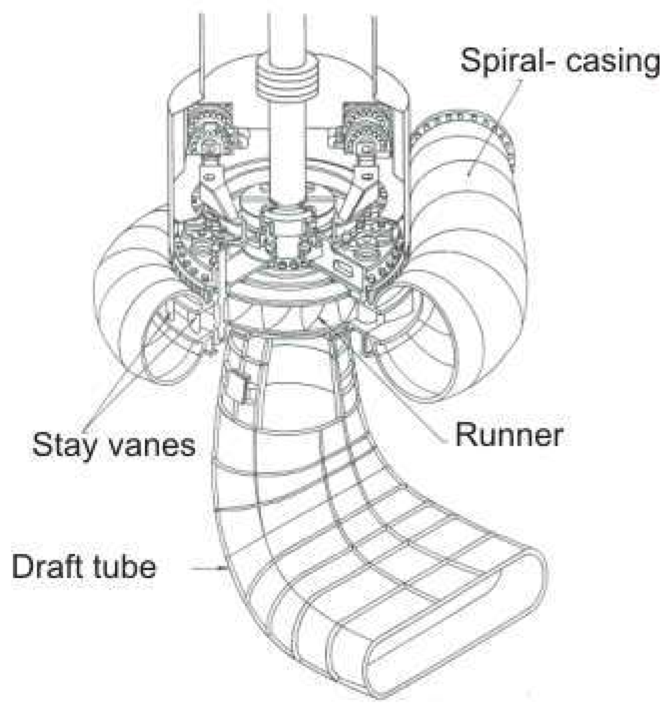


Figure 28.1 A Francis turbine

A Francis turbine comprises mainly the four components:

(i) sprical casing,

(ii) guide on stay vanes,

(iii) runner blades,

(iv) draft-tube as shown in Figure 28.1 .

Spiral Casing : Most of these machines have vertical shafts although some smaller machines of this type have horizontal shaft. The fluid enters from the penstock (pipeline leading to the turbine from the reservoir at high altitude) to a spiral casing which completely surrounds the runner. This casing is known as scroll casing or volute. The cross-sectional area of this casing decreases uniformly along the circumference to keep the fluid velocity constant in magnitude along its path towards the guide vane.

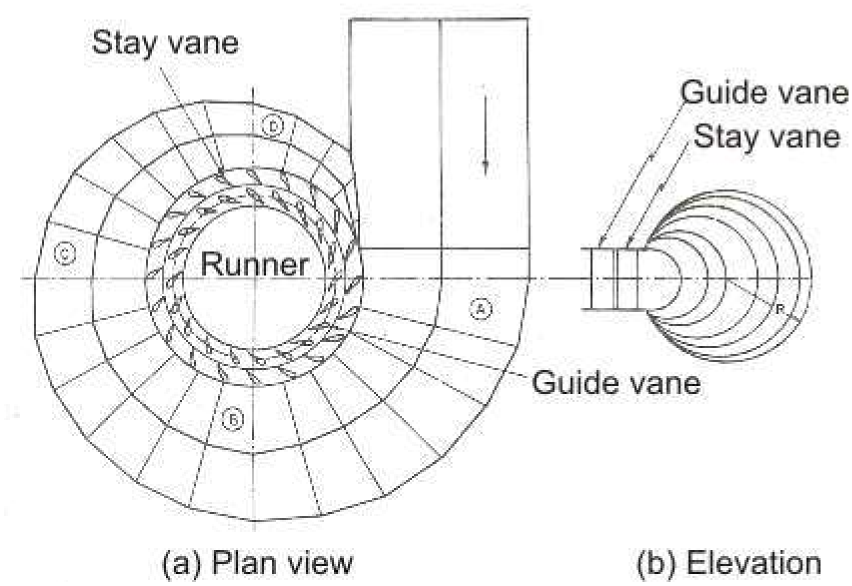


Figure 28.2 Spiral Casing

This is so because the rate of flow along the fluid path in the volute decreases due to continuous entry of the fluid to the runner through the openings of the guide vanes or stay vanes.

Guide or Stay vane:

The basic purpose of the guide vanes or stay vanes is to convert a part of pressure energy of the fluid at its entrance to the kinetic energy and then to direct the fluid on to the runner blades at the angle appropriate to the design. Moreover, the guide vanes are pivoted and can be turned by a suitable governing mechanism to regulate the flow while the load changes. The guide vanes are also known as wicket gates. The guide vanes impart a tangential velocity and hence an angular momentum to the water before its entry to the runner. The flow in the runner of a Francis turbine is not purely radial but a combination of radial and tangential. The flow is inward, i.e. from the periphery towards the centre. The height of the runner depends upon the specific speed. The height increases with the increase in the specific speed. The main direction of flow change as water passes through the runner and is finally turned into the axial direction while entering the draft tube.

Draft tube:

The draft tube is a conduit which connects the runner exit to the tail race where the water is being finally discharged from the turbine. The primary function of the draft tube is to reduce the velocity of the discharged water to minimize the loss of kinetic energy at the outlet. This permits the turbine to be set above the tail water without any appreciable drop of available head. A clear understanding of the function of the draft tube in any reaction turbine, in fact, is very important for the purpose of its design. The purpose of providing a draft tube will be better understood if we carefully study the net available head across a reaction turbine.

Net head across a reaction turbine and the purpose to providing a draft tube . The effective head across any turbine is the difference between the head at inlet to the machine and the head at outlet from it. A reaction turbine always runs completely filled with the working fluid. The tube that connects the end of the runner to the tail race is known as a draft tube and should completely to filled with the working fluid flowing through it. The kinetic energy of the fluid finally discharged into the tail race is wasted. A draft tube is made divergent so as to reduce the velocity at outlet to a minimum. Therefore a draft tube is basically a diffuser and should be designed properly with the angle between the walls of the tube to be limited to about 8 degree so as to prevent the flow separation from the wall and to reduce accordingly the loss of energy in the tube. Figure 28.3 shows a flow diagram from the reservoir via a reaction turbine to the tail race.

The total head H_1 at the entrance to the turbine can be found out by applying the Bernoulli's equation between the free surface of the reservoir and the inlet to the turbine as

$$H_0 = \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z + h_f \qquad (28.1)$$

or,

$$H_1 = H_0 - h_f = \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z \qquad (28.2)$$

where h_f is the head lost due to friction in the pipeline connecting the reservoir and the turbine. Since the draft tube is a part of the turbine, the net head across the turbine, for the conversion of mechanical work, is the difference of total head at inlet to the machine and the total head at discharge from the draft tube at tail race and is shown as *H* in Figure 28.3

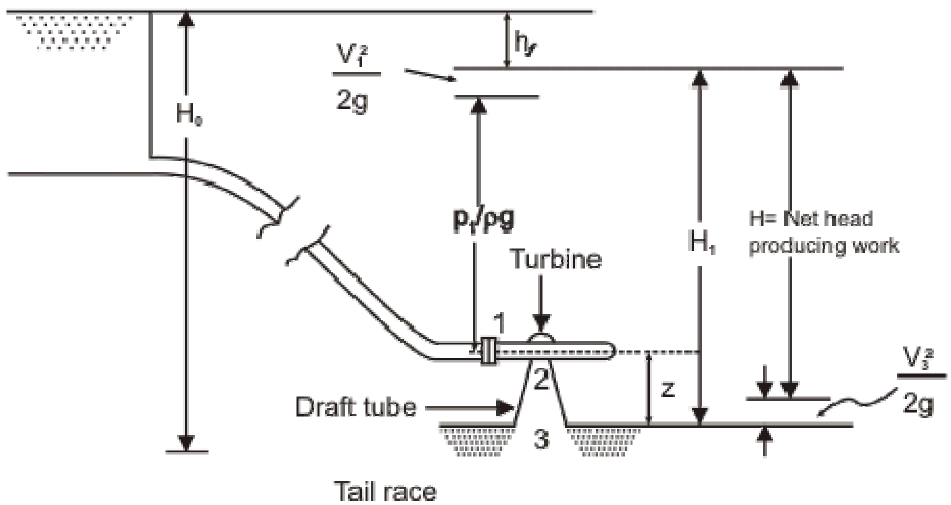


Figure 28.3 Head across a reaction turbine

Therefore, *H* = total head at inlet to machine (1) - total head at discharge (3)

$$= \frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z - \frac{V_3^2}{2g} = H_1 - \frac{V_3^2}{2g} \qquad (28.3)$$

$$= (H_0 - h_f) - \frac{V_3^2}{2g} \qquad (28.4)$$

The pressures are defined in terms of their values above the atmospheric pressure. Section 2 and 3 in Figure 28.3 represent the exits from the runner and the draft tube respectively. If the losses in the draft tube are neglected, then the total head at 2 becomes equal to that at 3. Therefore, the net head across the machine is either $(H_1 - H_3)$ or $(H_1 - H_2)$. Applying the Bernoull's equation between 2 and 3 in consideration of flow, without losses, through the draft tube, we can write.

$$\frac{P_2}{\rho g}+\frac{V_2^2}{2g}+z=0+\frac{V_3^2}{2g}+0 \qquad (28.5)$$

$$\frac{P_2}{\rho g}=-\left[z+\frac{V_2^2-V_3^2}{2g}\right] \qquad (28.6)$$

Since $V_3 < V_2$, both the terms in the bracket are positive and hence $p_2/\rho g$ is always negative, which implies that the static pressure at the outlet of the runner is always below the atmospheric pressure. Equation (28.1) also shows that the value of the suction pressure at runner outlet depends on z, the height of the runner above the tail race and $(V_2^2 - V_3^2)/2g$, the decrease in kinetic energy of the fluid in the draft tube. The value of this minimum pressure p_2 should never fall below the vapour pressure of the liquid at its operating temperature to avoid the problem of cavitation. Therefore, we fine that the incorporation of a draft tube allows the turbine runner to be set above the tail race without any drop of available head by maintaining a vacuum pressure at the outlet of the runner.

Runner of the Francis Turbine

The shape of the blades of a Francis runner is complex. The exact shape depends on its specific speed. It is obvious from the equation of specific speed that higher specific speed means lower head. This requires that the runner should admit a comparatively large quantity of water for a given power output and at the same time the velocity of discharge at runner outlet should be small to avoid cavitation. In a purely radial flow runner, as developed by James B. Francis, the bulk flow is in the radial direction. To be more clear, the flow is tangential and radial at the inlet but is entirely radial with a negligible tangential component at the outlet. The flow, under the situation, has to make a 90^o turn after passing through the rotor for its inlet to the draft tube. Since the flow area (area perpendicular to the radial direction) is small, there is a limit to the capacity of this type of runner in keeping a low exit velocity. This leads to the design of a mixed flow runner where water is turned from a radial to an axial direction in the rotor itself. At the outlet of this type of runner, the flow is mostly axial with negligible radial and tangential components. Because of a large discharge area (area perpendicular to the axial direction), this type of runner can pass a large amount of water with a low exit velocity from the runner. The blades for a reaction turbine are always so shaped that the tangential or whirling component of velocity at the outlet becomes zero $(V_{w_2} = 0)$. This is made to keep the kinetic energy at outlet a minimum.

Figure 29.1 shows the velocity triangles at inlet and outlet of a typical blade of a Francis turbine. Usually the flow velocity (velocity perpendicular to the tangential direction) remains constant throughout, i.e. $V_{f_1} = V_{f_2}$ and is equal to that at the inlet to the draft tube.

The Euler's equation for turbine [Eq.(1.2)] in this case reduces to

$$E/m = e = V_{w_1} U_1 \qquad (29.1)$$

where, *e* is the energy transfer to the rotor per unit mass of the fluid. From the inlet velocity triangle shown in Fig. 29.1

$$V_{w_1} = V_{f_1} \cot \alpha_1 \qquad (29.2a)$$

and

$$U_1 = V_{f_1} (\cot \alpha_1 + \cot \beta_1) \qquad (29.2b)$$

Substituting the values of V_{w_1} and U_1 from Eqs. (29.2a) and (29.2b) respectively into Eq. (29.1), we have

$$e = V_{f_1}^2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1) \qquad (29.3)$$

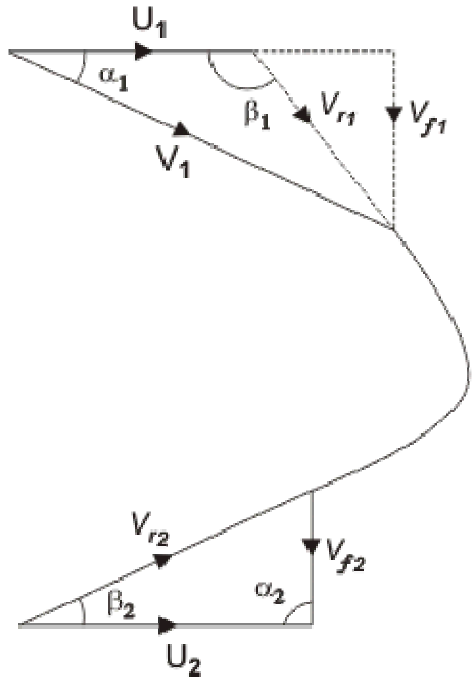


Figure 29.1 Velocity triangle for a Francis runner

The loss of kinetic energy per unit mass becomes equal to $V_{f_2}^2 / 2$. Therefore neglecting friction, the blade efficiency becomes

$$\eta_b = \frac{e}{e + (V_{f_2}^2 / 2)}$$

$$= \frac{2V_{f_1}^2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1)}{V_{f_2}^2 + 2V_{f_1}^2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1)}$$

since $V_{f_1} = V_{f_2}$, η_b can be written as

$$\eta_b = 1 - \frac{1}{1 + 2\cot \alpha_1 (\cot \alpha_1 + \cot \beta_1)}$$

The change in pressure energy of the fluid in the rotor can be found out by subtracting the change in its kinetic energy from the total energy released. Therefore, we can write for the degree of reaction.

$$R = \frac{e - \frac{1}{2}\left(V_1^2 - V_{f_2}^2\right)}{e} = 1 - \frac{\frac{1}{2}V_{f_1}^2 \cot^2 \alpha_1}{e}$$

[since $V_1^2 - V_{f_2}^2 = V_1^2 - V_{f_1}^2 = V_{f_1}^2 \cot^2 \alpha_1$]

Using the expression of *e* from Eq. (29.3), we have

$$R = 1 - \frac{\cot \alpha_1}{2(\cot \alpha_1 + \cot \beta_1)} \qquad (29.4)$$

The inlet blade angle β_1 of a Francis runner varies $45 - 120^o$ and the guide vane angle angle α_1 from $10 - 40^o$. The ratio of blade width to the diameter of runner B/D, at blade inlet, depends upon the required specific speed and varies from 1/20 to 2/3.

Expression for specific speed. The dimensional specific speed of a turbine, can be written as

$$N_{s_T} = \frac{NP^{1/2}}{H^{5/4}}$$

Power generated *P* for a turbine can be expressed in terms of available head *H* and hydraulic efficiency η_h as

$$P = \rho Q g H \eta_h$$

Hence, it becomes

$$N_{s_T} = N(\rho Q g \eta_h)^{1/2} H^{-3/4} \qquad (29.5)$$

Again, $N = U_1 / \pi D_1$,

Substituting U_1 from Eq. (29.2b)

$$N = \frac{V_{f_1}(\cot \alpha_1 + \cot \beta_1)}{\pi D_1} \qquad (29.6)$$

Available head *H* equals the head delivered by the turbine plus the head lost at the exit. Thus,

$$gH = e + (V_{f_2}^2 / 2)$$

since $$V_{f_1} = V_{f_2}$$

$$gH = e + (V_{f_1}^2 / 2)$$

with the help of Eq. (29.3), it becomes

$$gH = V_{f_1}^2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1) + \frac{V_{f_1}^2}{2}$$

or, $$H = \frac{V_{f_1}^2}{2g}[1 + 2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1)] \qquad (29.7)$$

Substituting the values of H and N from Eqs (29.7) and (29.6) respectively into the expression N_{s_T} given by Eq. (29.5), we get,

$$N_{s_T} = 2^{3/4} g^{5/4} (\rho \eta_h Q)^{1/2} \frac{V_{f_1}^{-1/2}}{\pi D_1} (\cot \alpha_1 + \cot \beta_1)[1 + 2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1)^{-3/4}$$

Flow velocity at inlet V_{f_1} can be substituted from the equation of continuity as

$$V_{f_1} = \frac{Q}{\pi D_1 B}$$

where B is the width of the runner at its inlet

Finally, the expression for N_{s_T} becomes,

$$N_{s_T} = 2^{3/4} g^{5/4} (\rho \eta_h)^{1/2} (\frac{B}{\pi D_1})^{1/2} (\cot \alpha_1 + \cot \beta_1)$$

$$[1 + 2 \cot \alpha_1 (\cot \alpha_1 + \cot \beta_1))^{-3/4}$$

KAPLAN TURBINE

Introduction

Higher specific speed corresponds to a lower head. This requires that the runner should admit a comparatively large quantity of water. For a runner of given diameter, the maximum flow rate is achieved when the flow is parallel to the axis. Such a machine is known as axial flow reaction turbine. An Australian engineer, Vikton Kaplan first designed such a machine. The machines in this family are called Kaplan Turbines.(Figure 30.1)

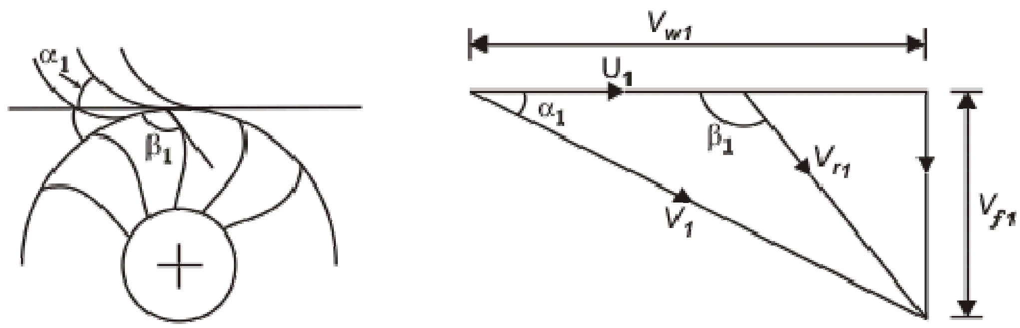
Figure 30.1 A typical Kaplan Turbine

Development of Kaplan Runner from the Change in the Shape of Francis Runner with Specific Speed

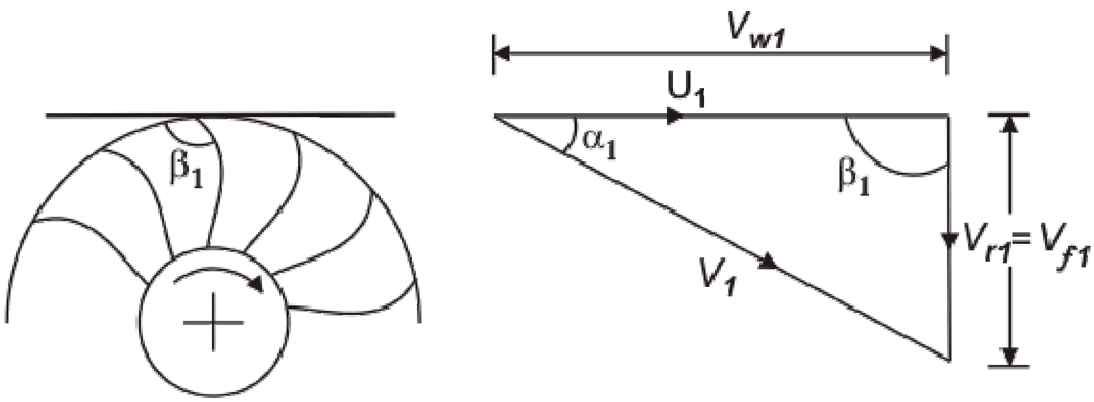
Figure 30.2 shows in stages the change in the shape of a Francis runner with the variation of specific speed. The first three types [Fig. 30.2 (a), (b) and (c)] have, in order. The Francis runner (radial flow runner) at low, normal and high specific speeds. As the specific speed increases, discharge becomes more and more axial. The fourth type, as shown in Fig.30.2 (d), is a mixed flow runner (radial flow at inlet axial flow at outlet) and is known as Dubs runner which is mainly suited for high specific speeds. Figure 30.2(e) shows a propeller type runner with a less number of blades where the flow is entirely axial (both at inlet and outlet). This type of runner is the most suitable one for very high specific speeds and is known as Kaplan runner or axial flow runner.

From the inlet velocity triangle for each of the five runners, as shown in Figs (30.2a to 30.2e), it is found that an increase in specific speed (or a decreased in head) is accompanied by a reduction in inlet velocity V_1. But the flow velocity V_{f1} at inlet increases allowing a large amount of fluid to enter the turbine. The most important point to be noted in this context is that the flow at inlet to all the runners, except the Kaplan one, is in radial and tangential directions. Therefore, the inlet velocity triangles of those turbines (Figure 30.2a to 30.2d) are shown in a plane containing the radial ant tangential directions, and hence the flow velocity V_{f1} represents the radial component of velocity.

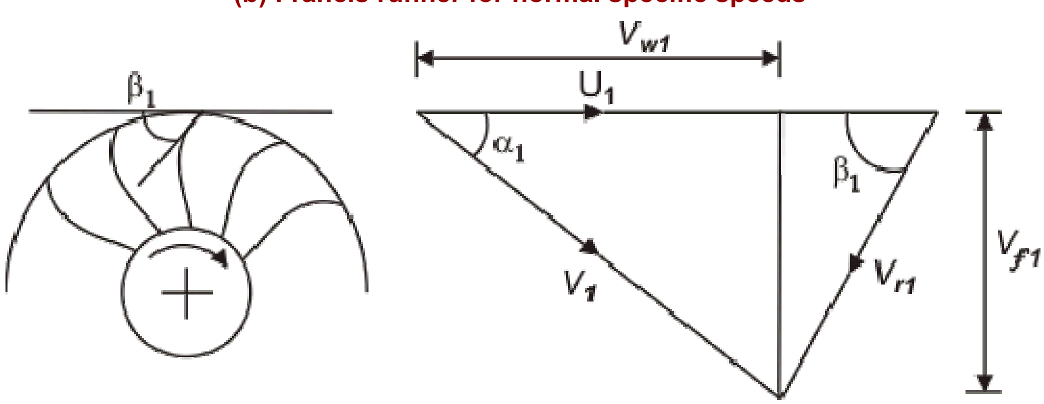
In case of a Kaplan runner, the flow at inlet is in axial and tangential directions. Therefore, the inlet velocity triangle in this case (Figure 30.2e) is shown in a place containing the axial and tangential directions, and hence the flow velocity V_{f1} represents the axial component of velocity V_a .The tangential component of velocity is almost nil at outlet of all runners. Therefore, the outlet velocity triangle (Figure 30.2f) is identical in shape of all runners. However, the exit velocity V_2 is axial in Kaplan and Dubs runner, while it is the radial one in all other runners.



