POWER SYSTEM ARCHITECTURE (20A02501)

LECTURE NOTES

III-B.Tech I-Semester

Prepared by

Dr. A. Hema Sekhar, Professor

Department of Electrical and Electronics Engineering

VEMU INSTITUTE OF TECHNOLOGY

(Approved By AICTE, New Delhi and Affiliated to JNTUA, Ananthapuramu)

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Near Pakala, P.Kothakota, Chittoor- Tirupathi Highway

Chittoor, Andhra Pradesh-517 112

Web Site: www.vemu.org

JAWAHARLAL NEHRU TECHNOLOGICAL UNIVERSITY ANANTAPUR

B.Tech (EEE)– III-I Sem **L T P C**
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(20A02501) POWER SYSTEM ARCHITECTURE

Course Objectives:
- Operation of Conventional Power generating systems and their components.
- The role of non-conventional power generating systems and their operation and economic aspects.
- Calculation of different transmission line parameters and their use.
- Modeling of transmission line and evaluation of constants.

Course Outcomes:
- Remember and understand the concepts of conventional and nonconventional power generating systems.
- Apply the economic aspects to the power generating systems.
- Analyse the transmission lines and obtain the transmission line parameters and constants.
- Design and develop the schemes to improve the generation and capability of transmission line to meet the day-to-day power requirements.

UNIT I POWER GENERATING SYSTEMS

Thermal Power: Block Diagram of Thermal Power Station (TPS), Brief Description of TPS Components
Hydro Power: Selection of Site, Classification, Layout, Description of Main Components.
Nuclear Power: Nuclear Fission and Chain Reaction-Principle of Operation of Nuclear Reactor.-Reactor Components: Moderators, Control Rods, Reflectors and Coolants- Radiation Hazards: Shielding and Safety Precautions- Types of Nuclear Reactors.
Solar Power Generation: Role and Potential of Solar Energy Options, Principles of Solar Radiation, Solar Energy Collectors, Different Methods of Energy Storage – PV Cell- V-I Characteristics.
Wind Power Generation: Role and potential of Wind Energy Options, Horizontal and Vertical Axis Windmills- Performance Characteristics-Pitch & Yaw Controls – Economic Aspects.

UNIT II TRANSMISSION LINE PARAMETERS

Types of conductors - calculation of resistance for solid conductors, Bundle conductors, Skin effect, Proximity effect, concept of GMR & GMD- Transposition of Power lines- Calculation of inductance for single phase and three phase, single and double circuit lines, symmetrical and asymmetrical conductor configurations with and without transposition. Calculation of capacitance for 2 wire and 3 wire systems, effect of ground on capacitance, capacitance calculations for symmetrical and asymmetrical single and three phase, single and double circuit lines, Numerical Problems.

UNIT III MODELING OF TRANSMISSION LINES

Classification of Transmission Lines - Short, medium and long lines and their models - representations - Nominal-T, Nominal-π and A, B, C, D Constants. Mathematical Solutions to estimate regulation and efficiency of all types of lines- Long Transmission Line-Rigorous Solution, evaluation of A,B,C,D Constants, Interpretation of the Long Line Equations – Representation of Long lines – Equivalent T and Equivalent – π, Numerical Problems – Surge Impedance and surge Impedance loading - Types of System Transients - Travelling or Propagation of Surges - Attenuation, Distortion, Reflection and Refraction Coefficients-Termination of lines with different types of conditions-wavelengths and Velocity of propagation – Ferranti effect, Charging current, Need of Shunt Compensation.

UNIT IV INSULATORS, CORONA AND MECHANICAL DESIGN OF LINES AND CABLES

Types of Insulators, String efficiency and Methods for improvement, Numerical Problems – Voltage Distribution, Calculation of string efficiency, Capacitance grading and Static shielding. Corona - Description of the phenomenon, factors affecting corona, critical voltages and power loss, Radio Interference. Sag and Tension Calculations with equal and unequal heights of towers, Effect of Wind and Ice on weight of Conductor, Numerical Problems - Stringing chart and sag template and its applications. Types of Cables, Construction, Types of Insulating materials, Calculations of Insulation resistance and stress in insulation, Numerical Problems.

UNIT V GENERAL ASPECTS OF DISTRIBUTION SYSTEMS

Classification of Distribution Systems - Comparison of DC & AC and Under-Ground & Over - Head Distribution Systems. Voltage Drop and power loss in D.C Distributors for the following cases: Radial D.C Distributors fed at one end and at ends (equal/unequal Voltages), Uniform loading and Ring Main Distributor, LVDC Distribution Network. Design Considerations of Distribution Feeders: Radial and loop types of primary feeders, feeder loading; basic design of secondary distribution. Voltage Drop and power loss in A.C. Distributors.

SUBSTATIONS:

Location of Substations: Rating of distribution substations, service area within primary feeders. Benefits derived through optimal location of substations.

Classification of substations: Air insulated substations - Indoor & Outdoor substations: Substation layout showing the location of all the substation equipment – Gas Insulated Substation (GIS).

Textbooks:

1. A Text Book on Power System Engineering by M.L.Soni, P.V.Gupta, U.S.Bhatnagar and A.Chakraborti, DhanpatRai& Co. Pvt. Ltd., 1999.
2. Electric Power Generation Distribution and Utilization by C.L Wadhwa, New Age International (P) Ltd., 2005.
3. Non Conventional Energy Sources by G.D. Rai, Khanna Publishers, 2000.

Reference Books:

1. Renewable Energy Resources – John Twidell and Tony Weir, Second Edition, Taylor and Francis Group, 2006.
2. Electrical Power Generation, Transmission and Distribution by S.N.Singh., PHI, 2003.
3. Principles of Power Systems by V.K. Mehta and Rohit Mehta, S.CHAND& COMPANY LTD., New Delhi 2004.
4. Wind Electrical Systems by S. N. Bhadra, D. Kastha& S. Banerjee – Oxford University Press, 2013.

Online Learning Resources

1. https://onlinecourses.nptel.ac.in/noc22_ee17/preview

Power System Architecture (PSA)

Dr. A. Hema Sekhar

Unit-1 : Power Generating Systems

Thermal power : Block diagram of Thermal power station (TPS), Brief Description of TPS components

Hydro power : Selection of site, classification, Layout, Description of main components.

Nuclear power : Nuclear Fission & chain Reaction - Principle of operation of Nuclear Reactor - Reactor components : moderators, control Rods, Reflectors and coolants - Radiation Hazards : shield and safety precautions - Types of Nuclear Reactors.

Solar power Generation : Role and potential of solar energy options, Principles of Solar Radiation, solar energy collectors, Different methods of energy storage - PV cell - VI characteristics

wind power Generation : Role & potential of wind energy options, Horizontal & Vertical axis wind mills - Performance characteristics, Pitch & Yaw controls - Economic Aspects.

Introduction:

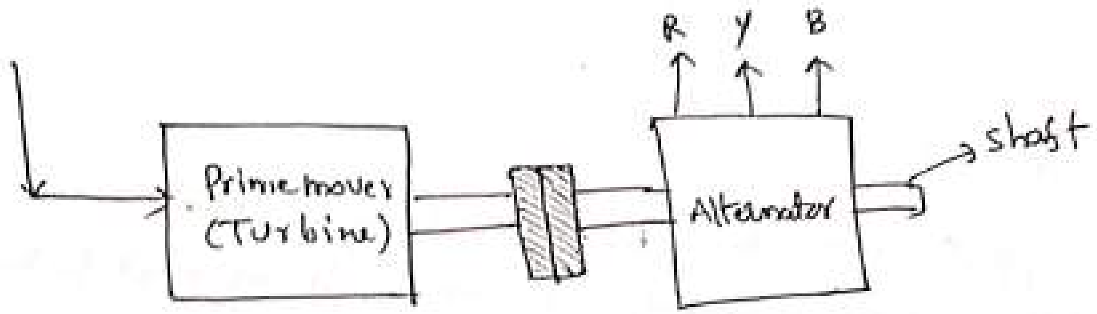
- Energy is basic necessity for the economic development of a country many functions necessary to present day living grind to halt when supply energy stops.
- This energy neither be created nor be destroyed but it can be converted from one form to another form.
- The generation of electrical energy is nothing but conversion of various ~~fossil~~ other forms of energy into an electrical energy. The various energy sources which are used to generate an electrical energy on the large scale are (i) Fuels (ii) water (iii) Nuclear energy (iv) Solar (v) wind (vi) GeoThermal (vii) Tidal energy.
- The electrical power is generated in bulk at the generating stations ~~are~~ which are also called as power stations.