(a) Francis runner for low specific speeds

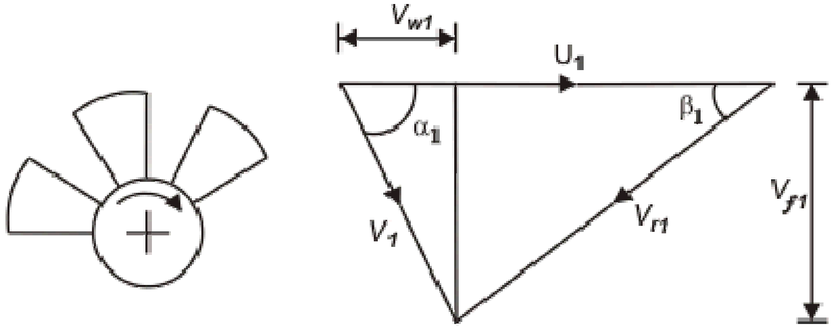


(b) Francis runner for normal specific speeds



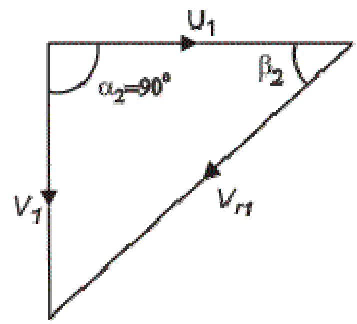
(c) Francis runner for high specific speeds

(d) Dubs runner



(e) Kalpan runner

(f) For allreaction (Francis as well as Kaplan) runners



Outlet velocity triangle

Fig. 30.2 Evolution of Kaplan runner form Francis one

Figure 30.3 shows a schematic diagram of propeller or Kaplan turbine. The function of the guide vane is same as in case of Francis turbine. Between the guide vanes and the runner, the fluid in a propeller turbine turns through a right-angle into the axial direction and then passes through the runner. The runner usually has four or six blades and closely resembles a ship's propeller. Neglecting the frictional effects, the flow approaching the runner blades can be considered to be a free vortex with whirl velocity being inversely proportional to radius, while on the other hand, the blade velocity is directly proportional to the radius. To take care of this different relationship of the fluid velocity and the blade velocity with the changes in radius, the blades are twisted. The angle with axis is greater at the tip that at the root.

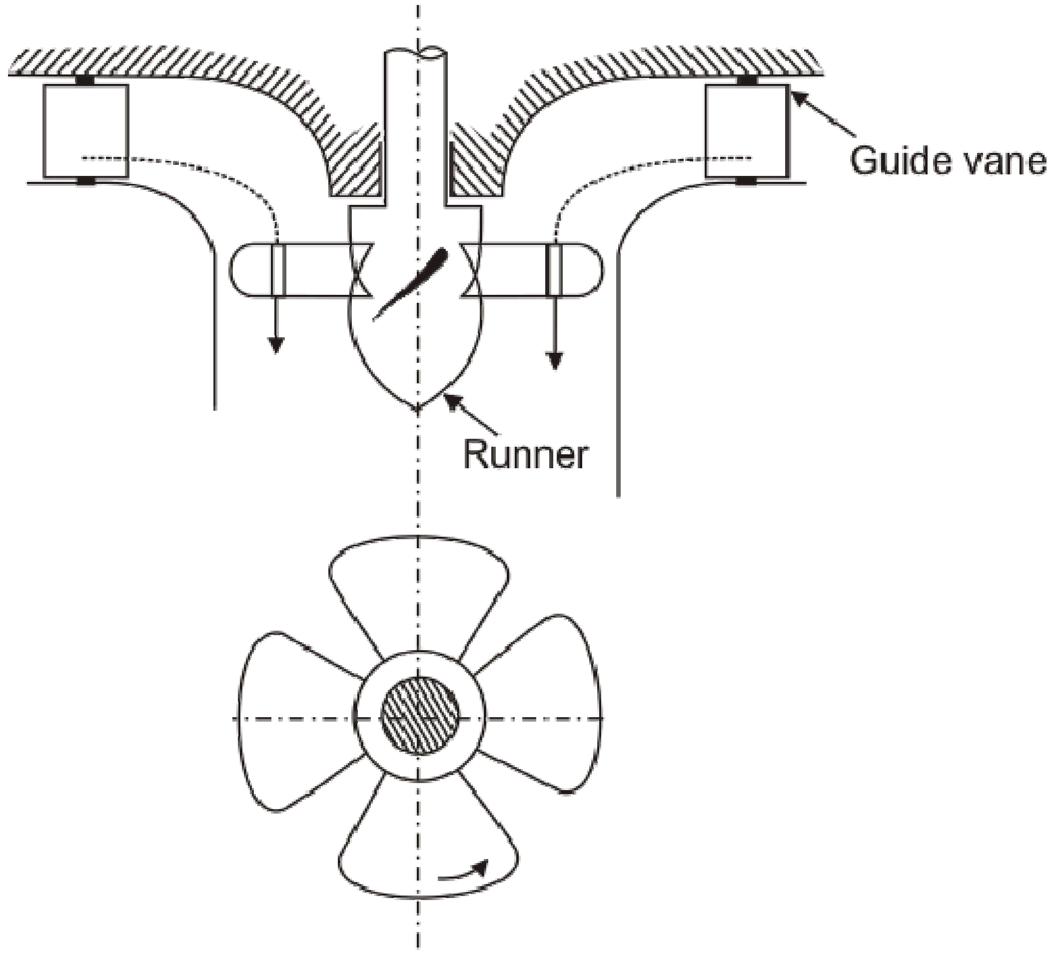


Fig. 30.3 A propeller of Kaplan turbine

Different types of draft tubes incorporated in reaction turbines The draft tube is an integral part of a reaction turbine. Its principle has been explained earlier. The shape of draft tube plays an important role especially for high specific speed turbines, since the efficient recovery of kinetic energy at runner outlet depends mainly on it. Typical draft tubes, employed in practice, are discussed as follows.

Straight divergent tube [Fig. 30.4(a)] The shape of this tube is that of frustum of a cone. It is usually employed for low specific speed, vertical shaft Francis turbine. The cone angle is restricted to 8 0 to avoid the losses due to separation. The tube must discharge sufficiently low under tail water level. The maximum efficiency of this type of draft tube is 90%. This type of draft tube improves speed regulation of falling load.

Simple elbow type (Fig. 30.4b) The vertical length of the draft tube should be made small in order to keep down the cost of excavation, particularly in rock. The exit diameter of draft tube should be as large as possible to recover kinetic energy at runner's outlet. The cone angle of the tube is again fixed from the consideration of losses due to flow separation. Therefore, the draft tube must be bent to keep its definite length. Simple elbow type draft tube will serve such a purpose. Its efficiency is, however, low(about 60%). This type of draft tube turns the water from the vertical to the horizontal direction with a minimum depth of excavation. Sometimes, the transition from a circular section in the vertical portion to a rectangular section in the horizontal part (Fig. 30.4c) is incorporated in the design to have a higher efficiency of the draft tube. The horizontal portion of the draft tube is generally inclined upwards to lead the water gradually to the level of the tail race and to prevent entry of air from the exit end.

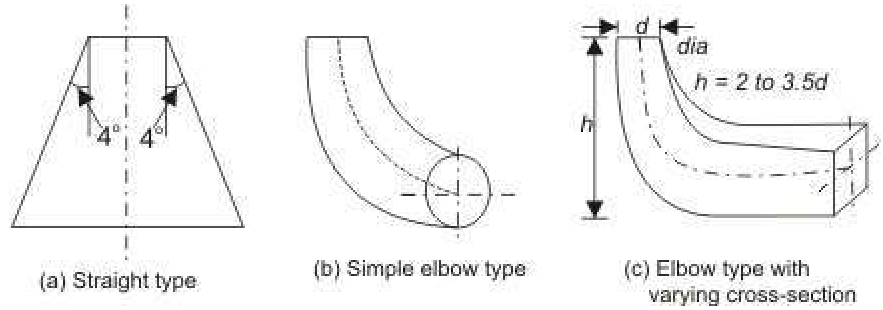


Figure 30.4 Different types of draft tubes

Cavitation in reaction turbines

If the pressure of a liquid in course of its flow becomes equal to its vapour pressure at the existing temperature, then the liquid starts boiling and the pockets of vapour are formed which create vapour locks to the flow and the flow is stopped. The phenomenon is known as cavitation. To avoid cavitation, the minimum pressure in the passage of a liquid flow, should always be more than the vapour pressure of the liquid at the working temperature. In a reaction turbine, the point of minimum pressure is usually at the outlet end of the runner blades, i.e at the inlet to the draft tube. For the flow between such a point and the final discharge into the trail race (where the pressure is atmospheric), the Bernoulli's equation can be written, in consideration of the velocity at the discharge from draft tube to be negligibly small, as

$$\frac{p_e}{p_g}+\frac{V_e^2}{2g}+z=\frac{p_{atm}}{\rho g}+hf \qquad (31.1)$$

where, p_e and V_e represent the static pressure and velocity of the liquid at the outlet of the runner (or at the inlet to the draft tube). The larger the value of V_e, the smaller is the value of p_e and the cavitation is more likely to occur. The term h_f in Eq. (31.1) represents the loss of head due to friction in the draft tube and z is the height of the turbine runner above the tail water surface. For cavitation not to occur $p_e > p_v$ where p_v is the vapour pressure of the liquid at the working temperature.

An important parameter in the context of cavitation is the available suction head (inclusive of both static and dynamic heads) at exit from the turbine and is usually referred to as the net positive suction head 'NPSH' which is defined as

$$NPSH=\frac{p_e}{\rho g}+\frac{V_e^2}{2g}-\frac{p_v}{\rho g} \qquad (31.2)$$

with the help of Eq. (31.1) and in consideration of negligible frictional losses in the draft tube $(hf = 0)$, Eq. (31.2) can be written as

$$NPSH=\frac{p_{atm}}{\rho g}-\frac{p_v}{\rho g}-z \qquad (31.3)$$

A useful design parameter σ known as Thoma's Cavitation Parameter (after the German Engineer Dietrich Thoma, who first introduced the concept) is defined as

$$\sigma = \frac{NPSH}{H} = \frac{(p_{atm}/\rho g) - (p_v/\rho g) - z}{H} \qquad (31.4)$$

For a given machine, operating at its design condition, another useful parameter σ_c, known as critical cavitaion parameter is define as

$$\sigma_c = \frac{(p_{atm}/\rho g) - (p_e/\rho g) - z}{H} \qquad (31.5)$$

Therefore, for cavitaion not to occur $\sigma > \sigma_c$ (since, $p_e > p_v$).

If either z or H is increased, σ is reduced. To determine whether cavitation is likely to occur in a particular installation, the value σ of may be calculated. When the value of σ is greater than the value of σ_c for a particular design of turbine cavitation is not expected to occur.

In practice, the value of σ_c is used to determine the maximum elevation of the turbine above tail water surface for cavitation to be avoided. The parameter of increases with an increase in the specific speed of the turbine. Hence, turbines having higher specific speed must be installed closer to the tail water level.

Performance Characteristics of Reaction Turbine

It is not always possible in practice, although desirable, to run a machine at its maximum efficiency due to changes in operating parameters. Therefore, it becomes important to know the performance of the machine under conditions for which the efficiency is less than the maximum. It is more useful to plot the basic dimensionless performance parameters (Fig. 31.1) as derived earlier from the similarity principles of fluid machines. Thus one set of curves, as shown in Fig. 31.1, is applicable not just to the conditions of the test, but to any machine in the same homologous series under any altered conditions.

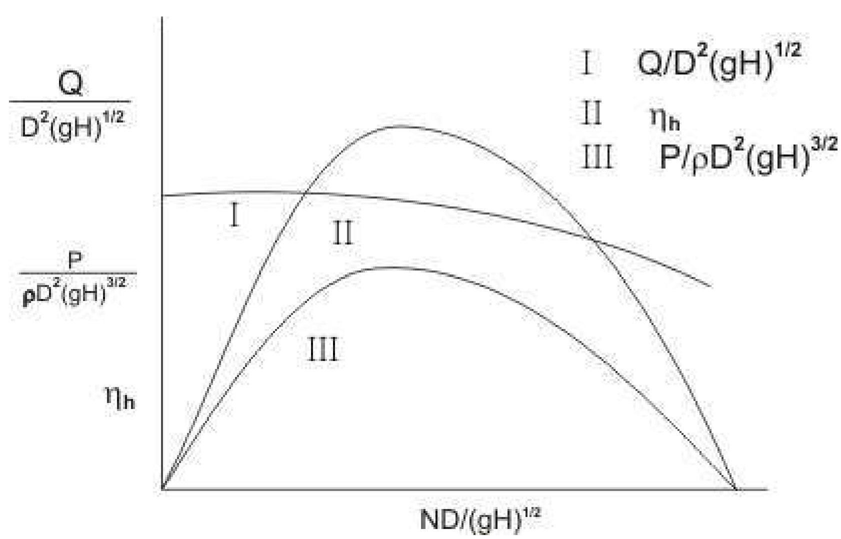


Figure 31.1 performance characteristics of a reaction turbine (in dimensionless parameters)

Figure 31.2 is one of the typical plots where variation in efficiency of different reaction turbines with the rated power is shown.

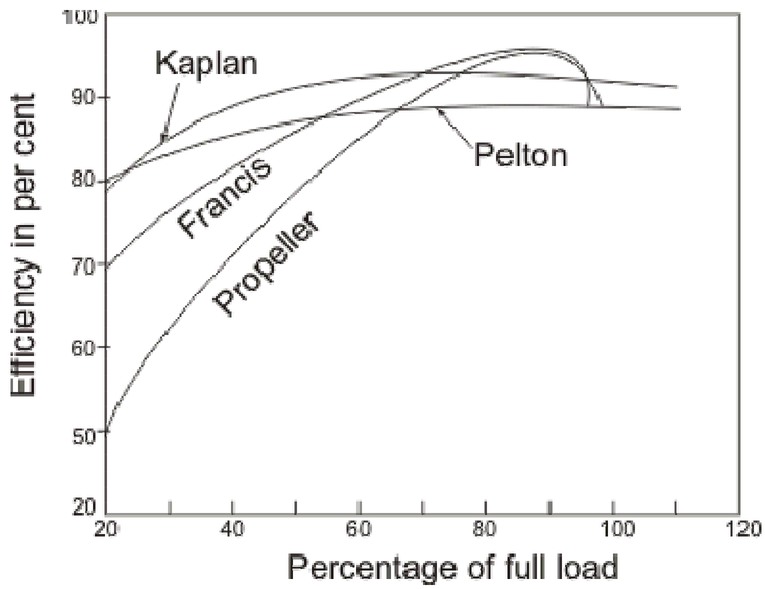


Figure 31.2 Variation of efficiency with load

Draft Tube:

Reaction turbines must be completely enclosed because a pressure difference exists between the working fluid (water) in the turbine and atmosphere. Therefore, it is necessary to connect the turbine outlet by means of a pipe known as draft tube upto tailrace level.

Types of Draft Tubes

(1) Conical Draft Tube.

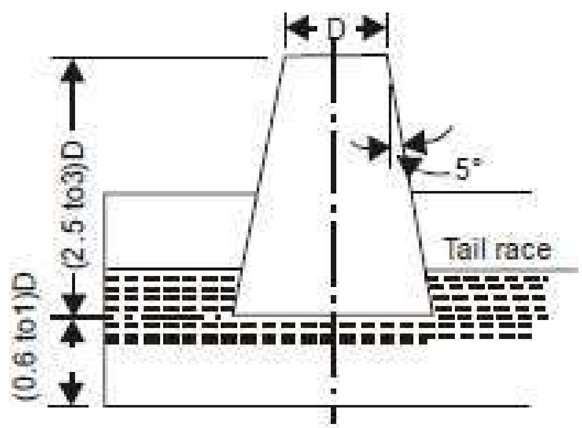
This is known as tapered draft tube and used in all reaction turbines where conditions permit. It is preferred for low specific speed and vertical shaft Francis turbine. The maximum cone angle of this draft tube is limited to 8° (a = 4°). The hydraulic efficiency of such type of draft tube is 90%.

Elbow Type Draft Tube.

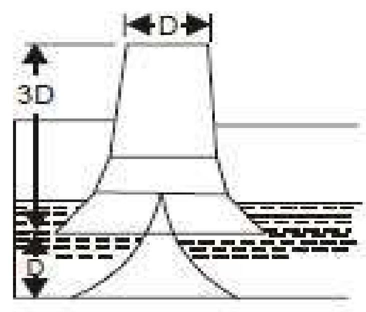
The elbow type draft tube is often preferred in most of the power plants, where the setting of vertical draft tube does not permit enough room without excessive cost of excavation.

Moody Draft Tube.

This draft tube has an advantage that its conical portion at the center reduces the whirl action of water moving with high velocity centre reduces.



(*a*) Conical draft tube



(*f*) Moody draft tube with law cone

UNIT II **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 aluminium and copper are used as conductors. The main advantages of aluminium conductors over copper conductors are:

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

The main problems with aluminium conductors are:

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

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 aluminium conductors are used which are classified as:

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

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

- Steel cored aluminium 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 unfavourable 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 subconductors 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 subconductors 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

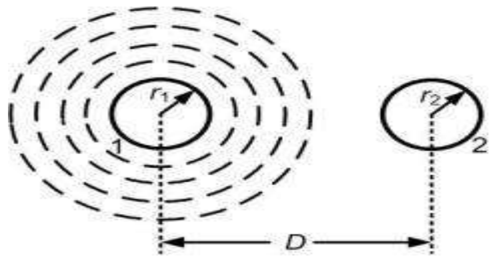


Fig. 1 A single-phase line with two conductors.

$$D + r_1 \approx D \text{ and } D - r_1 \approx D$$

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

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

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

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

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

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

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

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

Therefore the inductance of the complete circuit is

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

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

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

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

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

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.

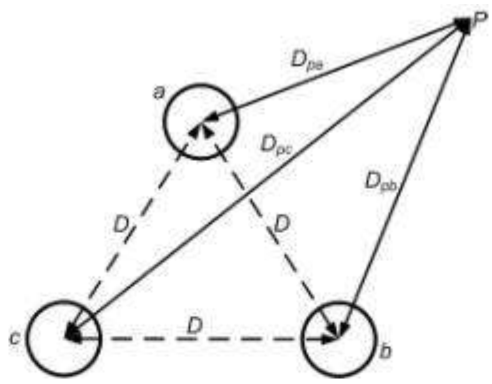


Fig.2 Three-phase symmetrically spaced conductors and an external point P.

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

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

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

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

Similarly the flux due to the current I_c is

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

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

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

We know

$$I_b + I_c = -I_a$$

Substituting the above expression in (5) we get

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

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

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

Hence the inductance of phase-a is given as

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

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

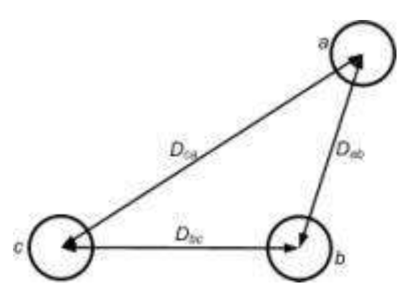


Fig. 3 Three-phase asymmetrically spaced line.

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

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

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

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 **Fig.3.**

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.

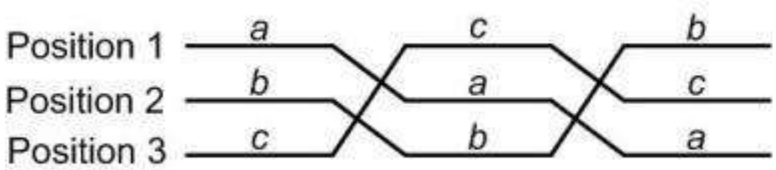


Fig. 4A segment of a transposed line**.**

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

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

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

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

The above equation can be simplified as

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

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

$$V_{12} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D}{r_1} - \frac{q}{2\pi\varepsilon_0}\ln\frac{r_2}{D} = \frac{q}{2\pi\varepsilon_0}\ln\frac{D^2}{r_1 r_2} \text{ V} \qquad (4)$$

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

$$V_{12} = \frac{q}{\pi\varepsilon_0}\ln\frac{D}{r} \text{ V} \qquad (5)$$

The capacitance between the conductors is given by

$$C_{12} = \frac{\pi\varepsilon_0}{\ln(D/r)} \text{ F/m} \qquad (6)$$

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. This is shown in Fig. 1.13.

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

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

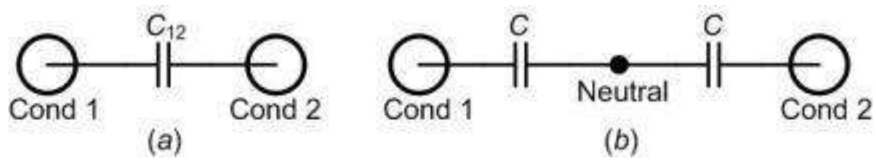


Fig.5 (a) Capacitance between two conductors and (b) equivalent capacitance to ground.

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

$$q_a + q_b + q_c = 0 \tag{1}$$

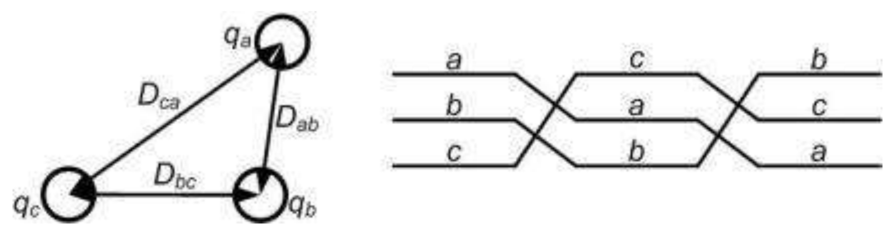


Fig. 6 Charge on a three-phase transposed line.

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

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

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

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

Then the average value of the voltage is

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

This implies

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

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

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

EFFECT OF EARTH ON CAPACITANCE

In calculatingthe capacitanceof transrnissionlines,the presenceof earth wasignored, so far. The effect of earth on capacitance can be conveniently takeninto account by the method of images.

METHOD OF IMAGES

- The electric field of transmissionline conductorsmust conform to the presenceof 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 thezero potential plane, the electric field remains undisturbed.
- Further, if theconductor carrying charge -q is now removed, the electric field above theconducting sheet stays intact, while that below it vanishes.
- Using these well-known resultsin reverse,we may equivalentlyreplacethe presenceof groundbelow a charged conductor by a fictitious conductor having equal and oppositecharge and located as far below the surface of ground as the overhead conductorabove it-such a fictitious conductor is the mirror image of the overheadconductor.
- This method of creating the same electric field as in the presence ofearth is known as the method of images originally suggestedby Lord Kelvin.

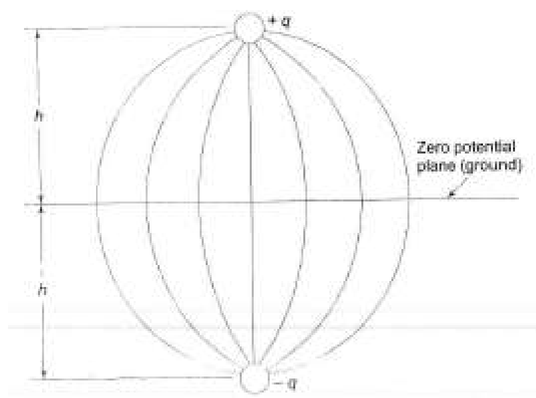
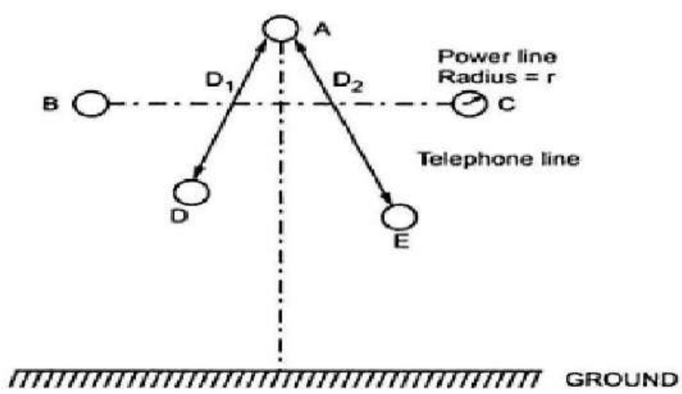


Fig. 7 Electric field of two long, parallel, oppositely charged conductors

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,

$$M = M_A + M_B + M_C$$

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

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.

[I] CORONA:

- It is defined as a self-sustained electric discharge in which the fieldintensified ionization is localized only over a portion of distancebetween electrodes.
- Corona is the phenomenon of violet glow, hissing noise andproduction of ozone gas in an overhead transmission line.