- Depending upon the source of energy used, these stations are called thermal power stations, Hydro electric power stations, nuclear power stations, solar & wind power stations etc.

Generation of electrical Energy:

"The conversion of different sources of energy available in nature into electrical energy is known as Generation of electrical energy.

Fig shows basically consists of prime mover coupled to alternator. The prime mover may be turbine, engine, water wheel or other similar machine. when the prime mover driven by the source of energy such as coal energy, water energy or wind energy, it converts the sources of energy into mechanical energy. The turbine in turn drives an alternator that converts mechanical energy into electrical energy.



Sources of energy:

To meet the ever increasing demand of electrical energy, we must make use of all sources of energy in nature.

The sources can be classified into two types.

(1) conventional sources

(2) Non conventional sources.

(1) conventional sources:

These sources are dependable & are commonly used for bulk power of electrical energy.

These are sources which provides a net supply of energy.

(a) solid fuels (Lignite, coal)

(b) Liquid fuels (Heavy oil, Diesel oil, petrol)

(c) Gaseous fuels (Natural gas, petrolium gas)

(d) water power

(e) Nuclear power

(2) Non conventional Sources:

- These sources are natural sources, which are new and alternate to conventional sources of energy.

- These sources are also called as ~~Renewab~~ Renewable energy sources

- These are

(a) The sun

(b) The wind

(c) ocean Tides & waves

(d) Geo Thermal energy

(e) Biomass energy

(f) Fuel cells

(g) magneto Hydro dynamic generation

(h) piezeo electric power

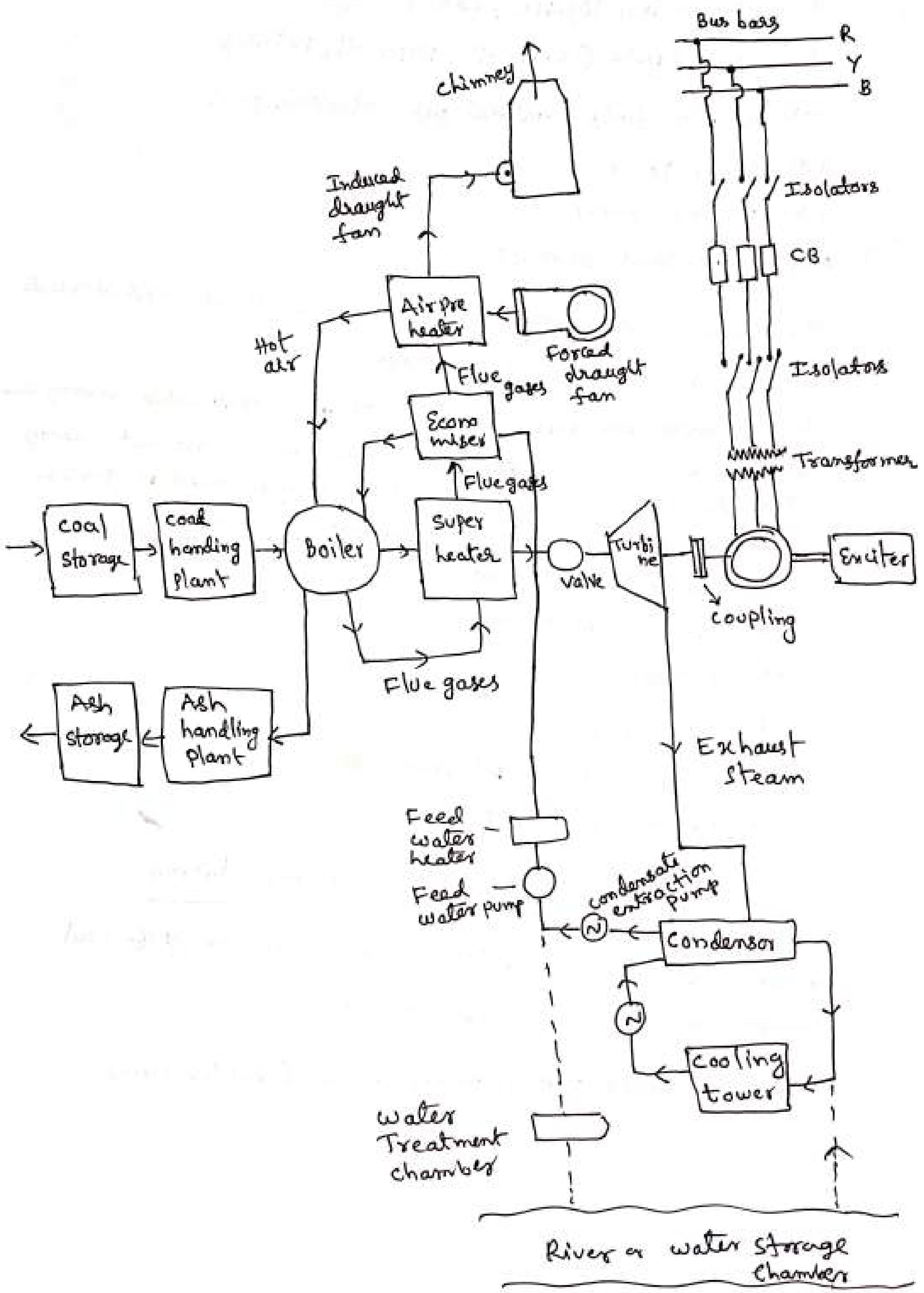
* These sources produce no net energy Though it may be necessary for the development of economy.

Thermal Power station or steam power station

A Generating station which converts heat energy of coal combustion into electrical energy

- steam power station works on the Rankine cycle.

Block diagram of Thermal Power plant



Various components in Thermal power plant

various components are

(a) coal handling Arrangement (50 to 60% of total operating cost)
(b) steam generating plant
(c) steam turbines
(d) alternator
(e) Feed water
(f) cooling arrangement
(g) Exciter
(h) Instrumentation equipement
(i) chimney
(j) Ash handling equipment

(a) coal handling arrangement :

- most of the thermal power plants use coal as the fuel.
- In order of increasing heat value, the coals are four types of available forms

1. Peat
2. Lignite (5000 kcal/kg, ash = 6%. c = 67, H = 5%. o = 20%.
3. Bituminous [sub. bituminous / semi bituminous (7600 kcal/kg, ash = 6.5%.) c = 83, H = 5.5, o = 5
4. Anthracite (8500 kcal/kg, ash 5%.) c = 90%. H = 3%. o = 2%. ash = 5%.

- Normally semi bituminous coal is used in thermal power plants. It has low percentage of moisture, ash and volatile matter and has good percentage of available hydrogen.
- Some of the equipments used in coal handling arrangement. These are
  - Unloading equipement : Unloading may be done by car shakers, rotatary car dampers, cranes, buckets, trucks and lifts etc.

Preparation:

- coal is delivered to power station in the form of big sizes. Hence it needs to prepare proper sizes of coal and it can be done by crushers, sizers, magnetic seperators, driers and breakers.

Transfer equipment:

After preparation of coal it is then transferred to dead storage by means of belt conveyors, Grab bucket elevators, screw conveyors, skip hoist and etc.

Storage equipment & weighing devices:

From the dead storage plant to live storage plant, the preparation coal is transfered by cranes and bulldozers, conveyors then moved to weighing equipment arrangent which consists of scales, coal meters and samplers. Note: For 100 mw PS, 20000 tons per month of coal needs

(b) Steam generating plant:

Steam generating plant consists of the following

- Boiler
- Super heater
- Economiser
- Air preheater

Boiler:

- Here, the heat is developed due to the combustion of coal is utilized in the boiler ~~by~~ for converting the water into steam at high temparature and pressure.
- The flue gases from the boiler will flow through super heater, Economiser, Air preheaters and finally exhausted to the atmosphere through the chimney. $\boxed{320^\circ c \ \& \ 170 \ kg/cm^2}$
- Two types of boilers are there
  1. water tube boilers: water flows through the tubes and hot gases of combustion flow over these tubes
  2. Fire tube boilers: hot products of combustion pass through the tubes surrounded by water. Note: Generally we use water tube boilers.

Super heater :

The steam produced in the boiler is wet and if this steam passed through the steam turbines causes turbines may get damaged. In order to avoid this condition, the steam produced from the boiler is passed through a super heater where it is dried & super heated upto $\boxed{565°c}$.

Note: ① Radient super heater ② Convection super heater
– Normally 2nd one is used.

adv : (i) by superheating the steam, overall efficiency is increased
(ii) too much condensation in the last stages of ~~condensate~~ turbine is avoided.

Economiser:

An economiser is essentially a feed water heater. The feed water is fed to the economiser before supplying to the boiler. The economiser increases the feed water temperature.

Air preheater :- It is placed in between boiler & economiser.

- An air preheater increases the temperature of the air supplied for coal burning by deriving heat from flue gases.
- Air is drawn from the atmosphere by a forced draught fan and is passed through air preheater before supplying to the boiler furnace.
- Air preheater extracts heat from the flue gases and increases the temperature of air used for coal combustion.
- Two types ① Recuperative type ② Regenerative type.
- Generally ~~Regenerative~~ Recuperative type is used.

(c) Steam turbines :

- A steam turbine is a rotating machine which converts heat energy of steam into mechanical energy.
- The super heated steam from the super heater is fed to the steam turbine which will convert heat energy into mechanical energy.

Steam turbines are of two types
(1) Impulse turbine
(2) Reaction turbine

- In case of Impulse turbines, the steam expands completely in the stationary nozzles or fixed blades, the pressure over the moving blades remains constant. In doing so, the steam attains a high velocity and impinges against the moving blades. Hence impulse force on the moving blades which sets the rotor rotating.
- In case of Reaction turbines, the steam is partially expanded in the stationary nozzles and for remaining expansion takes place during the flow over the moving blades
- Generally, for LP turbines reaction turbines and HP turbine impulse type are used.

(d) Alternator:

- An alternator is coupled on the same shaft of the turbine which will converts mechanical energy of turbine into electrical energy. and then this electrical energy is delivered to bus bars.

(e) Feed water:

- The steam coming out from the turbine is condensed and the condensate is fed back to the boiler as feed water.
- To reduce the losses in the closed water ckt, make up water is added.

(f) cooling arrangement:

- In order to improve the efficiency of the plant, the steam exhausted from the turbine condensed by means of a condenser.

- water is drawn from the natural source of supply such as river, canal or lake and is circulated through the condenser.
- The circulating water takes up the heat of the exhausted steam and itself becomes hot. This hot water is discharged at a suitable location down the river.
- In case of availability of water from the river is not assured throughout the year then cooling towers are used.
- Jet & Surface condensers. In that, surface type is used.

(g) Exciter:

- Exciters are nothing but DC generators. Its main function is to supply DC power to the field of alternator.
- The capacity of the exciter is 0.5 to 3% of alternator capacity.

(h) Instrument equipment:

- In TPS, different types of Instruments are needed for estimating the performance & cost calculations.
  - mechanical type are used for measuring the temperature, oil pressure, air pressure, ash level & coal level etc.
  - Electrical type are used are Ammeters, voltmeters, wattmeters, power factor meters, relays, CB and etc.

(i) chimney:

- chimneys are made up of steel or bricks & concrete.
- concrete chimneys are more popular
- Avg life for concrete type is 50 years & for steel is 15 years.
- chimneys are provided with lightning conductors & air craft warning lights.

(j) Ash handling equipment:

- For 20,000 tons coal per month, ash produced is 2000 to 3000 tons of ash.

– The ash handling equipement should have

- It should be able to handle large quantities of ash
- The equipment should be free from the troubles.
- It should be free from corrosion & wear.
- capital, operating & maintanance cost should be low.

Main components of steam Power Plant

① coal and ash handling plants:

- In steam power plant, The coal is used as fuel.
- Generally The coal is stored in a coal storage plant where coal is tranferred from all The parts of The country by rail or road. This helps to supply The coal continuously, in case of strikes, failure of transportation system.
- Then The coal is transferred to coal handling plant where The coal is pulverized i.e crushed into small pieces. The pulverization increases The surface exposure of The coal.
- Then The pulverization of coal helps for rapid combustion of coal without using large quantity of air. Then The crushed coal is transferred to boiler

⇒ As a result of combustion of The coal, large quantity of ash produced in The boiler. For The proper combustion of The coal, The ash is removed to ash handling plant, Then it is delivered to The ash storage plant, where it is disposed off.

② Steam Generating plant:

- The main component of steam generating plant is The boiler for The production of steam and other auxillary equipment for The utilization of flue gas

(a) Boiler:

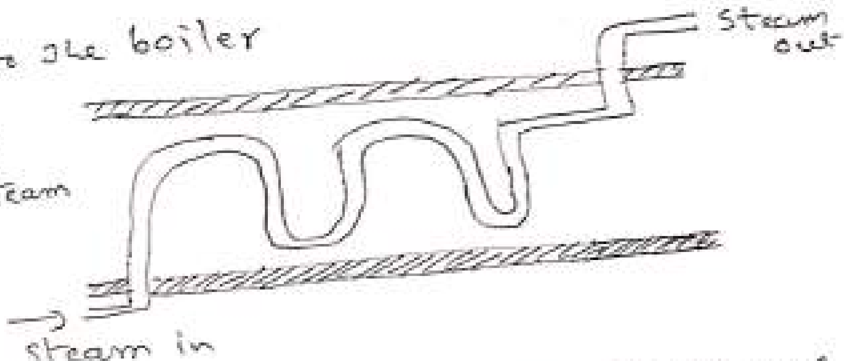
- Boiler is a closed vessel where water is converted to The steam using The heat of The coal combustion.

hence boiler is called steam generator.

- The steam produced in the boiler contains suspended water particles and hence called wet steam. and it has high temp & pressure (365°...)
- There are two types of boilers
  - water tube boiler: water moves inside the tubes and the tubes will be surrounded by hot flue gases.
  - Fire tube boiler: hot flue gases travels inside the tubes and water surrounds the tubes.

  Generally water tube boilers are used because it occupies less space, smaller in size & drum, high working pressure, less liable to explosion etc.

(b) Super heater:

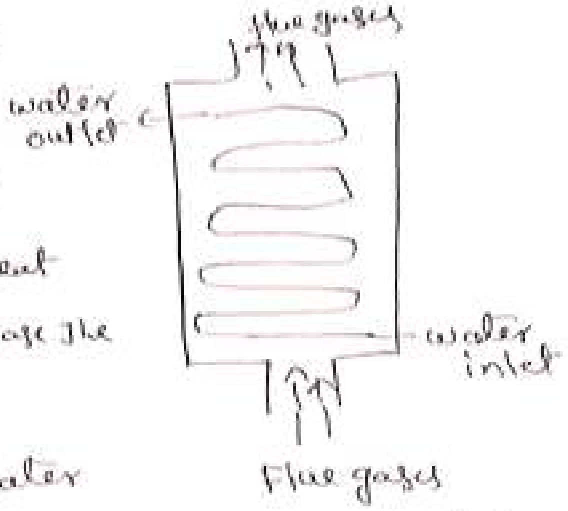


- It is accessory attached to the boiler
- super heater is a device which super heats the steam
- Generally, the steam produced in the boiler is wet, when this wet steam is passed through the superheater becomes dried and super heated by the flue gases on their way to chimney.
- super heater increase the overall efficiency.
- A superheater consists of group of tubes made of special alloy such as chromium-molybdenum. It is placed in the path of flue gases
- super heater are two types according to the system of heat transfer from the flue gases to steam.
  1. Radiant superheater: It is placed in furnace between the water walls and receives heat from the burning of fuel through radiation process. It has two disadvantages
     - due to high furnace temperature, it may get overheated so careful design is required.
     - temp of super heater falls with increase of steam output

- Convenction superheater : It is placed in the boiler tube bank and receives heat from the flue gases through convenction process. It has advantages that, the temp of superheater increases with increase of steam output.
- Normally convenction type are used.