[II] EFFECTS:
- Corona is affected by atmospheric conditions, conductor size, spacingbetween conductors and line voltage.
- Due to Corona, the transmission line efficiency of the line is reduced.
-Corona produces ozone and may cause corrosion of the conductor.

[III]VARIOUS FACTORS AFFECTING THE CORONA LOSS

The various factors affecting Corona and Corona loss are,
- Electrical Factors
- Line Voltage
- Atmospheric Conditions
- Size of the conductor
- Surface conditions
- Number of conductors per phase
- Spacing between conductors
- Shape of Conductor
-Clearance from ground
- Effect of load current

[IV]DISRUPTIVE CRITICAL VOLTAGE:

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

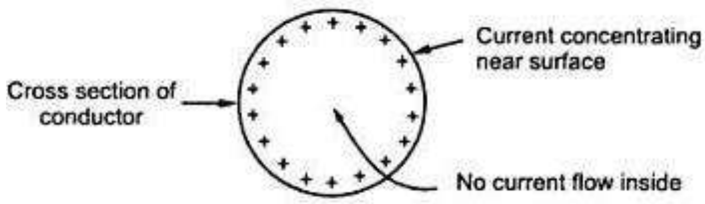
[V] VISUAL CRITICAL VOLTAGE:

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

[V] CORONA POWER LOSS:
- The energy required to keep the ions moving is derived from the supplysystem. This additional power required which is dissipated in the formof heat, sound and light in case of corona, is called corona loss.

The following are the methods used for reducing corona loss.
i] Large diameter conductor.
ii] Using hollow and bundled conductors.
Iii] Increasing the conductor spacing.

SKIN EFFECTS:
- A conductor carries a steady d.c. current. This current is uniformlydistributed over the whole cross-section of the conductor.
- The current distribution is non – uniform if conductor carriesalternating current.
- The current density is higher at the surface than at the surface than at itscentre
- This behavior of alternating current to concentrate near the surface ofthe conductor is known as skin effect.



The skin effect depends on following factors; a] Nature of material b]Diameter of wire c] frequency of supply d] Shape of wire.

PROXIMITY EFFECT:
- The current distribution may be non-uniform because of anothereffect 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 sectionshaving equal Cross-sectional area. These parallel loops are formed bythe pairs xx’, yy’ and zz’ .
- The inductance of inter loop is less. Thus, the current density is highestat inner edges of the conductor.
- Due to this non uniform distribution ofcurrent, the effective conductor resistance increases.
- The proximity effect also depends on the same factors as that of skineffect.

PROBLEMS

1. A three phase, 50Hz, 132KV overhead line has conductors placed in a horizontal plane 4m apart. Conductor diameter is 2cm. If the line length is 100km, calculate the charging current per phase assuming complete transposition.

GIVEN

r = 1cm, d1 = 4m, d2 = 4m, d3 = 8m

SOLUTION

Capacitance/ phase, C= $\frac{2\,\pi\varepsilon_\circ}{log_e{}^{d}/_{r}}$

where d = 3 $\sqrt{d1\ d2\ d3}$

= 3 $\sqrt{4*4*8}$ = 5.04m

Capacitance/ phase, C $= \dfrac{2 * \pi * 8.854 * 10^{-12}}{log \frac{5.04}{1 * 10^{-2}}}$ F/m

Capacitance/phase/km = $0.00885 * 10^{-6}$ F/km

Capacitance for 100km line, C = $0.00885 * 10^{-6} * 100$

$= 0.885 * 10^{-6}$ F

Charging current/ phase, $I_c = \frac{V_{ph}}{X_c} = V_{ph} * 2 \Pi f C$

$= \frac{132 * 10^3}{\sqrt{3}} * 2 * \Pi * 50 * 0.885 * 10^{-6} = 21.18$ A

2. Calculate the loop inductance per km of a single phase line comprising of 2 parallel comductors 1m apart and 1cm in diameter, when the material of conductor is (i) copper (ii) steel of relative permeability 50.

GIVEN

d = 1m = 100cm, r = 0.5cm

SOLUTION

(i) With copper conductor $\mu_r = 1$

Loop inductance/ m = $10^{-7} [\mu_r + 4 \log\frac{d}{r}]$ H

Loop inductance/ m = $10^{-7} [1 + 4 \log\frac{100}{0.5}]$ H

$= 22.19 * 10^{-7}$ H

Loop inductance/ km = $22.19 * 10^{-7} * 1000$

$= 2.219 * 10^{-3}$ H

(ii) with steel conductor $\mu_r = 50$

Loop inductance/ m = $10^{-7} [\mu_r + 4 \log\frac{d}{r}]$ H

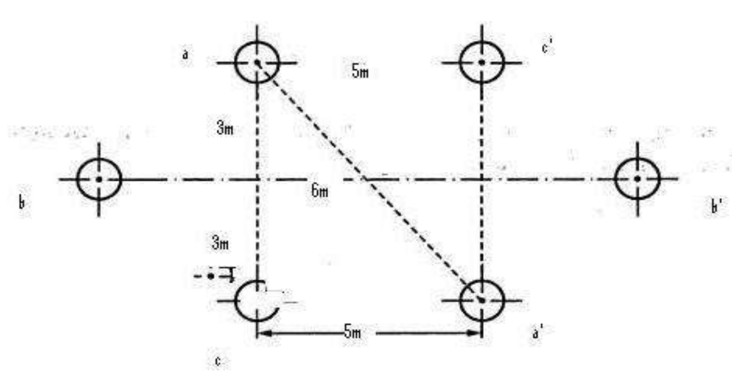
Loop inductance/ m = $10^{-7} [50 + 4 \log\frac{100}{0.5}]$ H

$= 71.19 * 10^{-7}$ H

Loop inductance/ km = $71.19 * 10^{-7} * 1000$

= 7.119mH

3. Find the inductance per phase per km of double circuit 3 phase line shownin figure . The line is completely transposed and operates at a frequency of50HZ, r = 6mm.



SOLUTION

GMR = 0.7788r

= 0.7788 * 0.6 = 0.467cm

Equivalent self GMD of one phase

Ds = 3√DS1 x DS2 x DS3

$D_{s1} = 4\sqrt{D_{aa} * D_{aa'} * D_{a'a} * D_{a'a'}}$

Distance a to b = $\sqrt{(0.5)^2 + (3)^2} = 3.04m$

Distance a to b' = $\sqrt{(5.5)^2 + (3)^2} = 6.26m$

Distance a to a' = $\sqrt{(6)^2 + (5)^2} = 7.81m$

$D_{s1} = 4\sqrt{D_{aa} * D_{aa'} * D_{a'a} * D_{a'a'}}$

$= 4\sqrt{(0.467 * 10^{-2}) * (7.81) * (7.81) * (0.467 * 10^{-2})}$

$= 0.19m = D_{s3}$

$D_{s2} = 4\sqrt{D_{bb} * D_{bb'} * D_{b'b} * D_{b'b'}}$

$= 4\sqrt{(0.467 * 10^{-2}) * (6) * (6) * (0.467 * 10^{-2})}$

= 0.17m

$D_s = 3\sqrt{0.19 * 0.17 * 0.19}$

= 0.18m

Mutual GMD,=Dm = 3√DAB x DBC x DCA

$D_{AB} = 4\sqrt{D_{ab} * D_{ab'} * D_{a'b} * D_{a'b'}}$

$= 4\sqrt{3.04 * 6.26 * 6.26 * 3.04}$

$= 4.36m = D_{BC'}$

$D_{CA} = 4\sqrt{D_{ca} * D_{ca'} * D_{c'a} * D_{c'a'}}$

$= 4\sqrt{6 * 5 * 5 * 6}$

= 5.48m

Dm = 3√DAB x DBC x DCA

$= 3\sqrt{4.36 * 4.36 * 5.48}$

= 4.7m

Inductance / phase/m = 10^{-7}x 2 loge [Dm/Ds]

= 10^{-7}x 2 loge [4.7/0.18]

= $6.52 * 10^{-7}$ H

= $0.652 * 10^{-3}$mH

Inductance / phase/m = $0.652 * 10^{-3} * 1000$

= 0.652mH

4. Estimate the corona loss for a three-phase, 110KV, 50Hz, 150km long transmission line consisting of three conductors each of 10mm diameter and spaced 2.5m apart in a equilateral triangle formation. The temperature of air is 30^0 C and the atmospheric pressure is 750mm of mercury. Assume the irregularity factor as 0.85. Ionization of air may be assumed to take place at a maximum voltage gradient of 30KV/cm.

GIVEN
Diameter = 10mm
r = 1/2 = 0.5cm
spacing d = 2.5m = 250cm
temperature t = 30^0 C
pressure b = 750mm = 75cm
voltage V = 110KV
V/ph = 110/√3 = 63.51KV
f = 50Hz

SOLUTION
Critical Disruptive Voltage $V_C = m_0\ g_0\ \delta\ r\ \log_e d/r$ KV
Dielectric strength of air $g_0 = 30/\sqrt{2} = 21.2$ KV per cm

$$\delta = \frac{3.92\,b}{273+t} = \frac{3.92*75}{273+30} = 0.97$$

$$V_C = 0.85 * 21.2 * 0.97 * 0.5 \log_e \frac{250}{0.5}$$

$= 54.31$ KV

$$\text{Corona loss} = \frac{242.2}{\delta}(f + 25)\sqrt{\frac{r}{d}}(V - V_c)^2 * 10^{-5}\ \text{KW/km/ph}$$

$$= \frac{242.2}{0.97}(50 + 25)\sqrt{\frac{0.5}{250}}(63.51 - 54.31)^2 * 10^{-5}$$

$= 0.709$ KW/km/ph

UNIT III MODELLING AND PERFORMANCE OF TRANSMISSION LINES

Classification of lines - short line, medium line and long line - equivalent circuits, phasor diagram,attenuation constant, phase constant, surge impedance; transmission efficiency and voltageregulation, real and reactive power flow in lines, Power - circle diagrams, surge impedance loading,methods of voltage control; Ferranti effect.

Classification of Overhead Transmission Lines

- A transmisson 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 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 upto about50km and the line voltage is comparatively low (<20kV) 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 Line:

- When the length of an overhead transmission line is about 50-150km and the line voltage is moderately high (>20kV < 100kV) 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 conductors shunted across the line at one or more points.

(iii) Long Transmission Lines:

- When the length of an overhead transmission line is more than 150km and line voltage is very high (>100kV) it is considered as 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.

Voltage Regulation:

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

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

Mathematically,

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

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

(*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 i.e.*

$$\% \text{ age Transmission efficiency, } \eta_T = \frac{\text{Receiving end power}}{\text{Sending end power}} \times 100$$

$$= \frac{V_R I_R \cos\phi_R}{V_S I_S \cos\phi_S} \times 100$$

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

Performance of Single Phase Short Transmission Lines

- 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.10.1 (i).
- Here the total resistance and inductance are shoen as concentrared or lumped instead of being distributed. The circuit is a simple ac series circuit.

Let
I = load current
R = loop resistance *i.e.*, resistance of both conductors
X_L = loop reactance
V_R = receiving end voltage
$\cos\phi_R$ = receiving end power factor (lagging)
V_S = sending end voltage
$\cos\phi_S$ = sending end power factor

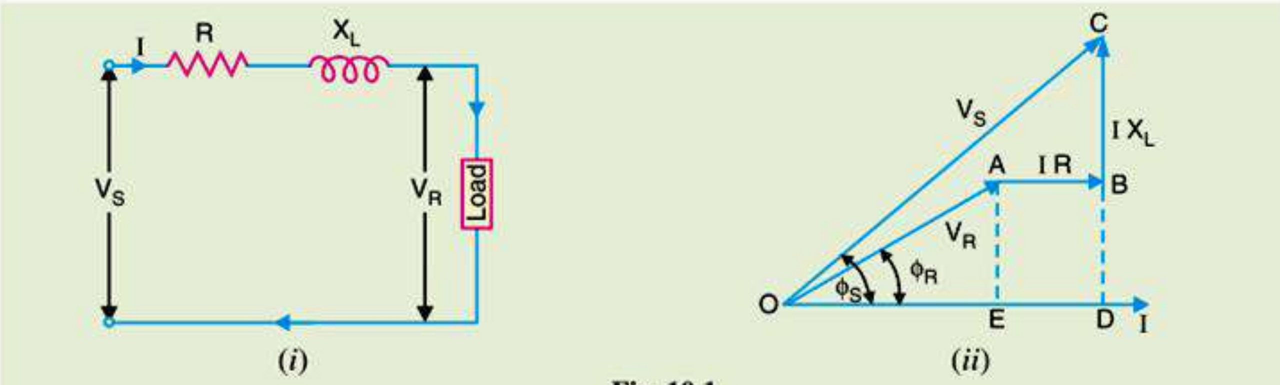


Fig. 10.1

The *phasor diagram of the line for lagging load power factor is shown in Fig. 10.1 (*ii*). From the right angled traingle *ODC*, we get,

Phasor diagram. Current *I* is taken as the reference phasor. *OA* represents the receiving end voltage V_R leading *I* by ϕ_R. *AB* represents the drop *IR* in phase with *I*. *BC* represents the inductive drop IX_L and leads *I* by 90°. *OC* represents the sending end voltage V_s and leads *I* by ϕ_S.

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

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

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

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

Line losses $= I^2 R$

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

%age Transmission efficiency $= \dfrac{\text{Power delivered}}{\text{Power sent out}} \times 100$

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

An approximate expression for the sending end voltage V_S can be obtained as follows. Draw perpendicular from B and C on OA produced as shown in Fig. 10.2. Then OC is *nearly* equal to OF *i.e.*,

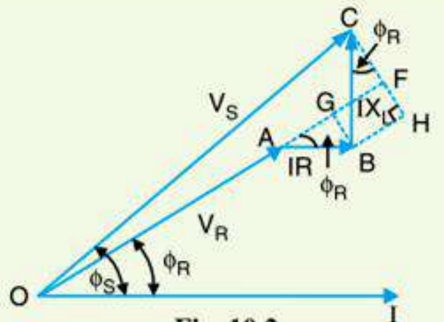


Fig. 10.2

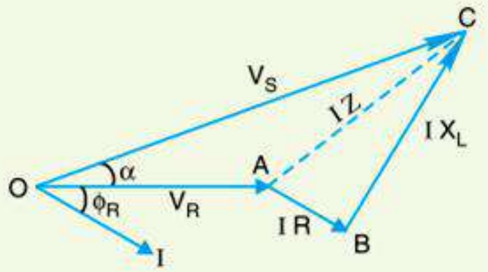


Fig. 10.3

$$OC = OF = OA + AF = OA + AG + GF$$
$$= OA + AG + BH$$
$$\therefore \quad V_S = V_R + I\,R \cos \phi_R + I\,X_L \sin \phi_R$$

Solution in complex notation. It is often convenient and profitable to make the line calculations in complex notation.

Taking $\vec{V_R}$ as the reference phasor, draw the phasor diagram as shown in Fig 10.3. It is clear that $\vec{V_S}$ is the phasor sum of $\vec{V_R}$ and $\vec{I}\,Z$.

$$^*\vec{V_R} = V_R + j\,0$$
$$\vec{I} = \vec{I} \angle -\phi_R = I\,(\cos \phi_R - j \sin \phi_R)$$
$$\vec{Z} = R + jX_L$$
$$\therefore \quad \vec{V_S} = \vec{V_R} + \vec{I}\,\vec{Z}$$
$$= (V_R + j\,0) + I\,(\cos \phi_R - j \sin \phi_R)\,(R + j\,X_L)$$

* Phasors are shown by arrows and their magnitudes without arrow. Thus $\vec{V_R}$ is the receiving end voltage phasor, whereas V_R is its magnitude.

$$= (V_R + I R \cos\phi_R + I X_L \sin\phi_R) + j\,(I X_L \cos\phi_R - I R \sin\phi_R)$$

$$\therefore \qquad V_S = \sqrt{(V_R + I R \cos\phi_R + I X_L \sin\phi_R)^2 + (I X_L \cos\phi_R - I R \sin\phi_R)^2}$$

The second term under the root is quite small and can be neglected with reasonable accuracy. Therefore, approximate expression for V_S becomes :

$$V_S = V_R + I R \cos\phi_R + I X_L \sin\phi_R$$

The following poins may be noted :

(i) The approximate formula for V_S $(= V_R + I R \cos\phi_R + I X_L \sin\phi_R)$ gives fairly correct results for lagging power factors. However, appreciable error is caused for leading power factors. Therefore, approximate expression for V_S should be used for lagging p.f. only.

(ii) The solution in complex notation is in more presentable form.

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 (<20kV).
- However, as the length and voltage of the line increase4, the capacitance gradually becomes of greater importance.
- Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20kV, 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.
- The most commonly used methods (known as localized capacitance methods) for the solution of medium transmission 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.

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. 10.8. This method of localising the line capacitance at the load end overestimates the effects of capacitance. In Fig. 10.8, 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

$\cos\phi_R$ = receiving end power factor (*lagging*)

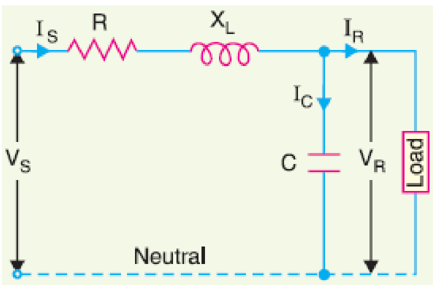


Fig. 10.8

V_S = sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig 10.9.

Taking the receiving end voltage $\vec{V_R}$ as the reference phasor,

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

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

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

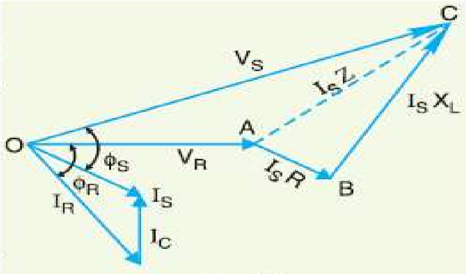


Fig. 10.9

The sending end current $\vec{I_S}$ is the phasor sum of load current $\vec{I_R}$ and capacitive current $\vec{I_C}$ i.e.,

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

Voltage drop/phase $= \vec{I_S}\,\vec{Z} = \vec{I_S}\,(R + jX_L)$

Sending end voltage, $\vec{V_S} = \vec{V_R} + \vec{I_S}\,\vec{Z} = \vec{V_R} + \vec{I_S}\,(R + j\,X_L)$

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.

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 resistance and reactance are lumped on its either side as shown in Fig.10.11.
- Therefore, in this arrangement, full charging current flows over half the line.
- In Fig.10.11, one phase of 3-phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.

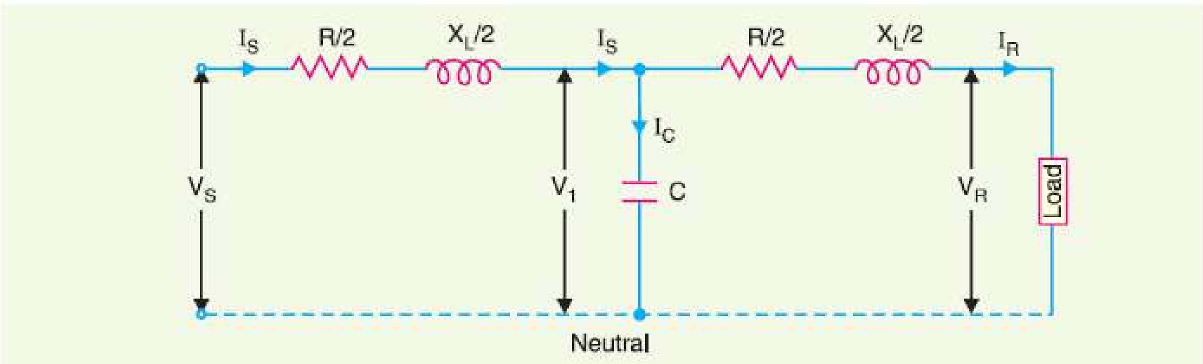


Fig. 10.11

Let $\quad I_R$ = load current per phase ; $\quad R$ = resistance per phase

X_L = inductive reactance per phase ; $\quad C$ = capacitance per phase

$\cos \phi_R$ = receiving end power factor (*lagging*) ; $\quad V_S$ = sending end voltage/phase

V_1 = voltage across capacitor C

The *phasor diagram for the circuit is shown in Fig. 10.12. Taking the receiving end voltage $\vec{V_R}$ as the reference phasor, we have,

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

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

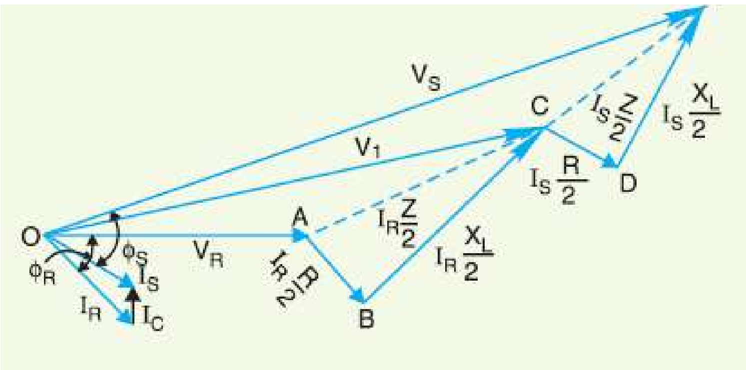


Fig. 10.12

Note the construction of phasor diagram. $\vec{V_R}$ is taken as the reference phasor represented by OA. The load current $\vec{I_R}$ lags behind $\vec{V_R}$ by ϕ_R. The drop $AB = I_R R/2$ is in phase with $\vec{I_R}$ and $BC = I_R X_L/2$ leads $\vec{I_R}$ by 90°. The phasor OC represents the voltage $\vec{V_1}$ across condenser C. The capacitor current $\vec{I_C}$ leads $\vec{V_1}$ by 90° as shown. The phasor sum of $\vec{I_R}$ and $\vec{I_C}$ gives $\vec{I_S}$. Now $CD = I_S R/2$ is in phase with $\vec{I_S}$ while $DE = I_S X_L/2$ leads $\vec{I_S}$ by 90°. Then, OE represents the sending end voltage $\vec{V_S}$.

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

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

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

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

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

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. 10.16. 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.

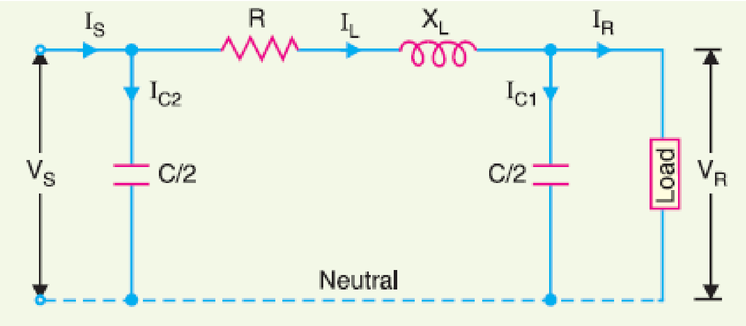


Fig. 10.16

Let I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

$\cos \phi_R$ = receiving end power factor (*lagging*)

V_S = sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig. 10.17. Taking the receiving end voltage as the reference phasor, we have,

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

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

Charging current at load end is

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

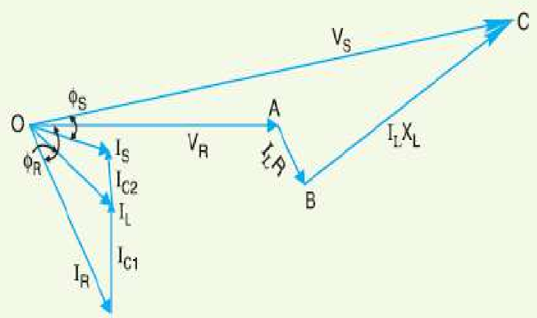


Fig. 10.17

Note the construction of phasor diagram. $\overrightarrow{V_R}$ is taken as the reference phasor represented by OA. The current $\overrightarrow{I_R}$ lags behind $\overrightarrow{V_R}$ by ϕ_R. The charging current $\overrightarrow{I_{C1}}$ leads $\overrightarrow{V_R}$ by 90°. The line current $\overrightarrow{I_L}$ is the phasor sum of $\overrightarrow{I_R}$ and $\overrightarrow{I_{C1}}$. The drop $AB = I_L R$ is in phase with $\overrightarrow{I_L}$ whereas drop $BC = I_L X_L$ leads $\overrightarrow{I_L}$ by 90°. Then OC represents the sending end voltage $\overrightarrow{V_S}$. The charging current $\overrightarrow{I_{C2}}$ leads $\overrightarrow{V_S}$ by 90°. Therefore, sending end current $\overrightarrow{I_S}$ is the phasor sum of the $\overrightarrow{I_{C2}}$ and $\overrightarrow{I_L}$. The angle ϕ_S between sending end voltage V_S and sending end current I_S determines the sending end p.f. $\cos \phi_S$.