Economiser:

- It is another type of accesory attached to boiler
- It consists of large number of closely spaced parallel tubes connected by headers of drums.



- It is used to extract heat from the flue gases to increase the feed water temperature.
- High temperature of feed water reduces the stress in the boiler and increases the boiler efficiency.

Dis adv : Economisers are extra expenses which in cost of installation & maintenance, regularly cleaning & more space area is required.

Air preheater :

- The function of Air preheater is to extract the heat from the flue gases and increases the temperature of air used for coal combustion.
- It increases the thermal efficiency of the plant.
- Depending upon the method of transfer of heat from the flue gases air preheaters are two types

(1) Recuperative type : It consists of group of steel tubes. The flue gases are passed through the tubes while air flows externally to the tubes by forced draught fan. Thus the heat of the flue gases transferred to air.

(2) Regenerative type : It consists of slowly moving

drum made up corrugated metal plates. The flue gases flow continuously on one side of drum and air on the other side. Thus, air becomes hot.

(3) Steam turbines:

- The dry and superheated steam from the superheater is supplied to the turbine. here the heat energy of steam is converted into mechanical energy as steam passes over the turbine blades
- steam turbines are two types
  (a) Impulse turbine: At the inlet of the turbine, If available energy is only kinetic energy, the the turbine known as impulse turbine.
  - In this the steam expands completely in the stationary nozzle and pressure over the moving blades remains const. here the steam attains very high velocity & impacts on moving blades giving rise to impulsive force on them. Thus turbine starts rotating.

    Eg: pelton wheel.
  - Generally Impulse turbines are used for high heads & low discharges.

  (b) Reaction turbine:
  - In this, At the inlet of the turbine, if the available energy is kinetic energy as well as pressure energy, then the turbine is known as Reaction turbine.
  - Also, the steam is partially expanded in the stationary nozzle and remaining expansion takes place on the moving blades. This cause reaction force on the moving blades & turbine starts rotating.

    Eg: Francis turbine, Kaplan turbine
  - It is used for low & medium heads & large discharges.
  - It has guide mechanism.

Hydro power Plant

Def: A Generating station which utilizes the potential energy of water at a high level for the generation of electrical energy is known as Hydro electrical power station.

- Generally it is located in hilly areas where dams can be built conveniently large water reservoir can be obtained.
- In Hydro power station, water head is created by constructing a dam across a river or lake.

Layout diagram of Hydro power plant:

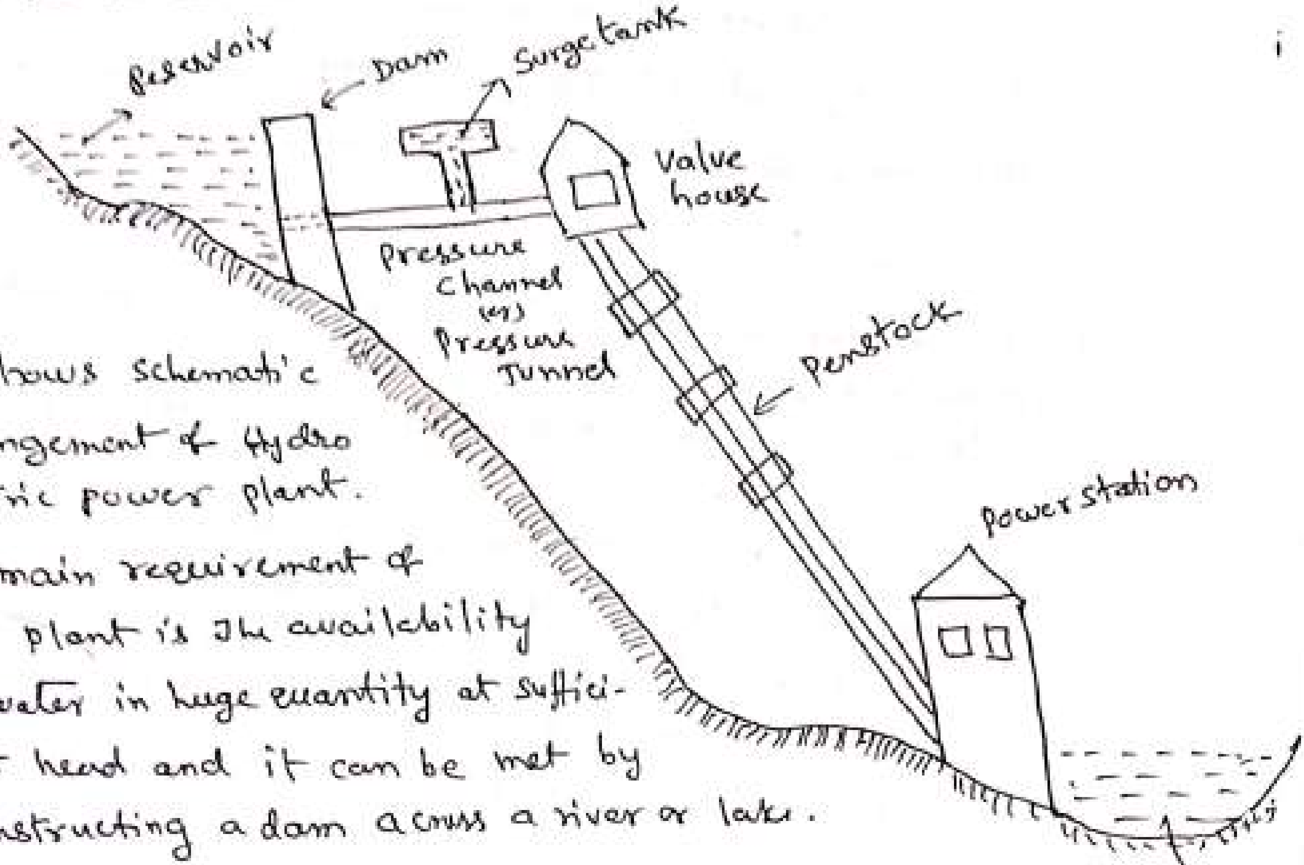


Fig shows schematic arrangement of Hydro electric power plant.

- The main requirement of this plant is the availability of water in huge quantity at sufficient head and it can be met by constructing a dam across a river or lake.
- A storage reservoir is formed by constructing a dam across a river and a pressure tunnel is taken off from the reservoir to the valve house at the start of the penstock.

• The valve house consists of some valves for controlling water flow to the power station and these automatic valves for cutting off the water supply in case of penstock bursts.

- A surge tank is also provided just before the valve house for better regulation of water pressure in the system.
- From the reservoir, water is carried to valve house through pressure tunnel and from valve house to water turbine through pipes of large diameter made of steel or reinforced concrete called penstock.
- Then the water turbine converts hydraulic energy into mechanical energy and the alternator which is coupled on the same shaft of the water turbine will converts mechanical enery into electrical energy and finally water after doing useful work is discharged to the tail race.

Advantages

(1) It requires no fuel as water is used for generation of electrical energy.
(2) It is quite neat and clean as no smoke or ash is produced.
(3) It requires very small running charges because water is source of energy which is available free of cost.
(4) It is comparatively simple in construction & requires less maintanance.
(5) It does not requires starting time like a steam power plant.
(6) It is robust & has a longer life
(7) These plants not only for generation of electric energy, also help in irrigation & controlling floods.

Disadvantages

(1) It involves high capital cost due to construction of dam.
(2) There is uncertainity about the availability water throughout year
(3) Skilled & experienced hands are required to build the dam
(4) It requires high cost of transmission lines as the plant is located in hilly areas which are away from the consumers.

Main components in Hydro Power Plant

There are several components in Hydro plant. These are

(1) Catchment area:

The area behind the dam, which collects the rain water is called catchment area.