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

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

Charging current at the sending end is

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

$\therefore$ Sending end current, $\vec{I_S} = \vec{I_L} + \vec{I_{C2}}$

Long Transmission Lines

- The 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 150km), it is found that serious errors are introduced in the performance of 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.

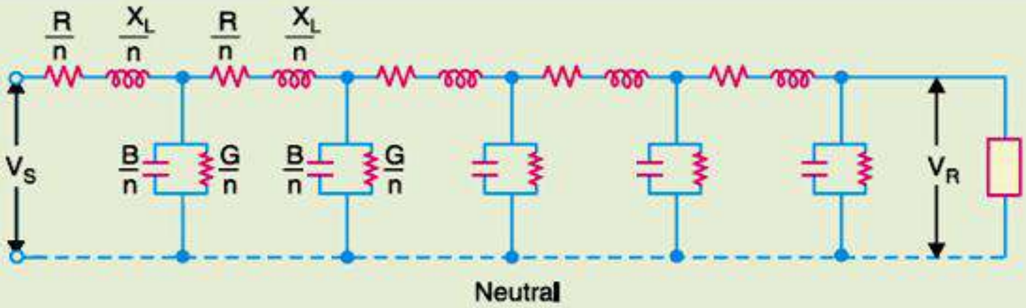


Fig. 10.21

Fig. 10.21 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 $\frac{1}{n}th$ 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.

(*iii*) The leakage susceptance (B) and leakage conductance (G) are shunt elements. 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 insulators or due to corona effect between conductors. Admittance = $\sqrt{G^2 + B^2}$.

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

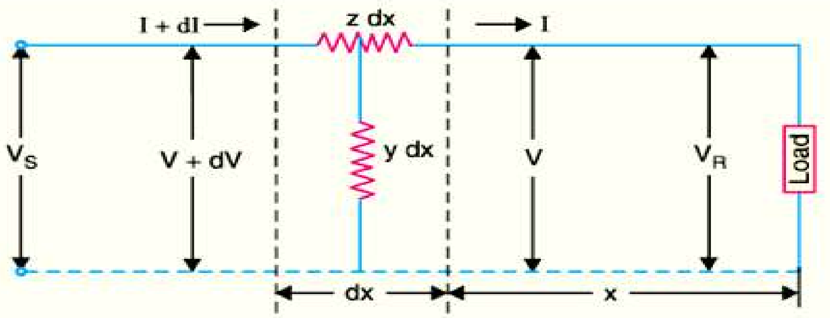


Fig. 10.22

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, $dV = I\,z\,dx$

or
$$\frac{dV}{dx} = I\,z \qquad ...(i)$$

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 $= V\,y\,dx$

or
$$\frac{dI}{dx} = V\,y \qquad ...(ii)$$

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

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

or
$$\frac{d^2V}{dx^2} = y\,z\,V \qquad ...(iii)$$

The solution of this differential equation is

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

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

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

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

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.

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

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

PROBLEMS:

Example 10.1. *A single phase overhead transmission line delivers 1100 kW at 33 kV at 0·8 p.f. lagging. The total resistance and inductive reactance of the line are 10 Ω and 15 Ω respectively. Determine : (i) sending end voltage (ii) sending end power factor and (iii) transmission efficiency.*

Solution.

Load power factor, $\cos \phi_R = 0{\cdot}8$ lagging

Total line impedance, $\vec{Z} = R + j\,X_L = 10 + j\,15$

Receiving end voltage, $V_R = 33$ kV $= 33{,}000$ V

$$\therefore \quad \text{Line current, } I = \frac{kW \times 10^3}{V_R \cos \phi_R} = \frac{1100 \times 10^3}{33{,}000 \times 0{\cdot}8} = 41{\cdot}67 \text{ A}$$

$$\text{As } \cos \phi_R = 0{\cdot}8 \quad \therefore \quad \sin \phi_R = 0{\cdot}6$$

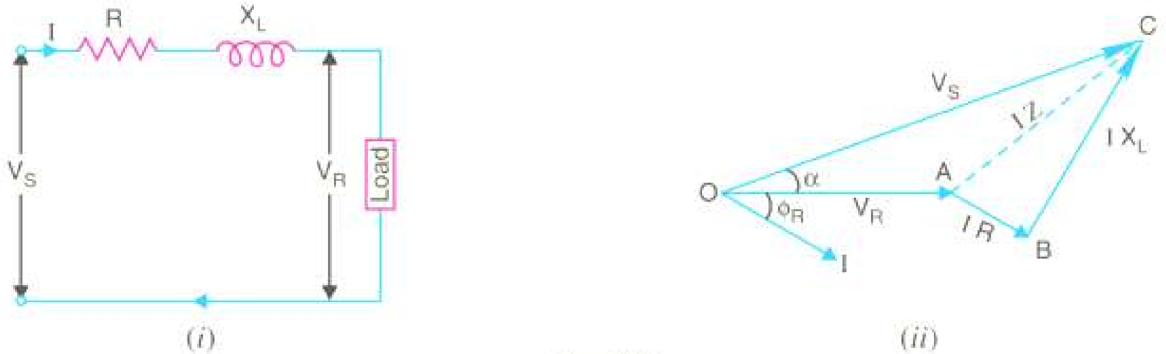


Fig. 10.5

The equivalent circuit and phasor diagram of the line are shown in Figs. 10.5 (*i*) and 10.5 (*ii*) respectively. Taking receiving end voltage $\vec{V_R}$ as the reference phasor,

$$\vec{V_R} = V_R + j\,0 = 33000 \text{ V}$$

$$\vec{I} = I(\cos \phi_R - j \sin \phi_R)$$

$$= 41{\cdot}67\,(0{\cdot}8 - j\,0{\cdot}6) = 33{\cdot}33 - j\,25$$

(*i*) Sending end voltage, $\vec{V_S} = \vec{V_R} + \vec{I}\,Z$

$$= 33{,}000 + (33{\cdot}33 - j\,25{\cdot}0)\,(10 + j\,15)$$

$$= 33{,}000 + 333{\cdot}3 - j250 + j500 + 375$$

$$= 33{,}708{\cdot}3 + j\,250$$

$$\therefore \quad \text{Magnitude of } V_S = \sqrt{(33{,}708 \cdot 3)^2 + (250)^2} = \mathbf{33{,}709\ V}$$

(*ii*) Angle between $\vec{V_S}$ and $\vec{V_R}$ is

$$\alpha = \tan^{-1} \frac{250}{33{,}708 \cdot 3} = \tan^{-1} 0{\cdot}0074 = 0{\cdot}42^\circ$$

∴ Sending end power factor angle is

$$\phi_S = \phi_R + \alpha = 36{\cdot}87^\circ + 0{\cdot}42^\circ = 37{\cdot}29^\circ$$

(*iii*) Line losses $= I^2R = (41{\cdot}67)^2 \times 10 = 17{,}364 \text{ W} = 17{\cdot}364 \text{ kW}$

Output delivered $= 1100$ kW

Power sent $= 1100 + 17{\cdot}364 = 1117{\cdot}364$ kW

$$\therefore \quad \text{Transmission efficiency} = \frac{\text{Power delivered}}{\text{Power sent}} \times 100 = \frac{1100}{1117 \cdot 364} \times 100 = \mathbf{98{\cdot}44\%}$$

Example 10.2. *What is the maximum length in km for a 1-phase transmission line having copper conductor of 0·775 cm^2 cross-section over which 200 kW at unity power factor and at 3300V are to be delivered ? The efficiecny of transmission is 90%. Take specific resistance as 1.725 μ Ω cm.*

Solution.

$$\text{Receiving end power} = 200 \text{ kW} = 2{,}00{,}000 \text{ W}$$

$$\text{Transmission efficiency} = 0{\cdot}9$$

$$\therefore \quad \text{Sending end power} = \frac{2{,}00{,}000}{0\cdot 9} = 2{,}22{,}222 \text{ W}$$

$$\therefore \quad \text{Line losses} = 2{,}22{,}222 - 2{,}00{,}000 = 22{,}222 \text{ W}$$

$$\text{Line current, } I = \frac{200 \times 10^3}{3{,}300 \times 1} = 60{\cdot}6 \text{ A}$$

Let R Ω be the resistance of one conductor.

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

or

$$22{,}222 = 2\,(60{\cdot}6)^2 \times R$$

$$\therefore \quad R = \frac{22{,}222}{2 \times (60\cdot 6)^2} = 3{\cdot}025 \ \Omega$$

Now,

$$R = \rho\, l/a$$

$$\therefore \quad l = \frac{Ra}{\rho} = \frac{3\cdot 025 \times 0\ 775}{1\cdot 725 \times 10^{-6}} = 1{\cdot}36 \times 10^6 \text{ cm} = \mathbf{13{\cdot}6\ km}$$

Example 10.3. *An overhead 3-phase transmission line delivers 5000 kW at 22 kV at 0·8 p.f. lagging. The resistance and reactance of each conductor is 4 Ω and 6 Ω respectively. Determine : (i) sending end voltage (ii) percentage regulation (iii) transmission efficiency.*

Solution.

$$\text{Load power factor, } \cos\phi_R = 0{\cdot}8 \text{ lagging}$$

$$\text{Receiving end voltage/phase, }^* V_R = 22{,}000/\sqrt{3} = 12{,}700 \text{ V}$$

$$\text{Impedance/phase, } \quad \vec{Z} = 4 + j\,6$$

$$\text{Line current, } \quad I = \frac{5000 \times 10^3}{3 \times 12700 \times 0\cdot 8} = 164 \text{ A}$$

As $\cos\phi_R = 0{\cdot}8 \quad \therefore \sin\phi_R = 0{\cdot}6$

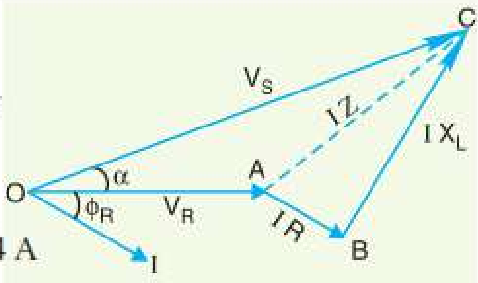


Fig. 10.6

Taking $\vec{V_R}$ as the reference phasor (see Fig. 10.6),

$$\vec{V_R} = V_R + j\,0 = 12700 \text{ V}$$

$$\vec{I} = I\,(\cos\phi_R - j\sin\phi_R) = 164\,(0{\cdot}8 - j\,0{\cdot}6) = 131{\cdot}2 - j\,98{\cdot}4$$

(*i*) Sending end voltage per phase is

$$\vec{V_S} = \vec{V_R} + \vec{I}\,Z = 12700 + (131{\cdot}2 - j\,98{\cdot}4)\,(4 + j\,6)$$

$$= 12700 + 524{\cdot}8 + j\,787{\cdot}2 - j\,393{\cdot}6 + 590{\cdot}4$$

$$= 13815{\cdot}2 + j\,393{\cdot}6$$

$$\text{Magnitude of } V_S = \sqrt{(13815\cdot 2)^2 + (393\ 6)^2} = 13820{\cdot}8 \text{ V}$$

$$\text{Line value of } V_S = \sqrt{3} \times 13820{\cdot}8 = 23938 \text{ V} = \mathbf{23{\cdot}938 \text{ kV}}$$

(ii) $$\text{\% age Regulation} = \frac{V_S - V_R}{V_R} \times 100 = \frac{13820{\cdot}8 - 12700}{12700} \times 100 = \mathbf{8{\cdot}825\%}$$

(iii) $$\text{Line losses} = 3I^2R = 3 \times (164)^2 \times 4 = 3{,}22{,}752 \text{ W} = 322{\cdot}752 \text{ kW}$$

$$\therefore \quad \text{Transmission efficiency} = \frac{5000}{5000 + 322{\cdot}752} \times 100 = \mathbf{93{\cdot}94\%}$$

Example 10.4. *Estimate the distance over which a load of 15000 kW at a p.f. 0·8 lagging can be delivered by a 3-phase transmission line having conductors each of resistance 1 Ω per kilometre. The voltage at the receiving end is to be 132 kV and the loss in the transmission is to be 5%.*

Solution.

$$\text{Line current,} \quad I = \frac{\text{Power delivered}}{\sqrt{3} \times \text{line voltage} \times \text{power factor}} = \frac{15000 \times 10^3}{\sqrt{3} \times 132 \times 10^3 \times 0{\cdot}8} = 82 \text{ A}$$

$$\text{Line losses} = 5\% \text{ of power delivered} = 0{\cdot}05 \times 15000 = 750 \text{ kW}$$

Let R Ω be the resistance of one conductor.

$$\text{Line losses} = 3I^2R$$

or $$750 \times 10^3 = 3 \times (82)^2 \times R$$

$$\therefore \quad R = \frac{750 \times 10^3}{3 \times (82)^2} = 37{\cdot}18 \; \Omega$$

Resistance of each conductor per km is 1 Ω (*given*).

$$\therefore \quad \text{Length of line} = \mathbf{37{\cdot}18 \text{ km}}$$

Example 10.5. *A 3-phase line delivers 3600 kW at a p.f. 0·8 lagging to a load. If the sending end voltage is 33 kV, determine (i) the receiving end voltage (ii) line current (iii) transmission efficiency. The resistance and reactance of each conductor are 5·31 Ω and 5·54 Ω respectively.*

Solution.

Resistance of each conductor, $R = 5{\cdot}31 \; \Omega$

Reactance of each conductor, $X_L = 5{\cdot}54 \; \Omega$

Load power factor, $\cos\phi_R = 0{\cdot}8$ (*lagging*)

Sending end voltage/phase, $V_S = 33{,}000/\sqrt{3} = 19{,}052$ V

Let V_R be the phase voltage at the receiving end.

$$\text{Line current,} \quad I = \frac{\text{Power delivered / phase}}{V_R \times \cos\phi_R} = \frac{1200 \times 10^3}{V_R \times 0{\cdot}8}$$

$$= \frac{150 \times 10^5}{V_R} \qquad \ldots(i)$$

(*i*) Using approximate expression for V_S, we get,

$$V_S = V_R + IR\cos\phi_R + IX_L\sin\phi_R$$

or $$19{,}052 = V_R + \frac{15 \times 10^5}{V_R} \times 5{\cdot}31 \times 0{\cdot}8 + \frac{15 \times 10^5}{V_R} \times 5{\cdot}54 \times 0{\cdot}6$$

or $$V_R^2 - 19{,}052\, V_R + 1{,}13{,}58{,}000 = 0$$

Solving this equation, we get, $V_R = 18{,}435$ V

$$\therefore \quad \text{Line voltage at the receiving end} = \sqrt{3} \times 18{,}435 = 31{,}930 \text{ V} = \mathbf{31{\cdot}93 \text{ kV}}$$

(*ii*) Line current, $I = \frac{15\times10^5}{V_R} = \frac{15\times10^5}{18{,}435} = \mathbf{81\cdot36\ A}$

(*iii*) Line losses, $= 3I^2R = 3\times(81\cdot36)^2\times5\cdot31 = 1{,}05{,}447\ W = 105\cdot447\ kW$

$\therefore$ Transmission efficiency $= \frac{3600}{3600+105\cdot447}\times100 = \mathbf{97\cdot15\%}$

Example 10.6. *A short 3-φ transmission line with an impedance of (6 + j 8) Ω per phase has sending and receiving end voltages of 120 kV and 110 kV respectively for some receiving end load at a p.f. of 0·9 lagging. Determine (i) power output and (ii) sending end power factor.*

Solution.

Resistance of each conductor, $R = 6\ \Omega$

Reactance of each conductor, $X_L = 8\ \Omega$

Load power factor, $\cos\phi_R = 0\cdot9$ lagging

Receiving end voltage/phase, $V_R = 110\times10^3/\sqrt{3} = 63508\ V$

Sending end voltage/phase, $V_S = 120\times10^3/\sqrt{3} = 69282\ V$

Let I be the load current. Using approximate expression for V_S, we get,

$$V_S = V_R + IR\cos\phi_R + IX_L\sin\phi_R$$

or $$69282 = 63508 + I\times6\times0\cdot9 + I\times8\times0\cdot435$$

or $$8\cdot88\,I = 5774$$

or $$I = 5774/8\cdot88 = 650\cdot2\ A$$

(*i*) Power output $= \frac{3V_R I\cos\phi_R}{1000}\ kW = \frac{3\times63508\times650\cdot2\times0\cdot9}{1000}$

$= \mathbf{1{,}11{,}490\ kW}$

(*ii*) Sending end p.f., $\cos\phi_S = \frac{V_R\cos\phi_R + IR}{V_S} = \frac{63508\times0\cdot9+650\cdot2\times6}{69282} = \mathbf{0\cdot88\ lag}$

Example 10.7. *An 11 kV, 3-phase transmission line has a resistance of 1·5 Ω and reactance of 4 Ω per phase. Calculate the percentage regulation and efficiency of the line when a total load of 5000 kVA at 0.8 lagging power factor is supplied at 11 kV at the distant end.*

Solution.

Resistance of each conductor, $R = 1\cdot5\ \Omega$

Reactance of each conductor, $X_L = 4\ \Omega$

Receiving end voltage/phase, $V_R = \frac{11\times10^3}{\sqrt{3}} = 6351\ V$

Load power factor, $\cos\phi_R = 0\cdot8$ lagging

Load current, $I = \frac{\text{Power delivered in kVA}\times1000}{3\times V_R}$

$$= \frac{5000\times1000}{3\times6351} = 262\cdot43A$$

Using the approximate expression for V_S (sending end voltage per phase), we get,

$$V_S = V_R + IR\cos\phi_R + IX_L\sin\phi_R$$
$$= 6351 + 262\cdot43\times1\cdot5\times0\cdot8 + 262\cdot43\times4\times0\cdot6 = 7295\cdot8\ V$$

$$\%\ \text{regulation} = \frac{V_S - V_R}{V_R}\times100 = \frac{7295\cdot8-6351}{6351}\times100 = \mathbf{14\cdot88\%}$$

$$\text{Line losses} = 3I^2R = 3\times(262\cdot43)^2\times1\cdot5 = 310\times10^3\ W = 310\ kW$$

$$\text{Output power} = 5000 \times 0{\cdot}8 = 4000 \text{ kW}$$

$$\text{Input power} = \text{Ouput power} + \text{line losses} = 4000 + 310 = 4310 \text{ kW}$$

$$\text{Transmission efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100 = \frac{4000}{4310} \times 100 = \mathbf{92{\cdot}8\%}$$

Example 10.8. *A 3-phase, 50 Hz, 16 km long overhead line supplies 1000 kW at 11 kV, 0·8 p.f. lagging. The line resistance is 0·03 Ω per phase per km and line inductance is 0·7 mH per phase per km. Calculate the sending end voltage, voltage regulation and efficiency of transmission.*

Solution.

Resistance of each conductor, $R = 0{\cdot}03 \times 16 = 0{\cdot}48\ \Omega$

Reactance of each conductor, $X_L = 2\pi f L \times 16 = 2\pi \times 50 \times 0{\cdot}7 \times 10^{-3} \times 16 = 3{\cdot}52\ \Omega$

Receiving end voltage/phase, $V_R = \dfrac{11 \times 10^3}{\sqrt{3}} = 6351 \text{ V}$

Load power factor, $\cos\phi_R = 0{\cdot}8$ lagging

$$\text{Line current, } I = \frac{1000 \times 10^3}{3 \times V_R \times \cos\phi} = \frac{1000 \times 10^3}{3 \times 6351 \times 0{\cdot}8} = 65{\cdot}6\text{A}$$

$$\text{Sending end voltage/phase, } V_S = V_R + I R \cos\phi_R + I X_L \sin\phi_R$$

$$= 6351 + 65{\cdot}6 \times 0{\cdot}48 \times 0{\cdot}8 + 65{\cdot}6 \times 3{\cdot}52 \times 0{\cdot}6 = 6515 \text{ V}$$

$$\therefore \quad \text{\%age Voltage regulation} = \frac{V_S - V_R}{V_R} \times 100 = \frac{6515 - 6351}{6351} \times 100 = \mathbf{2{\cdot}58\%}$$

$$\text{Line losses} = 3 I^2 R = 3 \times (65{\cdot}6)^2 \times 0{\cdot}48 = 6{\cdot}2 \times 10^3 \text{ W} = 6{\cdot}2 \text{ kW}$$

$$\text{Input power} = \text{Output power} + \text{Line losses} = 1000 + 6{\cdot}2 = 1006{\cdot}2 \text{ kW}$$

$$\therefore \quad \text{Transmission efficiency} = \frac{\text{Output power}}{\text{Input power}} \times 100 = \frac{1000}{1006{\cdot}2} \times 100 = \mathbf{99{\cdot}38\%}$$

Example 10.9. *A 3-phase load of 2000 kVA, 0·8 p.f. is supplied at 6·6 kV, 50 Hz by means of a 33 kV transmission line 20 km long and 33/6·6 kV step-down transfomer. The resistance and reactance of each conductor are 0·4 Ω and 0·5 Ω per km respectively. The resistance and reactance of transformer primary are 7.5 Ω and 13.2 Ω, while those of secondary are 0.35 Ω and 0.65 Ω respectively. Find the voltage necessary at the sending end of transmission line when 6.6 kV is maintained at the receiving end. Determine also the sending end power factor and transmission efficiency.*

Solution. Fig. 10.7 shows the single diagram of the transmission system. Here, the voltage drop will be due to the impedance of transmission line and also due to the impedance of transformer.

Resistance of each conductor $= 20 \times 0{\cdot}4 = 8\ \Omega$

Reactance of each conductor $= 20 \times 0{\cdot}5 = 10\ \Omega$

Let us transfer the impedance of transformer secondary to high tension side *i.e.*, 33 kV side.

Equivalent resistance of transformer referred to 33 kV side

$$= \text{Primary resistance} + 0{\cdot}35\ (33/6{\cdot}6)^2$$

$$= 7{\cdot}5 + 8{\cdot}75 = 16{\cdot}25\ \Omega$$

Equivalent reactance of transformer referred to 33 kV side

$$= \text{Primary reactance} + 0{\cdot}65\ (33/6{\cdot}6)^2$$

$$= 13{\cdot}2 + 16{\cdot}25 = 29{\cdot}45\ \Omega$$

Total resistance of line and transformer is

$$R = 8 + 16{\cdot}25 = 24{\cdot}25\ \Omega$$

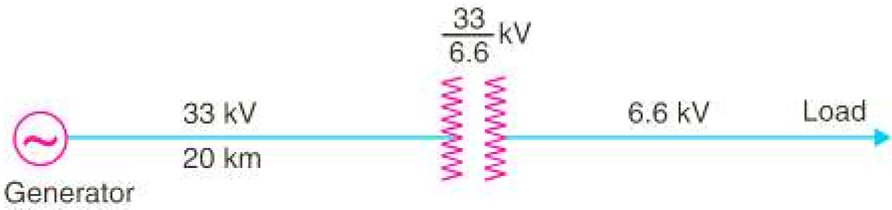


Fig. 10.7

Total reactance of line and transformer is

$$X_L = 10 + 29{\cdot}45 = 39{\cdot}45\ \Omega$$

Receiving end voltage per phase is

$$V_R = 33{,}000/\sqrt{3} = 19052\ \text{V}$$

Line current, $$I = \frac{2000 \times 10^3}{\sqrt{3} \times 33000} = 35\ \text{A}$$

Using the approximate expression for sending end voltage V_S per phase,

$$\begin{aligned} V_S &= V_R + I\,R\cos\phi_R + I\,X_L\sin\phi_R \\ &= 19052 + 35 \times 24{\cdot}25 \times 0{\cdot}8 + 35 \times 39{\cdot}45 \times 0{\cdot}6 \\ &= 19052 + 679 + 828 = 20559\ \text{V} = 20{\cdot}559\ \text{kV} \end{aligned}$$

Sending end line voltage $= \sqrt{3} \times 20{\cdot}559$ kV $=$ **35·6 kV**

Sending end p.f., $$\cos\phi_S = \frac{V_R\cos\phi_R + I\,R}{V_S} = \frac{19052 \times 0{\cdot}8 + 35 \times 24{\cdot}25}{20559} = \mathbf{0{\cdot}7826\ lag}$$

Line losses $$= \frac{3\,I^2 R}{1000}\ \text{kW} = \frac{3 \times (35)^2 \times 24{\cdot}25}{1000} = 89{\cdot}12\ \text{kW}$$

Output power $= 2000$ kVA $\times 0{\cdot}8 = 1600$ kW

∴ Transmission efficiency $$= \frac{1600}{1600 + 89{\cdot}12} \times 100 = \mathbf{94{\cdot}72\%}$$

Example 10.10. *A (medium) single phase transmission line 100 km long has the following constants :*

Resistance/km = 0·25 Ω ; *Reactance/km = 0·8 Ω*

Susceptance/km = 14 × 10^{-6} siemen ; *Receiving end line voltage = 66,000 V*

Assuming that the total capacitance of the line is localised at the receiving end alone, determine (i) the sending end current (ii) the sending end voltage (iii) regulation and (iv) supply power factor. The line is delivering 15,000 kW at 0.8 power factor lagging. Draw the phasor diagram to illustrate your calculations.

Solution. Figs. 10.10 (*i*) and (*ii*) show the circuit diagram and phasor diagram of the line respectively.

Total resistance, $R = 0{\cdot}25 \times 100 = 25\ \Omega$

Total reactance, $X_L = 0{\cdot}8 \times 100 = 80\ \Omega$

Total susceptance, $Y = 14 \times 10^{-6} \times 100 = 14 \times 10^{-4}\ S$

Receiving end voltage, $V_R = 66{,}000$ V

∴ Load current, $$I_R = \frac{15{,}000 \times 10^3}{66{,}000 \times 0{\cdot}8} = 284\ \text{A}$$

$$\cos\phi_R = 0{\cdot}8\ ; \qquad \sin\phi_R = 0{\cdot}6$$

Taking receiving end voltage as the reference phasor [see Fig.10.10 (*ii*)], we have,

$$\vec{V_R} = V_R + j\,0 = 66{,}000\,V$$

Load current, $\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 284\,(0{\cdot}8 - j\,0{\cdot}6) = 227 - j\,170$

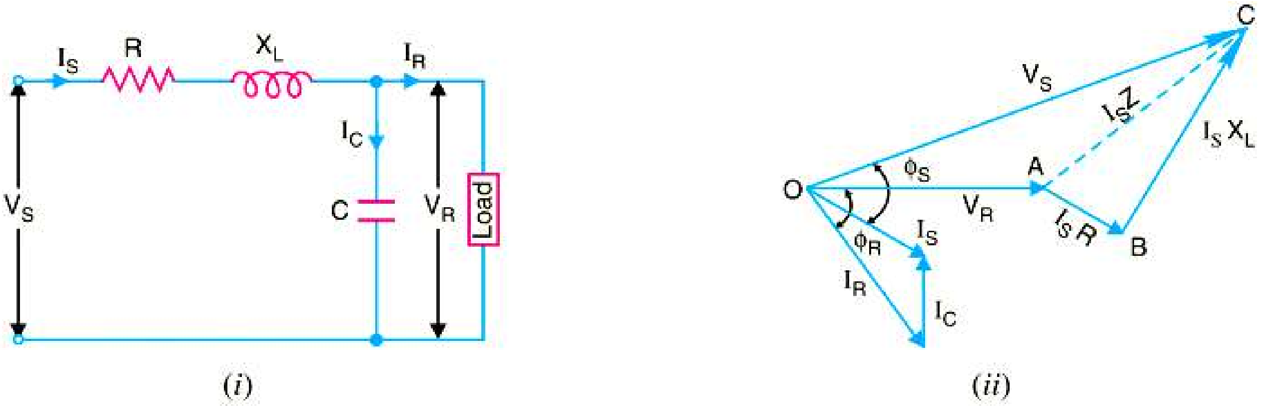


Fig. 10.10

Capacitive current, $\vec{I_C} = jY \times V_R = j\,14 \times 10^{-4} \times 66000 = j\,92$

(*i*) Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C} = (227 - j\,170) + j\,92$

$= 227 - j\,78$ ... (*i*)

Magnitude of $I_S = \sqrt{(227)^2 + (78)^2} =$ **240 A**

(*ii*) Voltage drop $= \vec{I_S}\,\vec{Z} = \vec{I_S}(R + j\,X_L) = (227 - j\,78)\,(25 + j\,80)$

$= 5{,}675 + j\,18{,}160 - j\,1950 + 6240$

$= 11{,}915 + j\,16{,}210$

Sending end voltage, $\vec{V_S} = \vec{V_R} + \vec{I_S}\,\vec{Z} = 66{,}000 + 11{,}915 + j\,16{,}210$

$= 77{,}915 + j\,16{,}210$ ...(*ii*)

Magnitude of $V_S = \sqrt{(77915)^2 + (16210)^2} =$ **79583V**

(*iii*) % Voltage regulation $= \dfrac{V_S - V_R}{V_R} \times 100 = \dfrac{79{,}583 - 66{,}000}{66{,}000} \times 100 =$ **20·58%**

(*iv*) Referring to exp. (*i*), phase angle between $\vec{V_R}$ and $\vec{I_R}$ is :

$$\theta_1 = \tan^{-1} - 78/227 = \tan^{-1}(-0{\cdot}3436) = -18{\cdot}96^\circ$$

Referring to exp. (*ii*), phase angle between $\vec{V_R}$ and $\vec{V_S}$ is :

$$\theta_2 = \tan^{-1}\frac{16210}{77915} = \tan^{-1}(0{\cdot}2036) = 11{\cdot}50^\circ$$

∴ Supply power factor angle, $\phi_S = 18{\cdot}96^\circ + 11{\cdot}50^\circ = 30{\cdot}46^\circ$

∴ Supply p.f. $= \cos\phi_S = \cos 30{\cdot}46^\circ =$ **0·86 lag**

Example 10.11. *A 3-phase, 50-Hz overhead transmission line 100 km long has the following constants :*

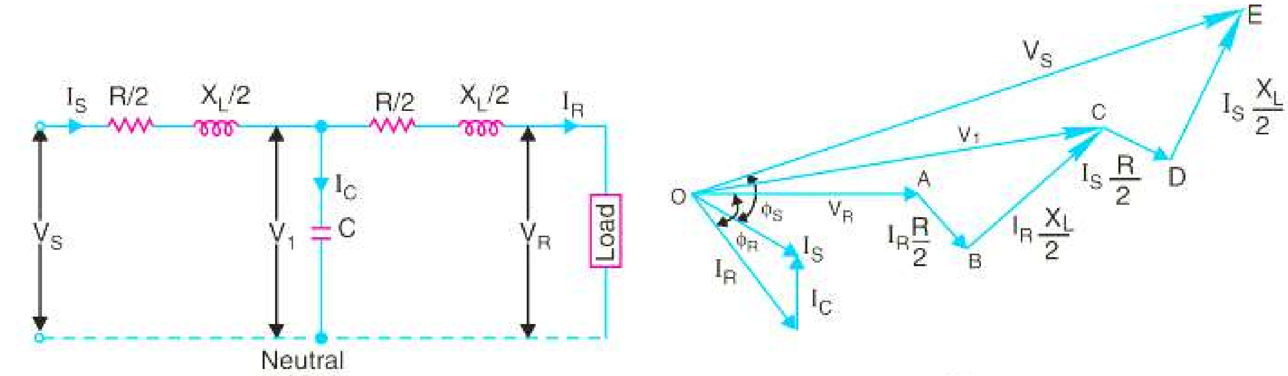
Resistance/km/phase $= 0.1\ \Omega$

Inductive reactance/km/phase $= 0{\cdot}2\ \Omega$

Capacitive susceptance/km/phase $= 0{\cdot}04 \times 10^{-4}$ *siemen*

Determine (i) the sending end current (ii) sending end voltage (iii) sending end power factor and (iv) transmission efficiency when supplying a balanced load of 10,000 kW at 66 kV, p.f. 0·8 lagging. Use nominal T method.

Solution. Figs. 10.13 (*i*) and 10.13 (*ii*) show the circuit diagram and phasor diagram of the line respectively.



(*i*) (*ii*)

Fig. 10.13

Total resistance/phase, $R = 0{\cdot}1 \times 100 = 10\ \Omega$

Total reactance/phase. $X_L = 0{\cdot}2 \times 100 = 20\ \Omega$

Capacitive susceptance, $Y = 0{\cdot}04 \times 10^{-4} \times 100 = 4 \times 10^{-4}$ S

Receiving end voltage/phase, $V_R = 66{,}000/\sqrt{3} = 38105\ V$

Load current, $I_R = \dfrac{10{,}000 \times 10^3}{\sqrt{3} \times 66 \times 10^3 \times 0{\cdot}8} = 109$ A

$\cos \phi_R = 0{\cdot}8 ;\quad \sin \phi_R = 0{\cdot}6$

Impedance per phase, $\vec{Z} = R + j\,X_L = 10 + j\,20$

(*i*) Taking receiving end voltage as the reference phasor [see Fig. 10.13 (*ii*)], we have,

Receiving end voltage, $\vec{V_R} = V_R + j\,0 = 38{,}105\ V$

Load current, $\vec{I_R} = I_R(\cos \phi_R - j \sin \phi_R) = 109\,(0{\cdot}8 - j\,0{\cdot}6) = 87{\cdot}2 - j\,65{\cdot}4$

Voltage across C, $\vec{V_1} = \vec{V_R} + \vec{I_R}\,\vec{Z}/2 = 38,\,105 + (87{\cdot}2 \; - j\,65{\cdot}4)\,(5 + j\,10)$

$= 38{,}105 + 436 + j\,872 - j\,327 + 654 = 39{,}195 + j\,545$

Charging current, $\vec{I_C} = j\,Y\,\vec{V_1} = j\,4 \times 10^{-4}(39{,}195 + j\,545) = -0{\cdot}218 + j\,15{\cdot}6$

Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C} = (87{\cdot}2 - j\,65{\cdot}4) + (-\,0{\cdot}218 + j\,15{\cdot}6)$

$= 87{\cdot}0 - j\,49{\cdot}8 = 100 \angle -29°47'$ A

$\therefore$ Sending end current $=$ **100 A**

(*ii*) Sending end voltage, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\vec{Z}/2 = (39{,}195 + j\,545) + (87{\cdot}0 - j\,49{\cdot}8)\,(5 + j\,10)$

$= 39{,}195 + j\,545 + 434{\cdot}9 + j\,870 - j\,249 + 498$

$= 40128 + j\,1170 = 40145 \angle 1°40'$ V

$\therefore$ Line value of sending end voltage

$= 40145 \times \sqrt{3} = 69\,533$ V = **69·533 kV**

(*iii*) Referring to phasor diagram in Fig. 10.14,

θ_1 = angle between $\vec{V_R}$ and $\vec{V_S} = 1°40'$

$$\theta_2 = \text{angle between } \vec{V_R} \text{ and } \vec{I_S} = 29^\circ\, 47'$$

$$\therefore \quad \phi_S = \text{angle between } \vec{V_S} \text{ and } \vec{I_S}$$

$$= \theta_1 + \theta_2 = 1^\circ 40' + 29^\circ 47' = 31^\circ 27'$$

$\therefore$ Sending end power factor, $\cos \phi_S = \cos 31^\circ 27' =$ **0·853 lag**

(iv) Sending end power $= 3\, V_S I_S \cos \phi_S = 3 \times 40{,}145 \times 100 \times 0{\cdot}853$

$= 10273105 \text{ W} = 10273{\cdot}105 \text{ kW}$

Power delivered $= 10{,}000$ kW

$\therefore$ Transmission efficiency $= \dfrac{10{,}000}{10273{\cdot}105} \times 100 =$ **97·34%**

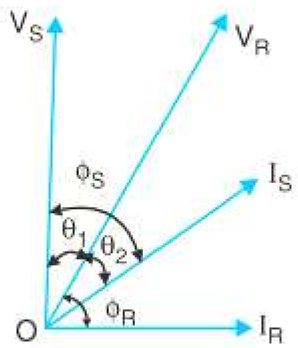


Fig. 10.14

Example 10.12. *A 3-phase, 50 Hz transmission line 100 km long delivers 20 MW at 0·9 p.f. lagging and at 110 kV. The resistance and reactance of the line per phase per km are 0·2 Ω and 0·4 Ω respectively, while capacitance admittance is $2{\cdot}5 \times 10^{-6}$ siemen/km/phase. Calculate : (i) the current and voltage at the sending end (ii) efficiency of transmission. Use nominal T method.*

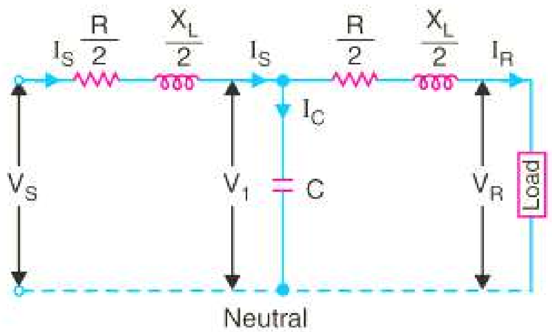
Solution. Figs. 10.15 (*i*) and 10.15 (*ii*) show the circuit diagram and phasor diagram respectively.

Total resistance/phase, $R = 0{\cdot}2 \times 100 = 20\ \Omega$

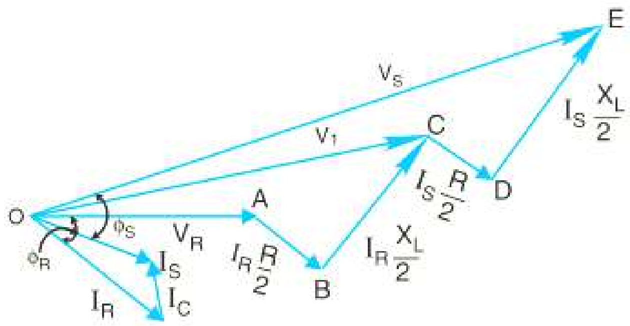
Total reactance/phase, $X_L = 0{\cdot}4 \times 100 = 40\ \Omega$

Total capacitance admittance/phase, $Y = 2{\cdot}5 \times 10^{-6} \times 100 = 2{\cdot}5 \times 10^{-4}$ S

Phase impedance, $\vec{Z} = 20 + j40$



(*i*)



(*ii*)

Fig. 10.15

Receiving end voltage/phase, $V_R = 110 \times 10^3/\sqrt{3} = 63508$ V

Load current, $I_R = \dfrac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0{\cdot}9} = 116.6$ A

$\cos \phi_R = 0{\cdot}9$; $\sin \phi_R = 0{\cdot}435$

(*i*) Taking receiving end voltage as the reference phasor [see phasor diagram 10.15 (*ii*)], we have,

$$\vec{V_R} = V_R + j0 = 63508 \text{ V}$$

Load current, $\vec{I_R} = I_R (\cos \phi_R - j \sin \phi_R) = 116{\cdot}6\,(0{\cdot}9 - j\,0{\cdot}435) = 105 - j50{\cdot}7$

Voltage across C, $\vec{V_1} = \vec{V_R} + \vec{I_R}\,\vec{Z}/2 = 63508 + (105 - j\,50{\cdot}7)\,(10 + j\,20)$

$= 63508 + (2064 + j1593) = 65572 + j1593$

Charging current, $\vec{I_C} = j\,Y\vec{V_1} = j\,2{\cdot}5 \times 10^{-4}\,(65572 + j1593) = -\,0{\cdot}4 + j\,16{\cdot}4$

Sending end current, $\vec{I_S} = \vec{I_R} + \vec{I_C} = (105 - j\,50{\cdot}7) + (-0{\cdot}4 + j16{\cdot}4)$

$= (104{\cdot}6 - j\,34{\cdot}3) = 110 \angle\ 18°9'$ A

∴ Sending end current $=$ **110 A**

Sending end voltage, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\vec{Z}/2$

$= (65572 + j1593) + (104{\cdot}6 - j34{\cdot}3)\,(10 + j20)$

$= 67304 + j\,3342$

∴ Magnitude of $V_S = \sqrt{(67304)^2 + (3342)^2} = 67387\ V$

∴ Line value of sending end voltage

$= 67387 \times \sqrt{3} = 116717$ V $=$ **116·717 kV**

(ii) Total line losses for the three phases

$= 3\,I_S^{\;2}\,R/2 + 3I_R^{\;2}\,R/2$

$= 3 \times (110)^2 \times 10 + 3 \times (116{\cdot}6)^2 \times 10$

$= 0{\cdot}770 \times 10^6$ W $= 0{\cdot}770$ MW

∴ Transmission efficiency $= \dfrac{20}{20 + 0\cdot770} \times 100 =$ **96·29%**

Example 10.13 *A 3-phase, 50Hz, 150 km line has a resistance, inductive reactance and capacitive shunt admittance of 0·1 Ω, 0·5 Ω and 3×10^{-6} S per km per phase. If the line delivers 50 MW at 110 kV and 0·8 p.f. lagging, determine the sending end voltage and current. Assume a nominal π circuit for the line.*

Solution. Fig. 10.18 shows the circuit diagram for the line.

Total resistance/phase, $R = 0{\cdot}1 \times 150 = 15\ \Omega$

Total reactance/phase, $X_L = 0{\cdot}5 \times 150 = 75\ \Omega$

Capacitive admittance/phase, $Y = 3 \times 10^{-6} \times 150 = 45 \times 10^{-5}$ S

Receiving end voltage/phase, $V_R = 110 \times 10^3/\sqrt{3} = 63{,}508$ V

Load current, $I_R = \dfrac{50 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0\cdot8} = 328$ A

$\cos\phi_R = 0{\cdot}8\ ;\ \ \sin\phi_R = 0{\cdot}6$

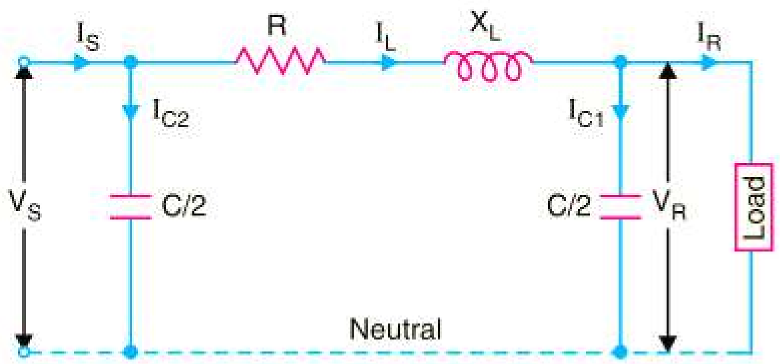


Fig. 10.18

Taking receiving end voltage as the reference phasor, we have,

$$\vec{V_R} = V_R + j\,0 = 63{,}508 \text{ V}$$

Load current, $\overrightarrow{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 328\,(0{\cdot}8 - j0{\cdot}6) = 262{\cdot}4 - j196{\cdot}8$

Charging current at the load end is

$$\overrightarrow{I_{C1}} = \overrightarrow{V_R}\, j\,\frac{Y}{2} = 63{,}508 \times\ j\,\frac{45\times10^{-5}}{2} = j\,14{\cdot}3$$

Line current, $\overrightarrow{I_L} = \overrightarrow{I_R} + \overrightarrow{I_{C1}} = (262{\cdot}4 - j\,196{\cdot}8) + j\,14{\cdot}3 = 262{\cdot}4 - j\,182{\cdot}5$

Sending end voltage,

$$\begin{aligned}\overrightarrow{V_S} &= \overrightarrow{V_R} + \overrightarrow{I_L}\,\overrightarrow{Z} = \overrightarrow{V_R} + \overrightarrow{I_L}\,(R + j\,X_L)\\ &= 63,\,508 + (262{\cdot}4 - j\,182{\cdot}5)\,(15 + j\,75)\\ &= 63{,}508 + 3936 + j\,19{,}680 - j\,2737{\cdot}5 + 13{,}687\\ &= 81{,}131 + j\,16{,}942{\cdot}5 = 82{,}881 \angle 11°47'\ \text{V}\end{aligned}$$

∴ Line to line sending end voltage = $82{,}881 \times \sqrt{3}$ = 1,43,550 V = **143·55 kV**

Charging current at the sending end is

$$\begin{aligned}I_{C2} &= j\overrightarrow{V_S}\,Y/2 = (81{,}131 + j\,16{,}942\cdot5)\,j\,\frac{45\times10^{-5}}{2}\\ &= -\,3{\cdot}81 + j\,18{\cdot}25\end{aligned}$$

Sending end current,

$$\begin{aligned}\overrightarrow{I_S} &= \overrightarrow{I_L} + \overrightarrow{I_{C_2}} = (262{\cdot}4 - j\,182{\cdot}5) + (-\,3{\cdot}81 + j\,18{\cdot}25)\\ &= 258{\cdot}6 - j\,164{\cdot}25 = 306{\cdot}4 \angle -\,32{\cdot}4°\ \text{A}\end{aligned}$$

∴ Sending end current = **306·4 A**

Example 10·14. *A 100-km long, 3-phase, 50-Hz transmission line has following line constants:*

Resistance/phase/km = 0·1 Ω

Reactance/phase/km = 0·5 Ω

Susceptance/phase/km = 10×10^{-6} S

If the line supplies load of 20 MW at 0·9 p.f. lagging at 66 kV at the receiving end, calculate by nominal π method :

(i) sending end power factor *(ii) regulation*

(iii) transmission efficiency

Solution. Fig. 10·19 shows the circuit diagram for the line.