(2) Reservoir:

The place in which the water is stored in a dam is called reservoir.

- Reservoirs may be natural or artificial
- A Natural reservoir is a lake in high mountains & artificial reservoir is made by constructing a dam across the river.

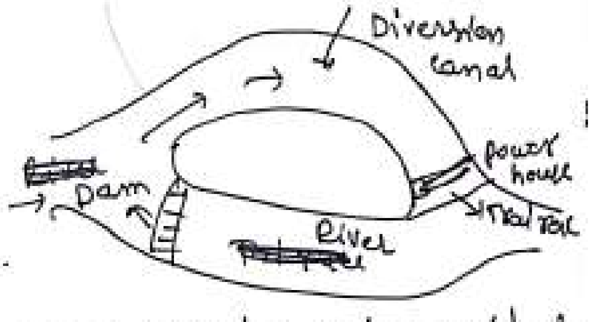
(3) Dam:

- A dam is a structure of stone masonry or some other material (concrete) built at a suitable location across a river.
- It provides head of water and it creates storage.

(4) Fore bays:

It acts as sort of regulating reservoir i.e water is temporarily stored in the fore bay in case of reject of load by turbine and supplies additional water from it when the load on the turbine is increased.

- In diversion canal plants fore bays are available.



(5) Spillway:

The spillways provides discharge of surplus water or flood water from storage reservoir into the down stream side of the dam.

- It also serves as a safety valve for the dam.
- These are constructed at the top of the dam with concrete piers.

- Gates are provided between these spillways concreate piers. and surplus water is discharged over the crest of the dam by opening these gates.

(6) Surge tank:

- A Surge tank is a small tank in which water level rises or falls to reduce the water hammerings inside the conduit or penstock.
- The main function of surge tank is to provide space for holding water during load rejection by the turbine and also supplies an additional water when the load on the turbine increases.
- It also relieves the water hammer pressures with in the penstock under sudden changes in the water flow.
- It is located near the beginning of the conduit or penstock.

(7) Penstock:

- Penstocks are open or closed conduit which carry water to the turbines.
- These are made up of reinforced concrete or steel.
- concrete penstocks are suitable for low heads (< 30m)
- The steel penstocks are designed for any head.
- The Thickness of the penstock increases with the head or working pressure.
- Generally, there are surge tanks, valves are provided for the protection of penstock.
- air valve maintains air pressure inside the penstock is equal to outside atmosphere pressure.
- when water runs out of a penstock faster than it enters, a vaccum is created which may cause the penstock to collapse. under such situations, air valve opens and admits air in the penstock to maintain inside air pressure equal to outside air pressure.

(8) Trash tracks:

These are mainly used to prevent the entry of debris to the intakes from the dam.

(9) water turbines:

water turbines are used to convert the energy of falling water into mechanical energy.

- Two types of water turbines
  (1) Impulse turbines (2) Reaction turbines.
- Impulse turbines are used for high heads
- Reaction turbines are used for low & medium heads.
  - Reaction turbines are of two types
    (a) Francis turbines : water flows radially inwards
    (b) Kaplan turbine : It is used for low heads and large quantities of water. It is similar to francis turbine except that the runner of Kaplan turbine receives water axially.

(10) Electrical equipment:

The electrical equipment of this plant includes alternators, transformers, CB & other switching and protecting devices.

Selection of site for locating a hydro power plant

while selecting the suitable location for hydro electric power plant the following factors to be considered

(1) Quantity of water available:

The primary requirement of hydro station is the availability of huge quantity of water. such plants are buit at a place where adequate water is available at a good head.

- This factor is necessary to decide the capacity of the plant.

(2) storage of water:

- we know that rainfall is usually varying from year to year and also it is not uniform during different months of a year. Hence flow of water in rivers and streams are not uniform.

In order to maintain the uniformity in the flow of water we will use storage of water system.

- storage capacity can be calculated on the basis of mass curve or minimum quantity of water for the available storage capacity.

(3) Availability of Head of water:

Geographical & geological conditions of the area along with the stream flow data is used for estimating the head of water.

(4) Distance from the Load centres:

- Generally Hydro plants are located far away from the load centres. For this reasons, the power transmission should be economical and distances should be carefully considered.

(5) Transportation facilities:

The site selected for hydro plant should have road and rail transportation facilities.

(6) cost & type of land:

The land for the construction of the plant should be available at a reasonable prices. Further, bearing capacity of the ground should be adequate to withstand the weight of heavy equipment (dam) to be installed.

(7) The selected site for hydro plant should also be free from earthquakes.

classification of Hydro plant

Hydro electric plants are classified into several types depending upon following factors.

(1) Based on the availability of head:

Based on the availability of head,

(a) Low head plants (< 30 m)

(b) medium head plants (30 to 100 m)

(c) High head plants (> 100 m)

(2) Based on the plant capacity:

(a) micro hydro plant (< 5 mw)

(b) medium capacity plants (5 to 100 mw)

(c) High capacity plants (100 to 1000 mw)

(d) super plants (> 1000 mw)

(3) Based on Nature of Load/duty

(a) Base Load plants:

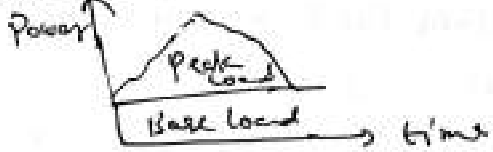
A plant supplying base load which is almost constant throughout a day is known as Base load Plants

Eg:- Thermal, Nuclear, Run of river without pondage

(b) Peak load Plants:

The plants which are used to supply Peak load of the system

Eg: Run of river without pondage, Hydro. plants, diesel Plants.



(4) Based on the type of location:

(a) out door type

(b) Indoor type

(c) semi outdoor station

(d) underground station

(a) outdoor type:

- In this type, generator and exciter units are individually placed in a weather tight casings.
- In this type, all equipments are in outdoor and maintenance cost is more as compared to in door type.

(b) Indoor type:

- This type of plants are fully located in indoor hence it requires more building area.
- cost is more
- These plants may not get heated during summer so it does not need any casing.

(c) Semi - outdoor type:

- In this type, it has small buildings with roof deck just higher then top of the generator.

(d) Underground plants :

- In this type, all the equipments are below the surface of the ground.
- The construction cost is very high & long time taking process.
- and utmost care should be taken from leakage of water

Eg : Srisailam left branch cannel.

(5) Based on the Hydraulic considerations :

(a) Run of river plants without pondage :

- In this type of plants does not store water & uses the water as it comes.
- no control over the river flow & hence water is wasted during low load & high flood conditions

Eg : Niagra falls Plant

(b) Run off River plants with pondage :

- The usefulness of this type of plant is increased by using pondage
- It works as base load & peak load stations (stream flow is less)

(c) storage plants :

- In this type of plants, water is stored during rainy seasons & uses from wet to dry season.
- So it can be used as base load plant.
- In India, majority of hydro plants are this type.

(d) pumped storage plants :

- This type of plants are mainly used for supplying the sudden peak loads for short duration.
- Eg : Srisailam left bank $6 \times 150 = 900$ mW

(6) Based on the turbine characteristics ie specific speed:

(a) High specific speed

(b) medium specific speed

(c) Low specific speed.

specific speed: speed of turbine, when it is working under unit head ie produce/develops unit horse power.

$$n_s = 4.45\, N \sqrt{h.p} / h^{5/4}$$

N → speed of wheel in rpm

h – head in metres

h.p – o/p in metric horse power

Pelton wheel – 10 to 35

– 35 to 60

Francis medium speed : – 60 to 300

~~ ~~ Kaplan high speed : – 300 to 1000

Nuclear power station:

A Generating station which converts nuclear energy into electrical energy is known as nuclear power station.

- In this power station, heavy radioactive elements like U^{235} or thorium (Th^{232}) are subjected to nuclear fission. The fission is breaking of nucleus of heavy atom into parts by bombarding neutrons. This is carried out in a special nuclear reactor. During the nuclear fission, huge amount of energy is released.

The heat energy thus released is used in raising the steam at high pressure & temperature. The steam turbines are operated using the high temperature steam. The turbine converts the heat energy into mechanical energy. The turbine drives the alternator which converts mechanical energy into an electrical energy.

Note: 1kg of U^{235} can produce as much energy as can be produced by burning of 4500 tonns of high grade coal.

Adv

1. The amount of fuel required is ~~small~~ quite small. Therefore, considerable saving in the fuel transportation.
2. It requires less space as compared to other type of same size.
3. It has low running charges
4. This type of plant is very economical for producing bulk amount of power.
5. It can be located near the load centres. Therefore, the cost of primary distribution is reduced.
6. There are large amount of fuels are available in the world. So such plants can ensure continuous & supply for years.
7. It has reliability of operation.

Disadvantages :

1. The fuel used is expensive & is difficult to recover
2. The capital cost of nuclear plant is very high as compared to other Plants.
3. The erection and commissioning of the plant requires greater technical know-how.
4. The Fission by products are generally radioactive and may cause a dangerous amount of radioactive pollution.
5. These plants are not well suited for varying loads as the reactor does not respond to the load fluctuations efficiently.
6. Disposal of by products, which are radioactive, is a big problem. They have to be disposed away from sea shore.

Nuclear Fission:

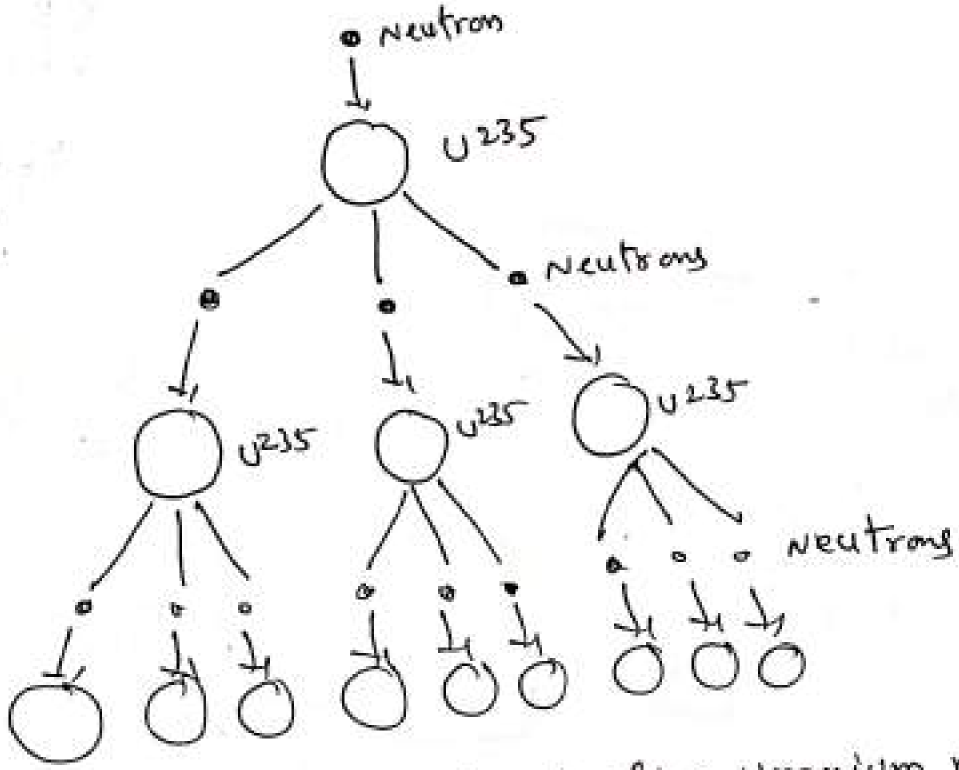
"The breaking up of a heavy nucleus into two nearly equal parts with release of huge amount of energy is known as Nuclear Fission"

- The release of huge amount of energy during fission is due to mass defect i.e mass of final product is less than the initial product
  - This mass defect is converted into heat energy according to Einstein's relation $E = mc^2$
- $${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{139}_{56}Ba + {}^{94}_{36}Kr + 3\,{}^{1}_{0}n + \underbrace{\text{energy}}_{200\text{ mev}}$$

$$200 \text{ mev} = 200 \times 1.6 \times 10^{-13} = 3.2 \times 10^{-11} \text{ Joules}$$

- 1kg of Uranium = 3×10^{6} kg of Coal

Nuclear chain Reaction

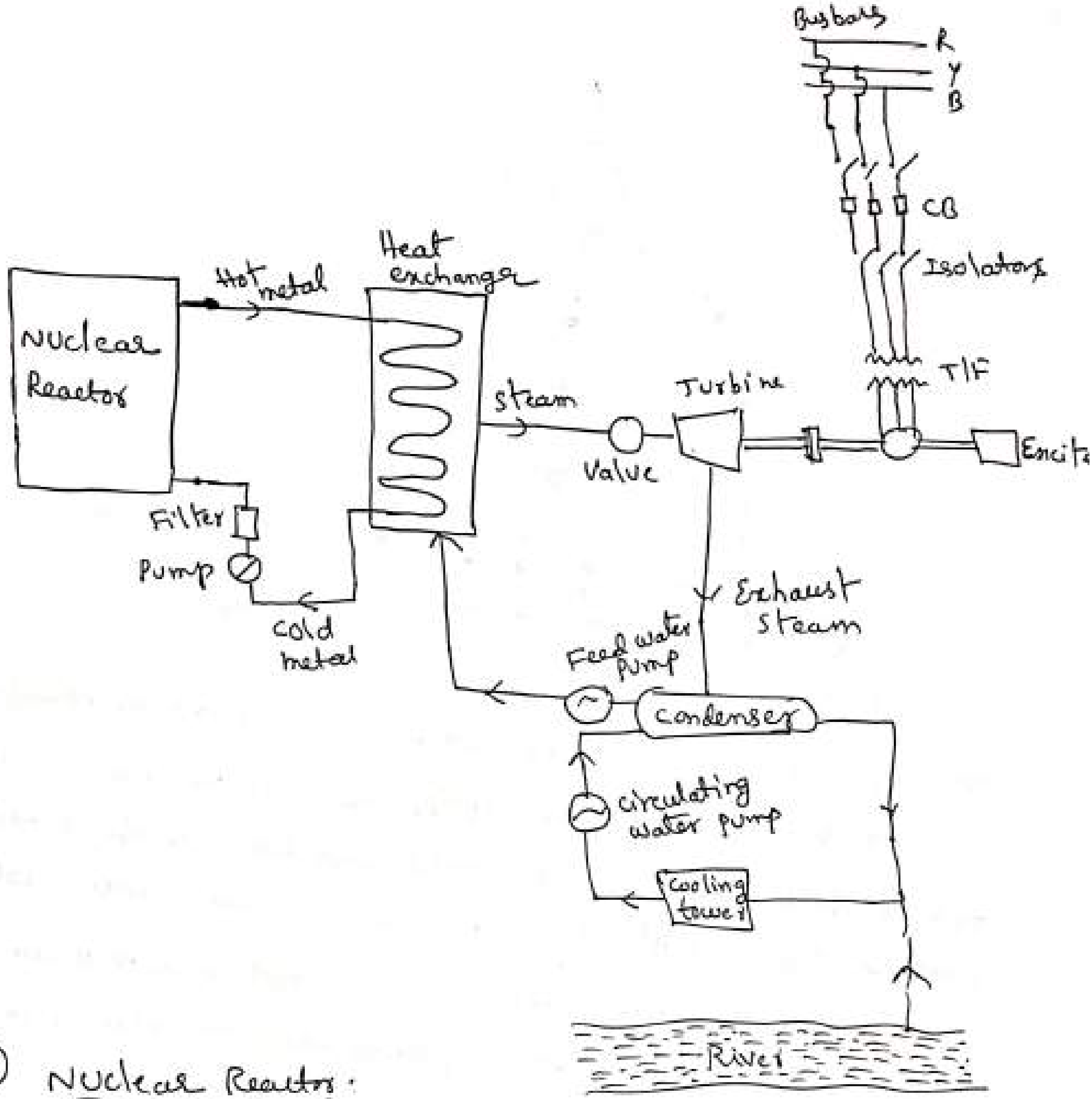


Nuclear Fission is done by bombarding Uranium nuclei with slow moving neutrons. This splits the Uranium nuclei with release of huge amount of energy and emission of 3 neutrons (called fission neutrons). This fission neutrons cause further fission. If this process continues, then in a very short time huge amount of energy will be relased which may cause explosion. This is called explosive chain reaction.