Total resistance/phase, $R = 0{\cdot}1 \times 100 = 10\ \Omega$

Total reactance/phase, $X_L = 0{\cdot}5 \times 100 = 50\ \Omega$

Susceptance/phase, $Y = 10 \times 10^{-6} \times 100 = 10 \times 10^{-4}$ S

Receiving end voltage/phase, $V_R = 66 \times 10^3/\sqrt{3} = 38105$ V

Load current, $$I_R = \frac{20\times10^6}{\sqrt{3}\times66\times10^3\times0\cdot9} = 195\ \text{A}$$

$$\cos\phi_R = 0{\cdot}9 \quad ; \quad \sin\phi_R = 0{\cdot}435$$

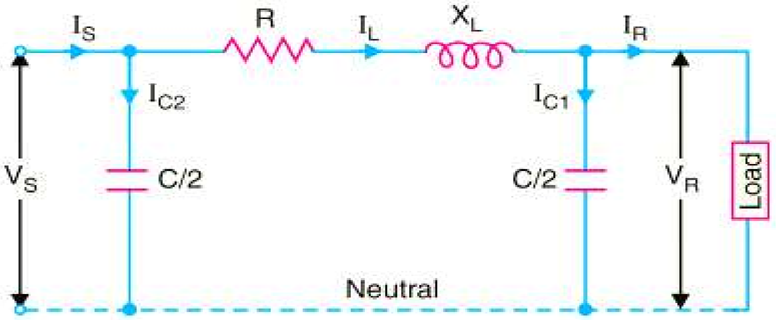


Fig. 10.19

Taking receiving end voltage as the reference phasor, we have,

$$\vec{V_R} = V_R + j0 = 38105 \text{ V}$$

Load current, $\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 195\,(0{\cdot}9 - j\,0{\cdot}435) = 176 - j\,85$

Charging current at the receiving end is

$$\vec{I_{C1}} = \vec{V_R}\, j\frac{Y}{2} = 38105 \times j\,\frac{10\times10^{-4}}{2} = j\,19$$

Line current, $\vec{I_L} = \vec{I_R} + \vec{I_{C1}} = (176 - j\,85) + j\,19 = 176 - j\,66$

Sending end voltage,
$$\begin{aligned}\vec{V_S} &= \vec{V_R} + \vec{I_L}\,\vec{Z} = \vec{V_R} + \vec{I_L}\,(R + j\,X_L)\\ &= 38{,}105 + (176 - j\,66)\,(10 + j\,50)\\ &= 38{,}105 + (5060 + j\,8140)\\ &= 43{,}165 + j\,8140 = 43{,}925\,\angle 10{\cdot}65^\circ \text{ V}\end{aligned}$$

Sending end line to line voltage $= 43,925 \times \sqrt{3} = 76 \times 10^3 \text{ V} = 76 \text{ kV}$

Charging current at the sending end is

$$\begin{aligned}\vec{I_{C2}} &= \vec{V_S}\, jY/2 = (43{,}165 + j\,8140)\, j\,\frac{10\times10^{-4}}{2}\\ &= -4{\cdot}0 + j\,21{\cdot}6\end{aligned}$$

∴ Sending end current,
$$\begin{aligned}\vec{I_S} &= \vec{I_L} + \vec{I_{C2}} = (176 - j\,66) + (-4{\cdot}0 + j\,21{\cdot}6)\\ &= 172 - j\,44{\cdot}4 = 177{\cdot}6\,\angle -14{\cdot}5^\circ \text{ A}\end{aligned}$$

(*i*) Referring to phasor diagram in Fig. 10·20,

θ_1 = angle between $\vec{V_R}$ and $\vec{V_S}$ = 10·65°

θ_2 = angle between $\vec{V_R}$ and $\vec{I_S}$ = − 14·5°

∴ ϕ_S = angle between $\vec{V_S}$ and $\vec{I_S}$ = $\theta_2 + \theta_1$

= 14·5° + 10·65° = 25·15°

∴ Sending end p.f., $\cos\phi_S = \cos 25{\cdot}15^\circ$ = **0·905 lag**

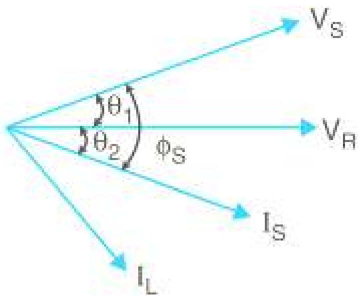


Fig. 10.20

(*ii*) % Voltage regulation $= \dfrac{V_S - V_R}{V_R} \times 100 = \dfrac{43925 - 38105}{38105} \times 100$ = **15·27 %**

(*iii*) Sending end power $= 3\,V_S\,I_S\cos\phi_S = 3 \times 43925 \times 177{\cdot}6 \times 0{\cdot}905$

$= 21{\cdot}18 \times 10^6 \text{ W} = 21{\cdot}18 \text{ MW}$

Transmission efficiency = (20/21·18) × 100 = **94 %**

TUTORIAL PROBLEMS

1. A single phase overhead transmission line delivers 4000 kW at 11 kV at 0·8 p.f. lagging. If resistance and reactance per conductor are 0·15 Ω and 0·02 Ω respectively, calculate :

   (*i*) percentage regulation (*ii*) sending end power factor
   (*iii*) line losses **[(*i*) 19·83% (*ii*) 0·77 lag (*iii*) 620 kW]**

2. A single phase 11 kV line with a length of 15 km is to transmit 500 kVA. The inductive reactance of the line is 0·5 Ω/km and the resistance is 0·3 Ω/km. Calculate the efficiency and regulation of the line for 0·8 lagging power factor. **[97·74%, 3·34%]**

3. A load of 1000 kW at 0·8 p.f. lagging is received at the end of a 3-phase line 20 km long. The resistance and reactance of each conductor are 0·25 Ω and 0·28 Ω per km. If the receiving end line voltage is maintained at 11 kV, calculate :

   (*i*) sending end voltage (line-to-line) (*ii*) percentage regulation
   (*iii*) transmission efficiency **[(*i*) 11·84 kV (*ii*) 7·61% (*iii*) 94·32%]**

4. Estimate the distance over which a load of 15000 kW at 0·85 p.f. can be delivered by a 3-phase transmission line having conductors of steel-cored aluminium each of resistance 0·905 Ω/phase per kilometre. The voltage at the receiving end is to be 132 kV and the loss in transmission is to be 7·5% of the load. **[69·55 km]**

5. A 3-phase line 3 km long delivers 3000 kW at a p.f. 0·8 lagging to a load. The resistance and reactance per km of each conductor are 0·4 Ω and 0·3 Ω respectively. If the voltage at the supply end is maintained at 11 kV, calculate :

   (*i*) receiving end voltage (line-to-line) (*ii*) line current
   (*iii*) transmission efficiency. **[(*i*) 10.46 kV (*ii*) 207 A (*iii*) 95%]**

6. A short 3-ϕ transmission line with an impedance of $(5 + j\,20)\ \Omega$ per phase has sending end and receiving end voltages of 46·85 kV and 33 kV respectively for some receiving end load at a p.f.of 0·8 lagging. Determine :

   (*i*) power output
   (*ii*) sending end power factor **[(*i*) 22·86 kW (*ii*) 0·657 lag]**

7. A substation receives 6000 kVA at 6 kV, 0.8 p.f. lagging on low voltage side of a transformer from a generating station through a 3-phase cable system having resistance of 7 Ω and reactance of 2 Ω per phase. Identical 6600/33000 V transformers are installed at each end, 6600 V side being delta connected and 33000 V side star connected. The resistance and reactance of each transformer are 1 Ω and 9 Ω respectively, referred to *h.v.* side. Calculate the voltage at the generating station bus bars **[6778 V]**

8. A short 3-phase transmission line connected to a 33kV, 50 Hz generating station at the sending end is required to supply a load of 10 MW at 0·8 lagging power factor at 30 kV at the receiving end. If the minimum transmission efficiency is to be limited to 96%, estimate the per phase value of resistance and inductance of the line. **[2·4 Ω; 0·028 H]**

9. A single phase transmission line is delivering 500 kVA load at 2 kV. Its resistance is 0·2 Ω and inductive reactance is 0·4 Ω. Determine the voltage regulation if the load power factor is (*i*) 0·707 lagging (*ii*) 0·707 leading. **[(*i*) 5·3% (*ii*) −1·65%]**

TUTORIAL PROBLEMS

1. A (medium) single phase transmission line 100 km long has the following constants :

   Resistance/km/phase = 0·15Ω
   Inductive reactance/km/phase = 0·377 Ω
   Capacitive reactance/km/phase = 31·87 Ω
   Receiving end line voltage = 132 kV

   Assuming that the total capacitance of the line is localised at the receiving end alone, determine :

   (*i*) sending end current (*ii*) line value of sending end voltage
   (*iii*) regulation (*iv*) sending end power factor

   The line is delivering 72 MW at 0·8 p.f. lagging.

   [(*i*) 377·3 A (*ii*) 155·7 kV (*iii*) 17·9% (*iv*) 0·774 lag]

2. A 3-phase, 50 Hz overhead transmission line has the following constants :

Resistance/phase = 9·6 Ω

Inductance/phase = 0·097 mH

Capacitance/phase = 0·765 μF

If the line is supplying a balanced load of 24,000 kVA 0·8 p.f. lagging at 66 kV, calculate :

(*i*) sending end current (*ii*) line value of sending end voltage

(*iii*) sending end power factor (*iv*) percentage regulation

(*v*) transmission efficiency **[(*i*) 204 A (*ii*) 75 kV (*iii*) 0·814 lag (*iv*) 13·63 % (*v*) 93·7%]**

3. A 3-phase, 50 Hz, overhead transmission line delivers 10 MW at 0·8 p.f. lagging and at 66 kV. The resistance and inductive reactance of the line per phase are 10 Ω and 20 Ω respectively while capacitance admittance is 4×10^{-4} siemen. Calculate :

(*i*) the sending end current (*ii*) sending end voltage (line-to-line)

(*iii*) sending end power factor (*iv*) transmission efficiency

Use nominal *T* method. **[(*i*) 100 A (*ii*) 69·8 kV (*iii*) 0·852 (*iv*) 97·5%]**

4. A 3-phase, 50 Hz, 100 km transmission line has the following constants :

Resistance/phase/km = 0·1 Ω

Reactance/phase/km = 0·5 Ω

Susceptance/phase/km = 10^{-5} siemen

If the line supplies a load of 20 MW at 0·9 p.f. lagging at 66 kV at the receiving end, calculate by using nominal π method :

(*i*) sending end current (*ii*) line value of sending end voltage

(*iii*) sending end power factor (*iv*) regulation

[(*i*) 177·6 A (*ii*) 76kV (*iii*) 0·905 lag (*iv*) 15·15%]

5. A 3-phase overhead transmission line has the following constants :

Resistance/phase = 10 Ω

Inductive reactance/phase = 35 Ω

Capacitive admittance/phase = 3×10^{-4} siemen

If the line supplied a balanced load of 40,000 kVA at 110 kV and 0·8 p.f. lagging, calculate :

(*i*) sending end power factor (*ii*) percentage regulation

(*iii*) transmission efficiency **[(*i*) 0·798 lag (*ii*) 10% (*iii*) 96·38%]**

6. A 3-phase, 50 Hz overhead transmission line, 100 km long, 110 kV between the lines at the receiving end has the following constants :

Resistance per km per phase = 0·153 Ω

Inductance per km per phase = 1·21 mH

Capacitance per km per phase = 0·00958 μF

The line supplies a load of 20,000 kW at 0·9 power factor lagging. Calculate using nominal π representation, the sending end voltage, current, power factor, regulation and the efficiency of the line. Neglect leakage. **[115·645 kV (line voltage) : 109 ∠ – 16·68° A ; 0·923 lag ; 5·13 %; 97·21 %]**

Example 10.15. *A 3-φ transmission line 200 km long has the following constants :*

Resistance/phase/km = 0·16 Ω

Reactance/phase/km = 0·25 Ω

Shunt admittance/phase/km = $1{\cdot}5 \times 10^{-6}$ S

Calculate by rigorous method the sending end voltage and current when the line is delivering a load of 20 MW at 0·8 p.f. lagging. The receiving end voltage is kept constant at 110 kV.

Solution :

Total resistance/phase, $R = 0{\cdot}16 \times 200 = 32\ \Omega$

Total reactance/phase, $X_L = 0{\cdot}25 \times 200 = 50\ \Omega$

Total shunt admittance/phase, $Y = j\,1{\cdot}5 \times 10^{-6} \times 200 = 0{\cdot}0003 \angle 90^\circ$

Series Impedance/phase, $Z = R + j\,X_L = 32 + j\,50 = 59{\cdot}4 \angle 58^\circ$

The sending end voltage V_S per phase is given by :

$$V_S = V_R \cosh\sqrt{Y\,Z} + I_R\sqrt{\frac{Z}{Y}}\sinh\sqrt{Z\,Y} \qquad ...(i)$$

Now

$$\sqrt{Z\,Y} = \sqrt{59{\cdot}4\angle 58^\circ \times 0{\cdot}0003\angle 90^\circ} = 0{\cdot}133\angle 74^\circ$$

$$Z\,Y = 0{\cdot}0178 \angle 148^\circ$$

$$Z^2Y^2 = 0{\cdot}00032 \angle 296^\circ$$

$$\sqrt{\frac{Z}{Y}} = \sqrt{\frac{59{\cdot}4\angle 58^\circ}{0{\cdot}0003\angle 90^\circ}} = 445 \angle -16^\circ$$

$$\sqrt{\frac{Y}{Z}} = \sqrt{\frac{0{\cdot}0003\angle 90^\circ}{59{\cdot}4\angle 58^\circ}} = 0{\cdot}00224\angle 16^\circ$$

$\therefore$

$$\cosh\sqrt{Y\,Z} = 1 + \frac{Z\,Y}{2} + \frac{Z^2\,Y^2}{24} \text{ approximately}$$

$$= 1 + \frac{0{\cdot}0178}{2}\angle 148^\circ + \frac{0{\cdot}00032}{24}\angle 296^\circ$$

$$= 1 + 0{\cdot}0089 \angle 148^\circ + 0{\cdot}0000133 \angle 296^\circ$$

$$= 1 + 0{\cdot}0089\,(-0{\cdot}848 + j\,0{\cdot}529) + 0{\cdot}0000133\,(0{\cdot}438 - j\,0{\cdot}9)$$

$$= 0{\cdot}992 + j\,0{\cdot}00469 = 0{\cdot}992 \angle 0{\cdot}26^\circ$$

$$\sinh\sqrt{Y\,Z} = \sqrt{Y\,Z} + \frac{(Y\,Z)^{3/2}}{6} \text{ approximately}$$

$$= 0{\cdot}133\angle 74^\circ + \frac{0{\cdot}0024\angle 222^\circ}{6}$$

$$= 0{\cdot}133 \angle 74^\circ + 0{\cdot}0004 \angle 222^\circ$$

$$= 0{\cdot}133\,(0{\cdot}275 + j\,0{\cdot}961) + 0{\cdot}0004\,(-0{\cdot}743 - j\,0{\cdot}67)$$

$$= 0{\cdot}0362 + j\,0{\cdot}1275 = 0{\cdot}1325 \angle 74^\circ 6'$$

Receiving end voltage per phase is

$$V_R = 110 \times 10^3/\sqrt{3} = 63508 \text{ V}$$

Receiving end current,
$$I_R = \frac{20 \times 10^6}{\sqrt{3} \times 110 \times 10^3 \times 0{\cdot}8} = 131\ A$$

Putting the various values in exp (i), we get,

$$V_S = 63508 \times 0{\cdot}992 \angle 0{\cdot}26^\circ + 131 \times 445 \angle -16^\circ 0' \times 0{\cdot}1325 \angle 74^\circ 6'$$

$$= 63000 \angle 0{\cdot}26^\circ + 7724 \angle 58^\circ 6'$$

$$= 63000\,(0{\cdot}999 + j\,0{\cdot}0045) + 7724\,(0{\cdot}5284 + j\,0{\cdot}8489)$$

$$= 67018 + j\,6840 = 67366 \angle 5^\circ 50' \text{ V}$$

Sending end line-to-line voltage $= 67366 \times \sqrt{3} = 116{\cdot}67 \times 10^3$ V = **116·67 kV**

The sending end current I_S is given by :

$$I_S = V_R\sqrt{\frac{Y}{Z}}\sinh\sqrt{Y\,Z} + I_R\cosh\sqrt{Y\,Z}$$

Putting the various values, we get,

$$I_S = 63508 \times 0{\cdot}00224 \angle 16^\circ \times 0{\cdot}1325 \angle 74^\circ 6' + 131 \times 0{\cdot}992 \angle 0{\cdot}26^\circ$$

$$= 18{\cdot}85 \angle 90^\circ 6' + 130 \angle 0{\cdot}26^\circ$$

$$= 18{\cdot}85\,(-0{\cdot}0017 + j\,0{\cdot}999) + 130\,(0{\cdot}999 + j\,0{\cdot}0045)$$

$$= 129{\cdot}83 + j\,19{\cdot}42 = 131{\cdot}1 \angle 8^\circ \text{ A}$$

$\therefore$ Sending end current = **131·1 A**

TUTORIAL PROBLEMS

1. A 3-phase overhead transmission line has a total series impedance per phase of 200 $\angle 80^{o}$ ohms and a total shunt admittance of $0{\cdot}0013\angle 90^{o}$ siemen per phase. The line delivers a load of 80 MW at 0·8 p.f. lagging and 220 kV between the lines. Determine the sending end line voltage and current by rigorous method. **[263·574 kV ; 187·5 A]**

2. A 3-phase transmission line, 160 km long, has the following constants :

   Resistance/phase/km = 0·2 Ω

   Reactance/phase/km = 0·3127 Ω

   Shunt admittance/phase/km = $1{\cdot}875 \times 10^{-6}$ S

   Determine the sending end voltage and current by rigorous method when the line is delivering a load of 25 MVA at 0·8 p.f. lagging. The receiving end voltage is kept constant at 110 kV. **[116·67 kV ; 131·1 A]**

Generalised Circuit Constants of a Transmission Line

In any four terminal *network, the input voltage and input current can be expressed in terms of output voltage and output current. Incidentally, a transmission line is a 4-terminal network ; two input terminals where power enters the network and two output terminals where power leaves the network.

Therefore, the input voltage $(\vec{V_S})$ and input current $(\vec{I_S})$ of a 3-phase transmission line can be expressed as :

$$\vec{V_S} = \vec{A}\,\vec{V_R} + \vec{B}\,\vec{I_R}$$

$$\vec{I_S} = \vec{C}\,\vec{V_R} + \vec{D}\,\vec{I_R}$$

where $\vec{V_S}$ = sending end voltage per phase

$\vec{I_S}$ = sending end current

$\vec{V_R}$ = receiving end voltage per phase

$\vec{I_R}$ = receiving end current

and $\vec{A}, \vec{B}, \vec{C}$ and $\vec{D}$ (generally complex numbers) are the constants known as *generalised circuit constants* of the transmission line. The values of these constants depned upon the particular method adopted for solving a transmission line. Once the values of these constants are known, performance calculations of the line can be easily worked out. The following points may be kept in mind :

(*i*) The constants $\vec{A}, \vec{B}, \vec{C}$ and $\vec{D}$ are generally complex numbers.

(*ii*) The constants $\vec{A}$ and $\vec{D}$ are dimensionless whereas the dimensions of $\vec{B}$ and $\vec{C}$ are ohms and siemen respectively.

(*iii*) For a given transmisson line,

$$\vec{A} = \vec{D}$$

(*iv*) For a given transmission line,

$$\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = 1$$

Determination of Generalised Constants for Transmission Lines

As stated previously, the sending end voltage $(\vec{V_S})$ and sending end current $(\vec{I_S})$ of a transmission line can be expressed as :

$$\vec{V_S} = \vec{A}\,\vec{V_R} + \vec{B}\,\vec{I_R} \qquad ...(i)$$

$$\vec{I_S} = \vec{C}\,\vec{V_R} + \vec{D}\,\vec{I_R} \qquad ...(ii)$$

(i) Short Transmission Lines: In short transmission lines, the effect of line capacitance is neglected. Therefore the line is considered to have series impedance. Fig.10.23 shows the circuit of a three phase transmission line on a single phase basis.

Here, $\vec{I_S} = \vec{I_R}$ ...(iii)

and $\vec{V_S} = \vec{V_R} + \vec{I_R}\,\vec{Z}$ ...(iv)

Comparing these with eqs. (*i*) and (*ii*), we have,

$\vec{A} = 1\,;\quad \vec{B} = \vec{Z},\quad \vec{C} = 0$ and $\vec{D} = 1$

Incidentally ; $\vec{A} = \vec{D}$

and $\vec{A}\,\vec{D} - \vec{B}\,\vec{C} = 1\times 1 - \vec{Z}\times 0 = 1$

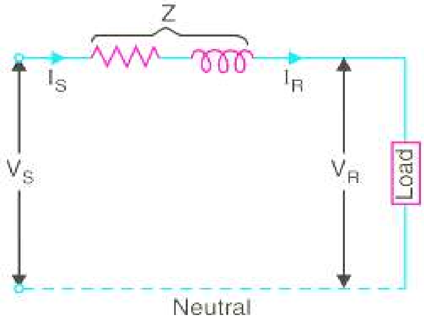


Fig. 10.23

(ii) Medium lines – Nominal T method: In this method, the whole line to neutral capacitance is assumed to be concentrated at the middle point of the line and half the line resistance and reactance are lumped on either side as shown in Fig.10.24

Here, $\vec{V_S} = \vec{V_1} + \vec{I_S}\,\vec{Z}/2$ ...(v)

and $\vec{V_1} = \vec{V_R} + \vec{I_R}\;\vec{Z}/2$

Now, $\vec{I_C} = \vec{I_S} - \vec{I_R}$

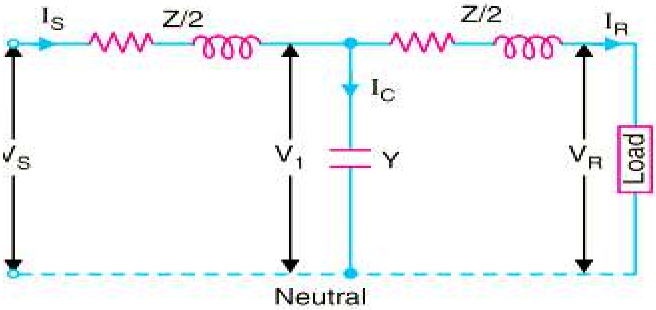


Fig. 10.24

$$= \vec{V_1}\,\vec{Y} \quad \text{where } Y = \text{shunt admittance}$$

$$= \vec{Y}\left(\vec{V_R} + \frac{\vec{I_R}\,\vec{Z}}{2}\right)$$

$$\therefore \quad \vec{I_S} = \vec{I_R} + \vec{Y}\,\vec{V_R} + \vec{Y}\,\frac{\vec{I_R}\,\vec{Z}}{2}$$

$$= \vec{Y}\,\vec{V_R} + \vec{I_R}\left(1 + \frac{\vec{Y}\,\vec{Z}}{2}\right) \qquad ...(vi)$$

Substituting the value of V_1 in eq. (*v*), we get,

$$\vec{V_S} = \vec{V_R} + \frac{\vec{I_R}\,\vec{Z}}{2} + \frac{\vec{I_S}\,\vec{Z}}{2}$$

Substituing the value of I_S, we get,

$$\vec{V_S} = \left(1 + \frac{\vec{Y}\,\vec{Z}}{2}\right)\vec{V_R} + \left(\vec{Z} + \frac{\vec{Y}\,\vec{Z}^2}{4}\right)\vec{I_R} \qquad ...(vii)$$

Comparing eqs. (*vii*) and (*vi*) with those of (*i*) and (*ii*), we have,

$$\vec{A} = \vec{D} = 1 + \frac{\vec{Y}\,\vec{Z}}{2}\,;\quad \vec{B} = \vec{Z}\left(1 + \frac{\vec{Y}\,\vec{Z}}{4}\right)\,;\quad \vec{C} = \vec{Y}$$

Incidentally : $\vec{A}\vec{D}-\vec{B}\vec{C} = \left(1+\frac{YZ}{2}\right)^2 - Z\left(1+\frac{YZ}{4}\right)Y$

$$= 1+\frac{Y^2Z^2}{4}+YZ-ZY-\frac{Z^2Y^2}{4}=1$$

(*iii*) Medium lines—Nominal π method. In this method, line-to-neutral capacitance is divided into two halves ; one half being concentrated at the load end and the other half at the sending end as shown in Fig. 10.25.

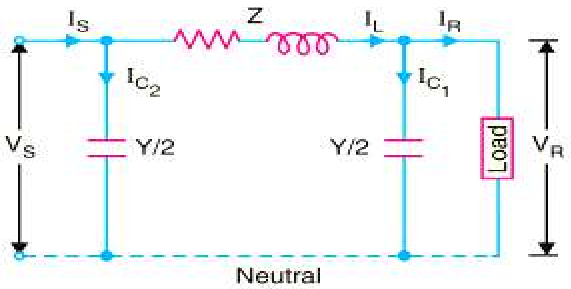


Fig. 10.25

Here, $\vec{Z} = R + jX_L$ = series impedenace/phase

$\vec{Y} = j\omega C$ = shunt admittance

$\vec{I_S} = \vec{I_L} + \vec{I_{C2}}$

or $\vec{I_S} = \vec{I_L} + \vec{V_S}\,\vec{Y}/2$ ...(*viii*)

Also $\vec{I_L} = \vec{I_R} + \vec{I_{C1}} = \vec{I_R} + \vec{V_R}\,\vec{Y}/2$ ...(*ix*)

Now $\vec{V_S} = \vec{V_R} + \vec{I_L}\,\vec{Z} = \vec{V_R} + \left(\vec{I_R} + \vec{V_R}\,\vec{Y}/2\right)\vec{Z}$ (Putting the value of $\vec{I_L}$)

$\therefore$ $$\vec{V_S} = \vec{V_R}\left(1+\frac{\vec{Y}\vec{Z}}{2}\right) + \vec{I_R}\,\vec{Z} \quad ...(x)$$

Also $\vec{I_S} = \vec{I_L} + \vec{V_S}\,\vec{Y}/2 = \left(\vec{I_R} + \vec{V_R}\,\vec{Y}/2\right) + \vec{V_S}\,\vec{Y}/2$

(Putting the value of $\vec{I_L}$)

Putting the value of $\vec{V_S}$ from eq. (*x*), we get,

$$\vec{I_S} = \vec{I_R} + \vec{V_R}\frac{\vec{Y}}{2} + \frac{\vec{Y}}{2}\left\{\vec{V_R}\left(1+\frac{\vec{Y}\vec{Z}}{2}\right) + \vec{I_R}\,\vec{Z}\right\}$$

$$= \vec{I_R} + \vec{V_R}\frac{\vec{Y}}{2} + \frac{\vec{V_R}\,\vec{Y}}{2} + \frac{\vec{V_R}\,\vec{Y}^2\,\vec{Z}}{4} + \frac{\vec{Y}\,\vec{I_R}\,\vec{Z}}{2}$$

$$= \vec{I_R}\left(1+\frac{\vec{Y}\vec{Z}}{2}\right) + \vec{V_R}\,\vec{Y}\left(1+\frac{\vec{Y}\vec{Z}}{4}\right) \quad ...(xi)$$

Comparing equations (*x*) and (*xi*) with those of (*i*) and (*ii*), we get,

$$\vec{A} = \vec{D} = \left(1+\frac{\vec{Y}\vec{Z}}{2}\right);\quad \vec{B} = \vec{Z};\quad \vec{C} = \vec{Y}\left(1+\frac{\vec{Y}\vec{Z}}{4}\right)$$

Also $\vec{A}\vec{D}-\vec{B}\vec{C} = \left(1+\frac{YZ}{2}\right)^2 - ZY\left(1+\frac{YZ}{4}\right)$

$$= 1+\frac{Y^2Z^2}{4}+YZ-ZY-\frac{Z^2Y^2}{4} = 1$$

(*iv*) Long lines—Rigorous method. By rigorous method, the sending end voltage and current of a long transmission line are given by :

$$V_S = V_R\cosh\sqrt{YZ} + I_R\sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ}$$

$$I_S = V_R\sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} + I_R\cosh\sqrt{YZ}$$

Comparing these equations with those of (*i*) and (*ii*), we get,

$$\vec{A} = \vec{D} = \cosh\sqrt{YZ};\quad \vec{B} = \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ};\quad \vec{C} = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ}$$

Incidentally

$$\vec{A}\vec{D}-\vec{B}\vec{C} = \cosh\sqrt{YZ}\times\cosh\sqrt{YZ} - \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ}\times\sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ}$$

$$= \cosh^2\sqrt{YZ} - \sinh^2\sqrt{YZ} = 1$$

Example 10.16. *A balanced 3-phase load of 30 MW is supplied at 132 kV, 50 Hz and 0·85 p.f. lagging by means of a transmission line. The series impedance of a single conductor is (20 + j52) ohms and the total phase-neutral admittance is 315×10^{-6} siemen. Using nominal T method, determine: (i) the A, B, C and D constants of the line (ii) sending end voltage (iii) regulation of the line.*

Solution. Fig. 10.26 shows the representation of 3-phase line on the single phase basis.

$$\text{Series line impedance/phase, } \vec{Z} = (20 + j\,52)\ \Omega$$

$$\text{Shunt admittance/phase, } \quad \vec{Y} = j\,315 \times 10^{-6}\ \text{S}$$

(i) Generalised constants of line. For nominal *T* method, various constants have the values as under :

$$\vec{A} = \vec{D} = 1 + \vec{Z}\ \vec{Y}/2 = 1 + \frac{20 + j\,52}{2} \times j\,315 \times 10^{-6}$$

$$= 0{\cdot}992 + j\,0{\cdot}00315 = \mathbf{0{\cdot}992\ \angle 0\ 18^\circ}$$

$$\vec{B} = \vec{Z}\left(1 + \frac{\vec{Z}\,\vec{Y}}{4}\right) = (20 + j\,52)\left[1 + \frac{(20 + j\,52)\,j\,315 \times 10^{-6}}{4}\right]$$

$$= 19{\cdot}84 + j\,51{\cdot}82 = \mathbf{55{\cdot}5\ \angle 69^\circ}$$

$$\vec{C} = \vec{Y} = \mathbf{0{\cdot}000315\ \angle 90^\circ}$$

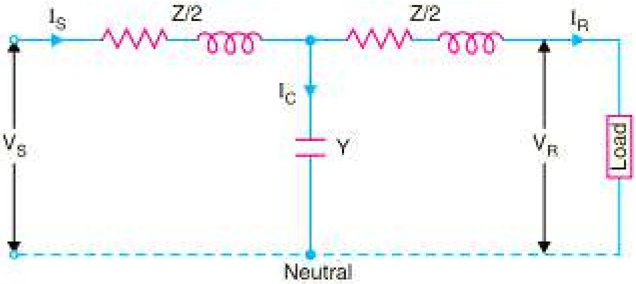


Fig. 10.26

(ii) Sending end voltage.

$$\text{Receiving end voltage/phase, } V_R = 132 \times 10^3/\sqrt{3} = 76210\ \text{V}$$

$$\text{Receiving end current, } \quad I_R = \frac{30 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0{\cdot}85} = 154\ \text{A}$$

$$\cos\phi_R = 0{\cdot}85\,; \quad \sin\phi_R = 0{\cdot}53$$

Taking receiving end voltage as the reference phasor, we have,

$$\vec{V_R} = V_R + j0 = 76210\ \text{V}$$

$$\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 154\,(0{\cdot}85 - j\,0{\cdot}53) = 131 - j\,81{\cdot}62$$

Sending end voltage per phase is

$$\vec{V_S} = \vec{A}\ \vec{V_R} + \vec{B}\ \vec{I_R}$$

$$= (0{\cdot}992 + j\,0{\cdot}0032)\,76210 + (19{\cdot}84 + j\,51{\cdot}82)\,(131 - j\,81{\cdot}62)$$

$$= 82{,}428 + j\,5413$$

$\therefore$ Magnitude of sending end voltage is

$$V_S = \sqrt{(82{,}428)^2 + (5413)^2} = 82{\cdot}6 \times 10^3\,\text{V} = 82{\cdot}6\ \text{kV}$$

$\therefore$ Sending end line-to-line voltage

$$= 82{\cdot}6 \times \sqrt{3} = \mathbf{143\ kV}$$

(iii) Regulation. Regulation is defined as the change in voltage at the receiving end when full-load is thrown off.

$$\text{Now,} \qquad \vec{V_S} = \vec{A}\ \vec{V_R} + \vec{B}\ \vec{I_R}$$

$$\text{At no load,} \qquad \vec{I_R} = 0$$

$$\therefore \qquad \vec{V_S} = \vec{A}\ \vec{V_{R0}}$$

where $\overrightarrow{V_{R0}}$ = voltage at receiving end at no load

or $\overrightarrow{V_{R0}} = \overrightarrow{V_S}/\overrightarrow{A}$

or $V_{R0} = V_S/A$ (in magnitude)

$\therefore$ $$\% \text{ Regulation} = \frac{(V_S/A - V_R)}{V_R} \times 100 = \frac{(82 \cdot 6/0 \cdot 992) - 76 \cdot 21}{76 \cdot 21} \times 100 = \mathbf{9 \cdot 25\%}$$

Example 10.17. *A 132 kV, 50 Hz, 3-phase transmission line delivers a load of 50 MW at 0·8 p.f. lagging at the receiving end. The generalised constants of the transmission line are :*

$A = D = 0{\cdot}95\ \angle 1{\cdot}4°$; $B = 96\ \angle 78°$; $C = 0{\cdot}0015\ \angle 90°$

Find the regulation of the line and charging current. Use Nominal-T method.

Solution.

Receiving end voltage/phase, $V_R = 132 \times 10^3/\sqrt{3} = 76210$ V

Receiving end current, $$I_R = \frac{50 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0 \cdot 8} = 273 \text{ A}$$

$\cos \phi_R = 0{\cdot}8$; $\sin \phi_R = 0{\cdot}6$

Taking receiving end voltage as the reference phasor, we have,

$$\overrightarrow{V_R} = V_R + j\,0 = 76210 \angle 0°$$

$$\overrightarrow{I_R} = I_R \angle -\phi_R = 273 \angle -36{\cdot}9°$$

Sending end voltage per phase is

$$\begin{aligned}
\overrightarrow{V_S} &= \vec{A}\ \overrightarrow{V_R} + \vec{B}\ \overrightarrow{I_R}\\
&= 0{\cdot}95 \angle 1{\cdot}4° \times 76210 \angle 0° + 96 \angle 78° \times 273 \angle -36{\cdot}9°\\
&= 72400 \angle 1{\cdot}4° + 26208 \angle 41{\cdot}1°\\
&= 72400 (\cos 1{\cdot}4° + j \sin 1{\cdot}4°) + 26208 (\cos 41{\cdot}1° + j \sin 41{\cdot}1°)\\
&= 72400 (0{\cdot}9997 + j\,0{\cdot}0244) + 26208 (0{\cdot}7536 + j\,0{\cdot}6574)\\
&= (72378 + j\,1767) + (19750 + j\,17229)\\
&= 92128 + j\,18996 = 94066 \angle 11{\cdot}65° \text{ V}
\end{aligned}$$

Sending end current,
$$\begin{aligned}
\overrightarrow{I_S} &= \vec{C}\ \overrightarrow{V_R} + \vec{D}\ \overrightarrow{I_R}\\
&= 0{\cdot}0015 \angle 90° \times 76210 \angle 0° + 0{\cdot}95 \angle 1{\cdot}4° \times 273 \angle -36{\cdot}9°\\
&= 114 \angle 90° + 260 \angle -35{\cdot}5°\\
&= 114 (\cos 90° + j \sin 90°) + 260 (\cos 35{\cdot}5° - j \sin 35{\cdot}5°)\\
&= 114 (0 + j) + 260 (0{\cdot}814 - j\,0{\cdot}58)\\
&= j\,114 + 211 - j\,150 = 211 - j\,36
\end{aligned}$$

Charging current,
$$\begin{aligned}
\overrightarrow{I_C} &= \overrightarrow{I_S} - \overrightarrow{I_R} = (211 - j36) - 273 \angle -36{\cdot}9°\\
&= (211 - j\,36) - (218 - j\,164) = -7 + j\,128 = \mathbf{128{\cdot}2 \angle 93{\cdot}1° \text{ A}}
\end{aligned}$$

$$\% \text{ Regulation} = \frac{(V_S/A) - V_R}{V_R} \times 100 = \frac{94066/0 \cdot 95 - 76210}{76210} \times 100 = \mathbf{30\%}$$

Example 10.18. *Find the following for a single circuit transmission line delivering a load of 50 M VA at 110 kV and p.f. 0·8 lagging :*

(i) sending end voltage (ii) sending end current (iii) sending end power (iv) efficiency of transmission. Given A = D = 0·98 ∠3°; B = 110 ∠75° ohm ; C = 0·0005 ∠80° siemen.

Solution.

Receiving end voltage/phase,

$$V_R = \frac{110}{\sqrt{3}} = 63{\cdot}5 \text{ kV}$$

Receiving end current, $$I_R = \frac{50 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 262{\cdot}4 \text{ A}$$

Taking receiving end voltage as the reference phasor, we have,

$$\overrightarrow{V_R} = (63500 + j0)$$

$$\vec{I_R} = 262{\cdot}4 \angle -\cos^{-1} 0{\cdot}8 = 262{\cdot}4\,(0{\cdot}8 - j\,0{\cdot}6) = (210 - j\,157{\cdot}5)\text{ A}$$

(i) Now sending-end voltage per phase is

$$\vec{V_S} = \vec{A}\,\vec{V_R} + \vec{B}\,\vec{I_R}$$

Here $\vec{A}\,\vec{V_R} = 0{\cdot}98 \angle 3^\circ \times 63500 \angle 0^\circ = 62230 \angle 3^\circ = (62145 + j\,3260)\text{ V}$

and $\vec{B}\,\vec{I_R} = 110 \angle 75^\circ \times 262{\cdot}4 \angle -36{\cdot}86^\circ$

$= 28865 \angle 38{\cdot}14^\circ = (22702 + j\,17826)\text{ V}$

$\therefore$ $\vec{V_S} = (62145 + j\,3260) + (22702 + j\,17826)$

$= 84847 + j\,21086 = 87427 \angle 14^\circ\text{ V}$

$\therefore$ Magnitude of sending-end voltage/phase = **87427 V**

(ii) Sending-end current is given by ;

$$\vec{I_S} = \vec{C}\,\vec{V_R} + \vec{D}\,\vec{I_R}$$

Here $\vec{C}\,\vec{V_R} = 0{\cdot}0005 \angle 80^\circ \times 63500 \angle 0^\circ = 31{\cdot}75 \angle 80^\circ = (5{\cdot}5 + j\,31{\cdot}3)\text{ A}$

and $\vec{D}\,\vec{I_R} = 0{\cdot}98 \angle 3^\circ \times 262{\cdot}4 \angle -36{\cdot}86^\circ$

$= 257{\cdot}15 \angle -33{\cdot}8^\circ = (213{\cdot}5 - j\,143{\cdot}3)\text{ A}$

$\therefore$ $\vec{I_S} = (5{\cdot}5 + j\,31{\cdot}3) + (213{\cdot}5 - j\,143{\cdot}3)$

$= 219 - j\,112 = 246 \angle -27^\circ\text{ A}$

$\therefore$ Magnitude of sending-end current = **246 A**

(iii) Sending-end power $= 3\,V_S\,I_S \cos\phi_S$

Here $V_S = 87427$ V ; $I_S = 246$ A ; $\cos\phi_S = \cos(-27^\circ - 14^\circ)$

$\therefore$ Sending-end power $= 3 \times 87427 \times 246 \times \cos(-27^\circ - 14^\circ)$

$= 48{\cdot}6 \times 10^6$ W = **48·6 MW**

(iv) Receiving end power $= 50 \times 0{\cdot}8 = 40$ MW

Transmission efficiency, $\eta = \dfrac{40}{48{\cdot}6} \times 100 =$ **82·3%**

TUTORIAL PROBLEMS

1. A 150 km, 3-φ, 110 kV, 50 Hz transmission line transmits a load of 40,000 kW at 0·8 p.f. lagging at the receiving end. Resistance/km/phase = 0·15Ω ; reactance/km/phase = 0·6 Ω; susceptance/km/phase = 10^{-5} S. Determine (*i*) the *A*, *B*, *C* and *D* constants of the line (*ii*) regulation of the line.

[(*i*) A = D = 0·968 ∠1° ; B = 92·8 ∠7·5°Ω ; C = 0·00145 ∠90·5° S (*ii*) 33·5%]

2. A balanced load of 30 MW is supplied at 132 kV, 50 Hz and 0·85 p.f. lagging by means of a transmission line. The series impedance of a single conductor is (20 + j52) ohms and the total phases-neutral admittance is 315 microsiemens. Shunt leakage may be neglected. Using the nominal *T* approximation, calculate the line voltage at the sending end of the line. If the load is removed and the sending end voltage remains constant, find the percentage rise in voltage at the receiving end.

[143 kV; 9%]

3. Calculate *A*, *B*, *C* and *D* constants of a 3-phase, 50 Hz transmission line 160 km long having the following distributed parameters :

$R = 0{\cdot}15\ \Omega/\text{km}$; $L = 1{\cdot}20 \times 10^{-3}$ H/km ; $C = 8 \times 10^{-9}$ F/km ; $G = 0$

[A = D = 0·988 ∠0·3° ; B = 64·2 ∠ 68·3° Ω ; C = 0·4 × 10^{-3} ∠90·2° S]

SURGE IMPEDANCE

In power system network, the characteristic impedance is sometimes referred as surge impedance. It is defined as square root of Z/Y where

Z = Series impedance of line = R+jX

Y = Shunt admittance of line = G+jB

- The term surge impedance is normally reserved for the special case of a lossless line.
- For a lossless line, its resistance and conductance are zero.
- Thus the characteristic impedance reduces to √L/C which is nothing but a pure resistance in terms of dimensions.
- Its value is normally 400 to 600 Ω for an overhead line while for underground cable its value is typically between 40 to 60 Ω.
- The surge impedance of the line can be determined in terms of Z_{OC} and Z_{SC} where Z_{OC} and Z_{SC} are impedances measured at sending end with the receiving end open circuited and short circuited respectively.

Now consider,
$$\bar{V}_S = \bar{A}\,\bar{V}_R + \bar{B}\,\bar{I}_R$$
$$\bar{I}_S = \bar{C}\,\bar{V}_R + \bar{D}\,\bar{I}_R$$

When receiving end is open circuited i.e. $I_R = 0$

$$\therefore \quad \bar{V}_S = \bar{A}\,\bar{V}_R$$
$$\bar{I}_S = \bar{C}\,\bar{V}_R$$
$$\therefore \quad Z_{OC} = \frac{\bar{V}_S}{\bar{I}_S} = \frac{\bar{A}}{\bar{C}}$$

When receiving end is short circuited i.e. $V_R = 0$

$$\bar{V}_S = \bar{B}\,\bar{I}_R$$
$$\bar{I}_S = \bar{D}\,\bar{I}_R$$
$$\therefore \quad Z_{SC} = \frac{\bar{V}_S}{\bar{I}_S} = \frac{\bar{B}}{\bar{D}}$$

Multiplying equations (1) and (2),

$$Z_{OC}\,Z_{SC} = \frac{\bar{A}}{\bar{C}}\,\frac{\bar{B}}{\bar{D}}$$

But $\quad \bar{A} = \bar{D}$

$$\therefore \quad Z_{OC}\,Z_{SC} = \frac{\bar{B}}{\bar{C}}$$

But $\quad \bar{B} = \sqrt{\frac{Z}{Y}}\,\sinh\left(\sqrt{YZ}\right)$

and $\quad \bar{C} = \sqrt{\frac{Y}{Z}}\,\sinh\left(\sqrt{YZ}\right)$

$$\therefore \quad \frac{\bar{B}}{\bar{C}} = \frac{Z}{Y}$$

But $\quad \frac{\bar{B}}{\bar{C}} = Z_{OC}\,Z_{SC}$

$$\therefore \quad Z_{OC}\, Z_{SC} = \frac{Z}{Y}$$

The characteristic impedance is given by,

$$Z_C = \sqrt{\frac{Z}{Y}} \qquad \therefore \quad Z_C^2 = \frac{Z}{Y}$$

$$\therefore \quad Z_{OC}\, Z_{SC} = Z_C^2$$

$$\therefore \quad Z_C = \sqrt{Z_{OC}\, Z_{SC}}$$

When dealing with high frequencies or with surges due to lightning, losses are often neglected and the surge impedance becomes important.

SURGE IMPEDANCE LOADING (SIL)

The surge impedance loading (SIL) of a line is the power delivered by a line to a purely resistive load equal to its surge impedance. The line is assumed to have no resistance. With such loading, the current will be

$$|I_R| = \frac{|V_R|}{\sqrt{3} \times \sqrt{L/C}}$$

where $|V_R|$ is the line to line voltage at the load.

As the load is purely resistive we have,

$$SIL = \sqrt{3}\,|V_R|\,\frac{|V_R|}{\sqrt{3} \times \sqrt{L/C}} = \frac{|V_R|^2}{\sqrt{L/C}}$$

$$\therefore \quad SIL = \frac{V_R^2}{Z_C}$$

- SIL is also called natural power of the line. Sometimes it is convenient to express the power transmitted by a line in terms of per unit of SIL which is the ratio of the power transmitted to the surge impedance loading.
- The permissible loading of a transmission line may be expressed as a fraction of its SIL and SIL provides a comparison of load carrying capabilities of lines.

POWER FLOW THROUGH TRANSMISSION LINE

- The flow of power at any point along a transmission line can be determined with voltage, current and power factor. This power can be derived in terms of the transmission or ABCD parameters. These equations can be applied to any two terminal pair network.
- Fig. 4.35 shows, a transmission line with sending end quantities represented by subscript '5' and receiving end quantities represented by subscript 'R'.

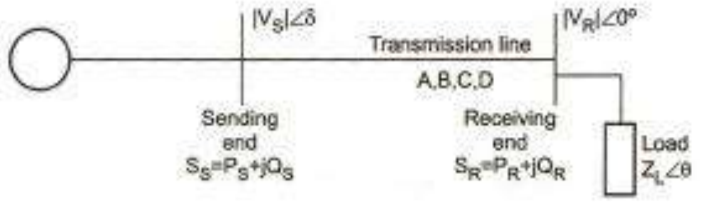


Fig. 4.35

The complex power delivered by the receiving end and that received by the sending end of the transmission line is given as,

$$S_R = P_R + j\,Q_R = V_R\, I_R^*$$

$$S_S = P_S + j\,Q_S = V_S\, I_S^*$$

Here I_R^* and I_S^* are complex conjugate of currents I_R and I_S.

Consider the Fig. 4.36.

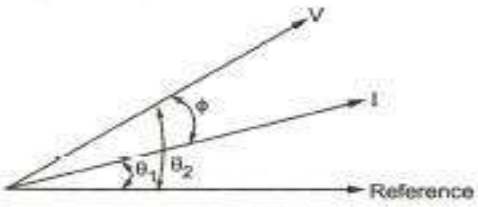


Fig. 4.36

$$P+jQ = VI^*$$

where,
$$V = V[\cos\theta_2 + j\sin\theta_2]$$
$$I = I[\cos\theta_1 + j\sin\theta_1]$$

and
$$I^* = I[\cos\theta_1 - j\sin\theta_1]$$
$$P+jQ = \left[V(\cos\theta_2 + j\sin\theta_2)\right]\left[I(\cos\theta_1 - j\sin\theta_1)\right]$$
$$= VI\left\{\left[\cos\theta_2\cos\theta_1 + \sin\theta_1\sin\theta_2\right] + j\left[\sin\theta_2\cos\theta_1 - \cos\theta_2\sin\theta_1\right]\right\}$$
$$= VI\left[\cos(\theta_2-\theta_1) + j\sin(\theta_2-\theta_1)\right] = VI\left[\cos\phi + j\sin\phi\right]$$
$$= VI\cos\phi + j\,VI\sin\phi$$

Consider the following equation for sending end voltage in terms of ABCD parameters.

$$\bar{V}_S = \bar{A}\bar{V}_R + \bar{B}\bar{I}_R$$

$$\therefore \quad \bar{I}_R = \frac{\bar{V}_S - \bar{A}\bar{V}_R}{\bar{B}}$$

Let $\bar{A} = |A|\angle\alpha$, $\bar{B} = |B|\angle\beta$, $\bar{V}_R = |V_R|\angle 0^\circ$

$$\bar{V}_S = |V_S|\angle\delta$$

Substituting these values in the equation for $\bar{I}_R$

$$\bar{I}_R = \frac{|V_S|\angle\delta - [|A|\angle\alpha][|V_R|\angle 0^\circ]}{|B|\angle\beta}$$

$$\therefore \quad \bar{I}_R = \frac{|V_S|}{|B|}\angle\delta-\beta - \frac{|A|\,|V_R|}{|B|}\angle\alpha-\beta$$

The complex power at the receiving end is given by,

$$P_R + jQ_R = V_R I_R^* = \frac{|V_R||V_S|}{|B|}\angle\beta-\delta - \frac{|A|\,|V_R|^2}{|B|}\angle\beta-\alpha$$

The real and reactive power at receiving end are,

$$P_R = \frac{|V_S|\;|V_R|}{|B|}\cos(\beta-\delta) - \frac{|A|\;|V_R|^2}{|B|}\cos(\beta-\alpha)$$

$$Q_R = \frac{|V_S|\;|V_R|}{|B|}\sin(\beta-\delta) - \frac{|A|\;|V_R|^2}{|B|}\sin(\beta-\alpha)$$

Similarly the sending end complex power is given by

$$P_S + jQ_S = \frac{|D|}{|B|}\,|V_S|^2\angle\beta-\alpha - \frac{|V_S|\;|V_R|}{|B|}\angle\beta+\delta$$

The real and reactive power at sending end are,

$$P_S = \frac{|D|\;|V_S|^2}{|B|}\cos(\beta-\alpha) - \frac{|V_S|\;|V_R|}{|B|}\cos(\beta+\delta)$$

$$Q_S = \frac{|D|\ |V_S|^2}{|B|} \sin(\beta - \alpha) - \frac{|V_S|\ |V_R|}{|B|} \sin(\beta + \delta)$$

The receiving end power will be maximum when $\beta = \delta$ as seen from above equation.