But in a reactor, controlled chain reaction is allowed. This is done by systamatically removing the fission neutrons from the reactor. This ~~lsst~~ greater number of fission neutrons removed, the lesser is the intensity or fission rate of energy released.

Schematic Arrangement of Nuclear power station

Fig shows schematic arrangent of Nuclear power station. The whole arrangement can be devided into following main stages
(1) Nuclear Reactor (2) Heat exchanger (3) steam turbine
(4) Alternator (5) cooling water circuit.



① Nuclear Reactor:

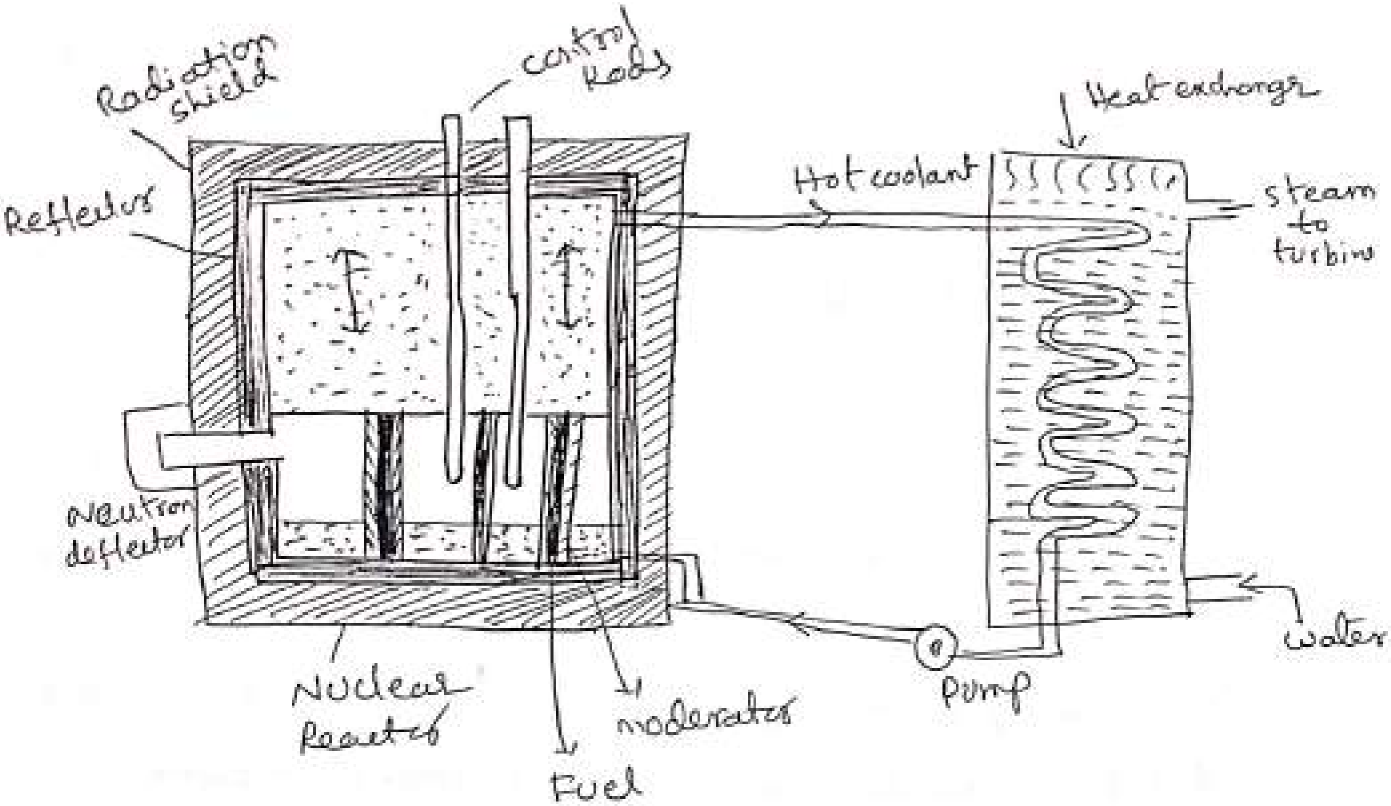
It is an apparatus in which Nuclear fuel (U^{235}) is subjected to ~~nuclear fission~~. controlled fission chain reaction, during which tremendous energy is generated.

Fig shows the various components of a nuclear reactor and a heat exchanger.

The following are the components of the nuclear reactor.

(a) Fuel (b) moderators (c) Reflectors (d) control Rods

(e) coolant (f) Radiation shield.



(a) Fuel :

- The commonly used fuel is uranium containing 0.7% of U^{235} or enriched uranium containing 1.5 - 2.5% U^{235}.
- Fuel is used in the form of rods or plates which are surrounded by moderators. The fuel rods are arranged in cluster and the entire assembly is called core.
- The minimum amount of the fuel required to maintain the chain reaction is called the critical mass.

(b) moderators :

- The main function of the moderators is to reduce the speed (or) slows down the energy of neutrons involved during fission(or) slows down the neutrons before they bombard the fuel rods.
- The moderators consists of graphite rods which encloses the fuel rods and ~~bot~~ beryllium & heavy water also used as moderators.
- By slowing down the high energy neutron, the possibility escape of neutrons is reduced while possibility of absorption of neutrons by fuel to cause further fission is increased.

(c) Reflector:

- The reflector is placed around the core to reflect back some of the neutrons which may leak out from the surface of the core, without taking part in the fission.
- A blanket of reflector can reduce the critical mass required.

(d) control rods:

- Generally, the cadmium rods are used as control rods which are strong neutron absorber. Thus control rods can regulate the supply of neutrons for chain reaction.
- If the no. of neutrons are not controlled, there is a possibility of explosion due to large amount of energy released.
- By pushing or pulling out of these rods, the rate of chain reaction & hence the heat produced can be controlled.
- The control rods can be operated automatically as per the requirement.
- The other material used for control rod is boron or hafnium

(e) coolant:

- The main purpose of the coolant is to transfer heat generated in the reactor core and use it for the steam generation
- The coolant in the reactor keeps the temperature of fuel below safe level by continuous removal of the energy from the core.
- The liquid metals like Sodium or potassium are used as coolants.

(f) Radiation shield:

- The radiations of a radioactive substances are harmful to the human life.
- Hence, radiation shield is used to prevent the escape of these

radiations to the atmosphere.

- Generally, 5 to 6 cm thick steel plate and few metres of the concrete outside are used as the radiation shield.

(2) <u>Heat exchanger :</u>

- It is a device which is used to exchange the heat from the primary circuit to the secondary circuit.
- The coolant carries the heat in the reactor to the exchanger where it is exchanged to the water, to convert water into steam.
- Thus, the heat exchanger is nothing but a steam generator.
- once the heat is exchanged, the coolant is feed back to the reactor, using the coolant recirculating pump.

(3) <u>Steam turbine :</u>

- The steam generated from the water in the secondary circuit is taken to the steam turbine through main valve, where it is expanded.
- Due to this, turbine starts rotating, they the heat energy is converted into a mechanical energy.

(4) <u>Alternator :</u>

- The shaft of an alternator is coupled to the turbine shaft. The when the turbine rotates, the alternator starts rotating.
- The alternator converts mechanical energy into an electrical energy. The energy output is given to the bus bar through Transformers, circuit breakers & Isolators.

(5) <u>Cooling water ckt :</u>

- The expanded steam from the turbine is the exhausted steam which is taken to the condenser.
- In the condenser, the steam is condensed into water. (feed water)

- For condensation of steam, a flow of natural cold water is circulated through the condenser. Thus water takes heat from the exhaust steam.
- Then this hot water is passed through cooling tower, where it is again converted to cold water. Then it is recirculated through the condenser by pump.
- The condensed steam is then recirculated through the secondary ckt of exchanger, using the feed water pumps.