Substituting $\beta = \delta$ in the expression for P_R we get

$$P_{R\,max} = \frac{|V_S|\ |V_R|}{|B|} - \frac{|A|\ |V_R|^2}{|B|} \cos(\beta - \alpha)$$

The corresponding Q_R when P_R is maximum is given by,

$$Q_R = -\frac{|A|\ |V_R|^2}{|B|} \sin(\beta - \alpha)$$

- Thus maximum real power will be received if the load draws the leading reactive power given by above equation.
- Thus it can be seen that there is limit to the power that can be transmitted to the receiving end of the line for specified magnitudes of sending and receiving end voltages.
- When angle 8 becomes equal to 13, maximum power will be transferred or delivered.
- Further increase in 8 results in less power received.
- For achieving the condition of maximum power the load must draw a large amount of leading current which is not practicable. But by using leading VAR compensation the power transfer can be improved.

CIRCLE DIAGRAM

- By taking either V_S, V_R, I_S or I_R as a reference these characteristics can be plotted. These characteristics are nothing but representing circles. Hence such diagrams are called circle diagram.
- A circle diagram is drawn with real power P on X-axis and Q on Y axis on complex plane. The circle diagram can be drawn at the sending end as well as at the receiving end.
- These diagrams are helpful for determination of active power P, reactive power Q, power angle 8, power factor for given load conditions, voltage conditions and impedance Z of the line.

RECEIVING END CIRCLE DIAGRAM

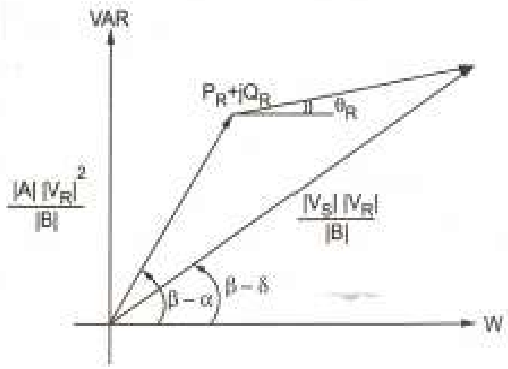
The complex power at the receiving end is given by,

$$S_R = P_R + jQ_R$$

$$= \frac{|V_S|\ |V_R|}{|B|} \angle\beta - \delta - \frac{|A|\ |V_R|^2}{|B|} \angle\beta - \alpha$$

$$P_R = \frac{|V_S|\ |V_R|}{|B|} \cos(\beta - \delta) - \frac{|A|\ |V_R|^2}{|B|} \cos(\beta - \alpha)$$

$$Q_R = \frac{|V_S|\ |V_R|}{|B|} \sin(\beta - \delta) - \frac{|A|\ |V_R|^2}{|B|} \sin(\beta - \alpha)$$



The real component of $(P_R + jQ_R)$ is,

$P_R = |V_R|\ |I_R| \cos\theta_R$

where θ_R is p.f. at the receiving end

The imaginary component of $(P_R + jQ_R)$ is,

$Q_R = |V_R|\ |I_R| \sin\theta_R$

Here θ_R is the phase angle by which I_R lags behind V_R. the inductive load draws positive reactive power. Now the phasor diagram is redrawn with the origin of the co-ordinates axes shifted, the resultant figure is shown in Fig.4.38.

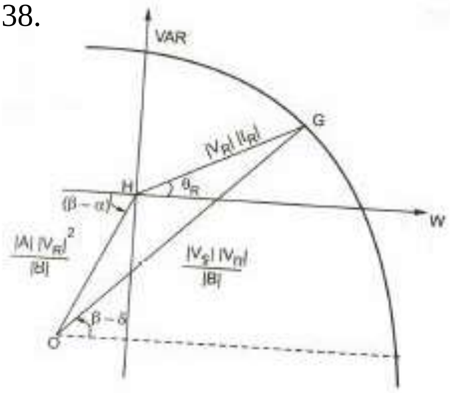


Fig. 4.38

It can be shown that for constant values of V_R and V_S and for variable values of I_R the point G moves on a circle with centre O.

In Δ OGH

$$V_S = |A|\ |V_R|[-\cos(\beta-\alpha)+j\sin(\beta-\alpha)]+|B|\ |I_R|[\cos\theta_R - j\sin\theta_R]$$

$$= |A|\ |V_R|[-\cos(\beta-\alpha)]+|B|\ |I_R|\cos\theta_R + j[|A|\ |V_R|\sin(\beta-\alpha)-|B|\ |I_R|\sin\theta_R]$$

Let $|A|\ |V_R|[\cos(\beta-\alpha)] = -x_1$

$|B|\ |I_R|\cos\theta_R = x_2$

$|A|\ |V_R|\sin(\beta-\alpha) = y_1$

$|B|\ |I_R|\sin\theta_R = -y_2$

The above equations are now reduced as,

$$V_S = (x_1+x_2)+j(y_1+y_2) \quad \text{... (1)}$$

The conjugate of V_S can be written as,

$$V_S^* = (x_1+x_2)-j(y_1+y_2) \quad \text{... (2)}$$

Multiplying equations (1) and (2),

$$V_S^2 = (x_1+x_2)^2+(y_1+y_2)^2$$

The above equation represents a circle with its centre at O and having co-ordinates $(-x_1,-y_1)$

All the phasors shown in Fig. 4.39 represent voltage. In order to represent them as volt amperes, multiply each phasor by constant V_R/B, which represents a current phasor because B has dimensions of impedance.
The co-ordinates of the centre of the receiving end circle are given as

$$x_1 = -\frac{|A|\ |V_R|^2}{|B|}\cos(\beta-\alpha)$$

$$y_1 = -\frac{|A|\ |V_R|^2}{|B|}\sin(\beta-\alpha)$$

The radius OG of the circle is given by,

$$\text{Radius} = \frac{|V_S|\ |V_R|}{|B|}$$

The θ_R is the phase angle by which V_R leads I_R. The position of point O is independent of load current I_R and will not change as long as IVRI is constant. Further more if values of Vs and V_R are constant then distance OG remains constant.
Now with change in load, the distance between points Hand G goes on changing. As the values of Vs and V_R are fixed, distance between points O and G remains same which constrain point G to move on a circle with centre at *O* and radius as O*G*.
In order to keep point G on the circle it is required that with change in P_R, Q_R should also change. If values of sending end voltages are changed then for same values IVRI, the position of point O is unchanged but a new circle with different radius is obtained.

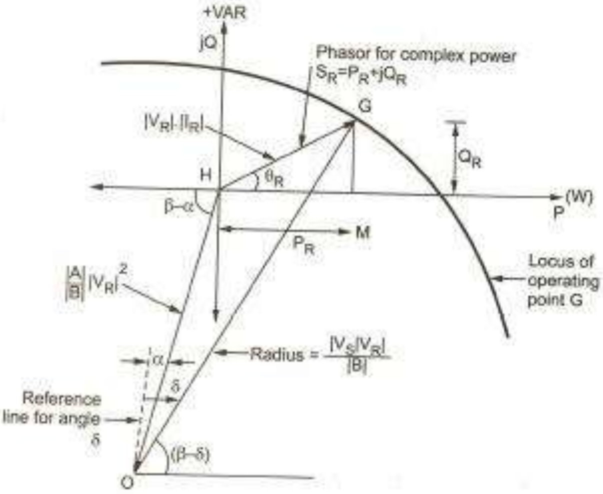


Fig. 4.40

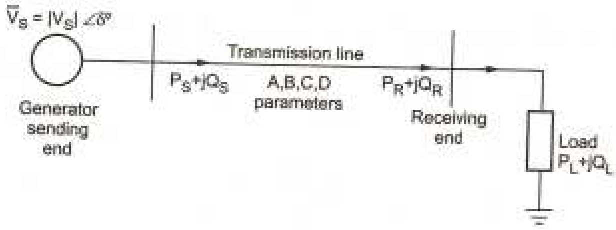
An increase in power delivered means that point G will move along the circle until the angle $\beta-\delta$ is zero. Thus so long as $\delta=\beta$, maximum power is delivered. With further increase in δ, results in less power at receiving end. The equation for maximum power is given by,

$$P_{R\,max} = \frac{|V_S|\ |V_R|}{|B|} - \frac{|A|\ |V_R|^2}{|B|}\cos(\beta-\alpha)$$

Methods of Voltage Control

- The electrical energy generated in the generating station is supplied to the consumers through the network of transmission and distribution. For satisfactory operation of various loads at the consumer end, it must be supplied with fairly constant voltage.

- In order to avoid erratic operation or malfunctioning of appliances at the consumer end, the voltage must be controlled and kept within permissible limits.



- Consider the two bus system shown in Fig. 4.47. Let the line is having negligible resistance and consists of series reactance. For fixed sending end voltage and at the given receiving end voltage, the real and reactive powers are given by,

$$P_R = \frac{|V_R^s|\ |V_S|}{X_L} \sin\delta$$

$$Q_R^s = \frac{|V_R^s|}{X_L}\left[|V_S| - |V_R^s|\right]$$

$$Q_R^s X_L = |V_R^s|\ |V_S - |V_R^s|^2$$

$$\therefore\ |V_R^s|^2 - |V_S|\ |V_R^s| + Q_R^s X_L = 0$$

The roots of above quadratic equation are given by,

$$|V_R^s| = \frac{1}{2}|V_S| + \frac{1}{2}|V_S|\left[1 - \frac{4X_L Q_R^s}{|V_S|^2}\right]^{1/2}$$

As the real power demanded by the load must be delivered by line

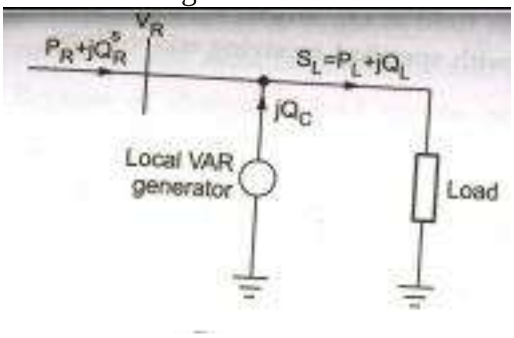
$$P_R = P_L$$

The various methods employed for voltage control include
i) Use of series capacitors
ii) Use of shunt capacitors
ill) Use of static VAR sources
iv) Use of shunt reactors
v) Tap changing of transformers.

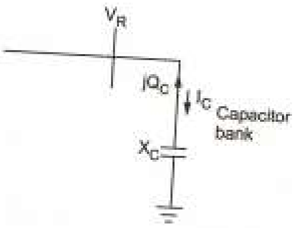
Reactive Power Injection

1. It can be seen from the previous section that to maintain the receiving end voltage at its specified value, a fixed amount of VARs (Q_R^S) must be drawn from the line. A local VAR generator must be used for conditions of varying VAR demand Q_L.
2. The VAR balance equation at the receiving end is given as,
$$Q_R^S + Qc = Q_L$$
3. The fluctuations in QL are absorbed by local VAR generator in such a way that total VAR drawn by the line remain fixed at Q_R^S.
4. The receiving end voltage is therefore maintained at fixed value of IV $_R$ ^{S} I. This is shown in Fig. 4.48.

5. This is nothing but compensation of VAR which can be made automatic by taking signal from VAR meter installed at receiving end.



Static VAR Generator



It consists of bank of 3 phase static capacitors and/ or inductors.

$$I_C = \frac{|V_R|}{\sqrt{3}[-jX_C]} = j\frac{|V_R|}{\sqrt{3}\,X_C}$$

For 3 phases,

$$jQ_C = j\,3\,\frac{|V_R|}{\sqrt{3}}\left(I_C^{*}\right) = j3\frac{|V_R|}{\sqrt{3}}\left[-j\frac{|V_R|}{\sqrt{3}\,X_C}\right]$$

$$\therefore \qquad Q_C = \frac{|V_R|^2}{X_C}\ \text{MVAR}$$

If inductors are used instead of capacitors,

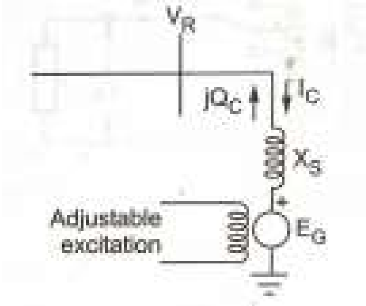
$$Q_L = -\frac{|V_R|^2}{X_L}\ \text{MVAR}$$

1. When the load on power system is high then positive VARs are required. The capacitor banks are used while when light load is there on the system, negative VARs are required the inductor banks are switched ON.
2. The variation of Q_C is proportional to V_R^2. So under heavy load condition when voltage decreases Q_C may not prove to be effective.

Rotating VAR Generator

1. It is nothing but a synchronous motor running at no load. The excitation of this motor can be adjusted over a wide range.
2. In overexcited condition it supplies positive VARs whereas gives negative VARs when underexcited. The synchronous motor running under this condition is called synchronous condenser.
3. The synchronous condenser is connected to the receiving end bus bars and runs under no load condition.
4. It takes negligibly small real power such that Ec and VR are almost in phase. Xs is the synchronous reactance of the motor. The motor is having negligible resistance.

$$I_C = \frac{(|V_R| - |E_G|)\angle 0^{\circ}}{\sqrt{3}\times j\,X_S}$$



$$\text{Reactive power, } jQ_C = j\,3\,\frac{|V_R| \angle 0^\circ}{\sqrt{3}}\, I_C^*$$

$$= j\,3\,\frac{|V_R|}{\sqrt{3}}\left[+\frac{|V_R| - |E_G|}{\sqrt{3}\times(-jX_S)}\right]$$

$$\therefore \quad Q_C = |V_R|\,\{[\,|E_G| - |V_R|\,]/X_S\} \text{ MVAR}$$

Control by Tap Changing Transformer

1. This method is employed for narrow range of voltage control. Due to VAR demands of load, the receiving end voltage tends to decrease which can be raised by simultaneous tap changing on sending and receiving end transformers.
2. It can be done either on no load or on load. Thus there are two types of tap changing transformers viz on load and on no load.
3. The impedances of the transformers are taken along with line impedances. These tap changing transformers do not control the voltage by controlling the flow of VARs but by changing the transformation ratio, the voltage in the secondary circuit is varied and voltage control is achieved.
4. Let ts and tr are the fractions of the nominal transformation ratios i.e. tap ratio/nominal ratio. The product of ts and tr is taken as unity for ensuring uniformity in voltage level.

$$t_s V_s = t_r V_R + IZ$$

The approximate line drop is given as

$$IZ = \Delta V = IR\cos\phi + IX\sin\phi$$

$$= RI\cos\phi + XI\sin\phi$$

$$= \frac{RP}{t_r V_R} + \frac{XQ}{t_r V_R}$$

$$= \frac{R\cdot P X\cdot Q}{t_r V_R}$$

$$\therefore \quad t_s V_S = t_r V_R + \frac{R\cdot P + X\cdot Q}{t_r V_R}$$

$$\therefore \quad t_s = \frac{1}{V_S}\left[t_r V_R + \frac{R\cdot P + X\cdot Q}{t_r V_R}\right]$$

$$\text{But} \quad t_s t_r = 1$$

$$\therefore \quad t_s = \frac{1}{V_S}\left[\frac{V_R}{t_s} + \frac{R\cdot P + X\cdot Q}{V_R / t_s}\right]$$

$$t_s = \frac{1}{V_S}\left[\frac{V_R}{t_s} + \frac{t_s(R\cdot P + X\cdot Q)}{V_R}\right]$$

$$t_s^2 = \frac{V_R}{V_S} + \left(\frac{R\cdot P + X\cdot Q}{V_R V_S}\right) t_s^2$$

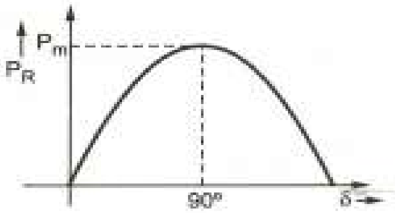
$$t_s^2\left[1 - \left(\frac{R\cdot P + X\cdot Q}{V_R V_S}\right)\right] = \frac{V_R}{V_S}$$

Power Angle Diagram

1. We have already seen that after neglecting resistance and shunt admittance of the line the power at the receiving end is given by,

$$P_R = \frac{|V_S|\ |V_R|}{X_L} \sin \delta$$

2. The angle δ is called phase angle or the torque angle or load angle between sending and receiving end voltages.
3. With increase in load, angle δ also increases.
4. But it has limit beyond which power flow is not increased. This upper limit is called stability limit.



5. When there is sudden change in transmission system, change in load, tripping of generator or load, sudden switching load, any fault etc. brings about oscillations in angle δ.
6. If load angle δ goes beyond 90°, the synchronism is lost and the transmission system fails to transfer the power. Pm is called steady state stability limit and is given by,

$$P_m = \frac{|V_S|\ |V_R|}{X_L}$$

Ferranti effect

A long transmission line under no conditions, the voltage at receiving end is more than that at sending end because of the effect of line capacitance. This is called Ferranti effect.

In case of long transmission line, the equation for V_S is given by,

$$V = \left(\frac{V_R + I_R Z_C}{2}\right) e^{\gamma x} + \left(\frac{V_R - I_R Z_C}{2}\right) e^{-\gamma x}$$

But $\gamma = \alpha + j\beta x$

$$V = \left(\frac{V_R + I_R Z_C}{2}\right) e^{\alpha x} e^{j\beta x} + \left(\frac{V_R - I_R Z_C}{2}\right) e^{-\alpha x} - e^{-j\beta x}$$

For a line length of l

$$V_S = \left(\frac{V_R + I_R Z_C}{2}\right) e^{\alpha l} e^{j\beta l} + \left(\frac{V_R - I_R Z_C}{2}\right) e^{-\alpha l} - e^{-j\beta l}$$

At $l = 0$, $I_R = 0$ as the line is at no load.

$$V_S = \frac{V_R}{2} + \frac{V_R}{2} = V_R$$

Series Compensation

1. This is one of the method of reactive power control. Compensation of a transmission line with the help of series capacitor is called as series compensation.
2. For compensating the series reactance of the line the series capacitor is inserted in the line at a specified point. This type of compensation is provided for long transmission lines having voltages 220 kV and above.
3. The capacitors are connected in series with the line for the compensation of inductive reactance of the line as shown in the Fig. 4.58.

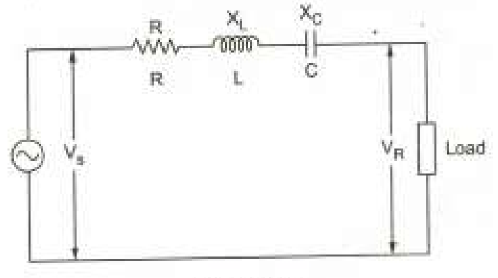


Fig. 4.58

Fig. 4.60 shows how the voltage drop increases with the distance from the sending end and how the voltage increases due to series capacitor.

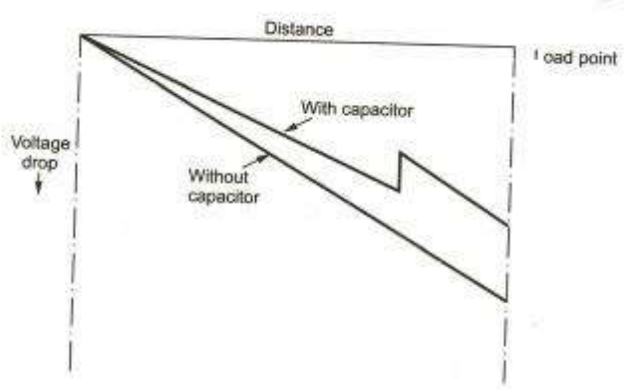


Fig. 4.60

Advantages of Series Compensation

1. Increase in power transmission capacity of the line.
2. Improvements in system stability
3. Improved voltage regulation
4. Load division between parallel circuits
5. Damping effect

Shunt Compensation

1. The provision of shunt capacitor involves insertion of shunt capacitor across the line in order to improve the power factor and voltage as well as to reduce losses.
2. The simplified equivalent of a transmission line with shunt connected capacitor is shown in the Fig. 4.62 and the corresponding phasor diagram is shown in the Fig.4.63.

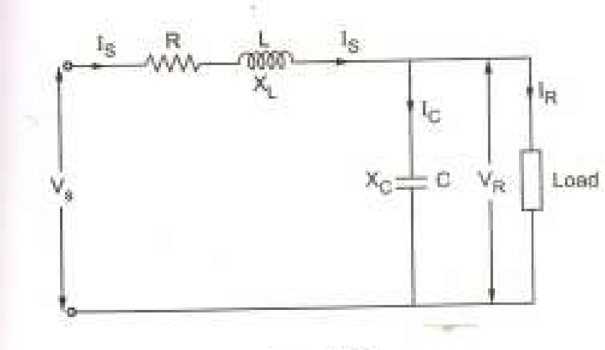


Fig. 4.62

The Fig. 4.64 shows that, unlike the effect with a series capacitor, the voltage rise is distributed uniformly along the length of the line.

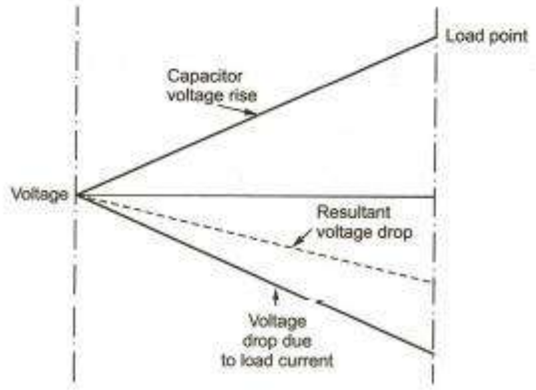


Fig. 4.64

The phase angle between the voltage and the current is reduced when shunt capacitor is applied. It has the following effects.

1. It reduces line current losses owing to generation of reactive power.
2. It reduces the transmission line current to a value less than the current in the load.
3. It improves the power factor of the transmitted power.
4. It reduces the voltage drop uniformly along the length of the line.

Advantages

As the power factor is improved with shunt capacitor, we get following advantages

1. The kW of alternators, transformers and lines are increased.
2. The line current is reduced.
3. The losses in power tra n sformer and cables are reduced which saves energy.
4. It prevents overloading of transformers and switchgears.
5. Improved voltage is obtained at the receiving end.
6. The life of connected equipment likes cables, switchgear etc. is increased due to improved voltage and reduced current.
7. It saves penalty imposed by electricity boards for lower power factor.