Types of Nuclear Reactors

I) Based on the neutron energy, the reactors are classified as

(1) Thermal reactors

(2) Fast Reactors

(1) Thermal reactors are those in which the neutrons are slowed down with a material called moderator, to a velocity of about 2000 m/s, before they collide with nucleus of the fissioning fuel.

(2) ~~In~~ Fast Reactors are those in which moderator is not used and the neutrons, as they are released from fission, are used for producing fission of additional fuel, without slowing them internally.

II) There are various classification of reactors based on the fuel material used, arrangement of elements, moderator material etc.

① Pressurised water Reactor (PWR)

- PWR emplyos light water (H_2O) both as ~~cat~~ coolant and a moderator and hence it uses enriched uranium as fuel.
- This reactor is designed to prevent the boiling of water coolant, in the core. This is achieved with the help of a circulating pump, which circulate the water coming out from the heat exchanger at high pressure (100 to 120 atm) round the core,

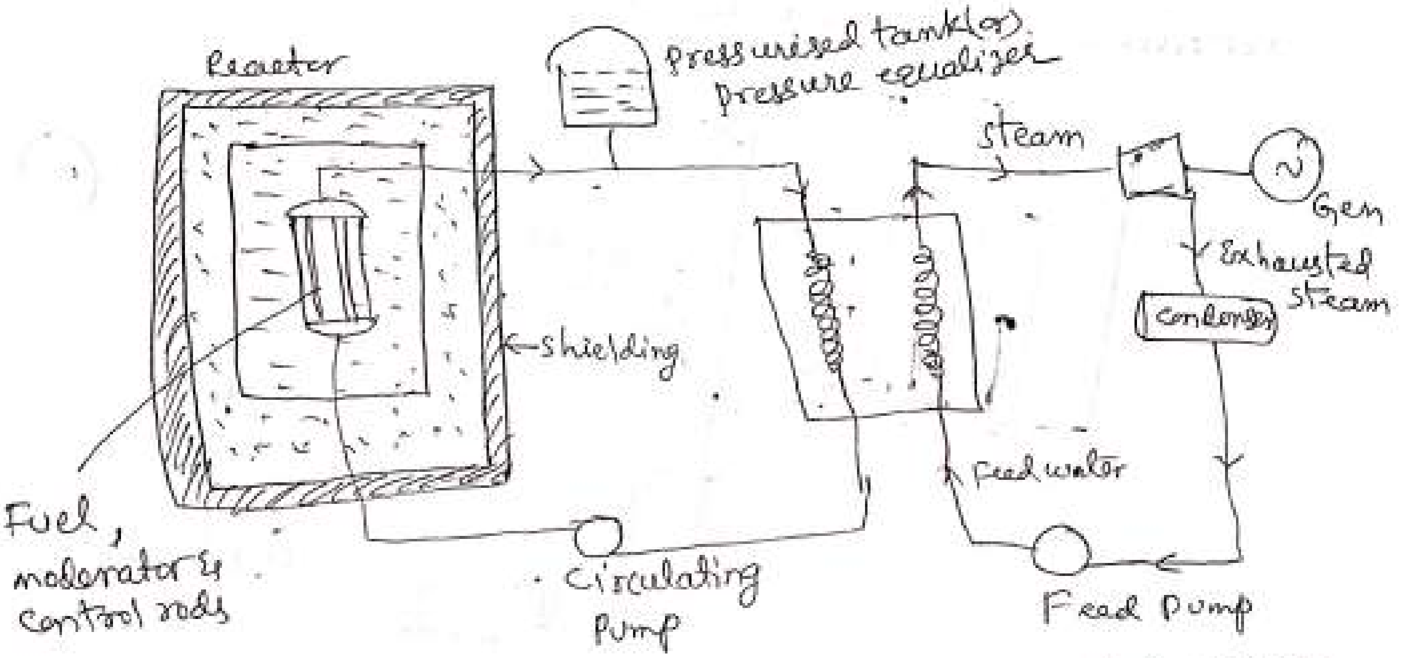
So that water in the liquid states absorbs heat from its nuclear fuel & transfers it to the Heat exchanger.

- The pressure in the water system is maintained by a pressurised tank, which is included in the ckt as shown in fig.

- ~~Here~~, In heat exchanger, other side tubes of water are inserted. This will help us to boil the water and produces steam at high pressure.

- Then this steam passes to the steam turbine for the generation of electrical energy with the help of alternator. After that the exhausted steam passes to the condenser.

- In the condenser, the exhausted steam gets condensed and condensed water can be used as feed water feed to Heat exchanger.



Note: In this reactor, water, it comes in direct contact with the nuclear fuel, becomes radioactive, therefore entire primary ckt i.e Reactor and Heat exchanger must be shielded for safety reasons.

Advantages:

① These reactor is compact in size, as enriched uranium is used as a nuclear fuel.

② water is cheap as it is used as coolant & moderator

③ The reactor requires smaller no. of control rods. About 60 control rods are required for a 1000 mw capacity reactor.

(4) The separation of Heat exchanger from the reactor core ckt makes the maintenance job easier and safer as the steam is not contaminated by radiation.

Disadvantages :

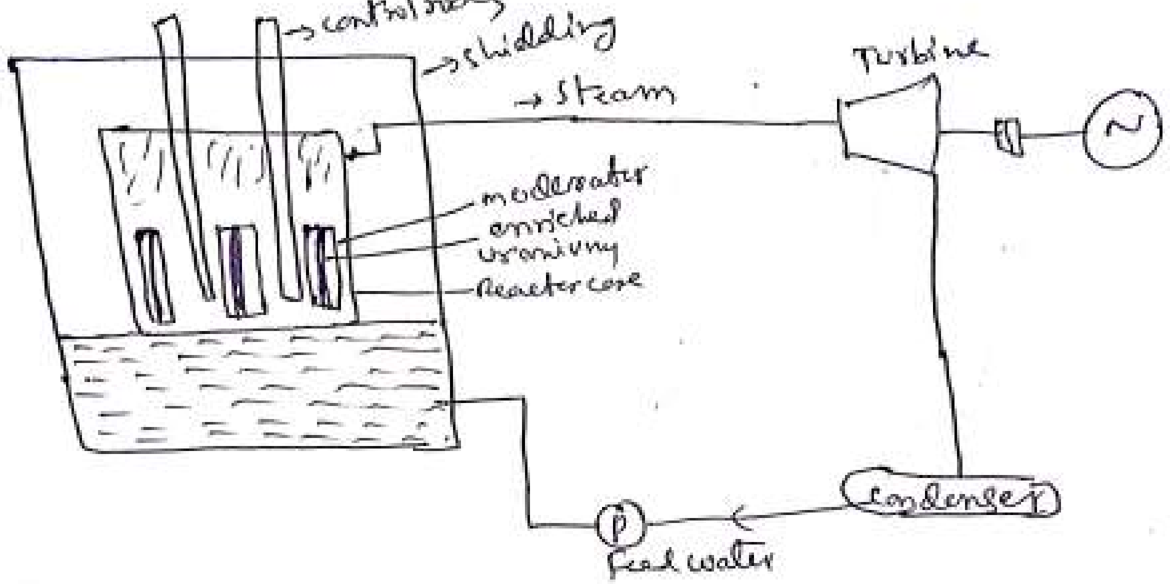
① For recharging the core, the plant has to be shut down for a couple of months.

(2) As the pressure in the primary ckt (Reactor core) is high, high pressure vessels are required which increases cost.

Boiling water Reactor (BWR)

- This type of reactor also employ water as the coolant, moderator & reflector as PWR and the fuel used is the enriched uranium.

-



- In this type of reator, water is directly passes to the bottom of the reactor core.

when chain reaction starts, the reactor core produces a heat energy, which inturn boiled the water & produced steam at high temperature & pressure.

This steam passes to the turbine, which produce mechanical energy. Then alternator converts this mechanical energy into electrical energy.

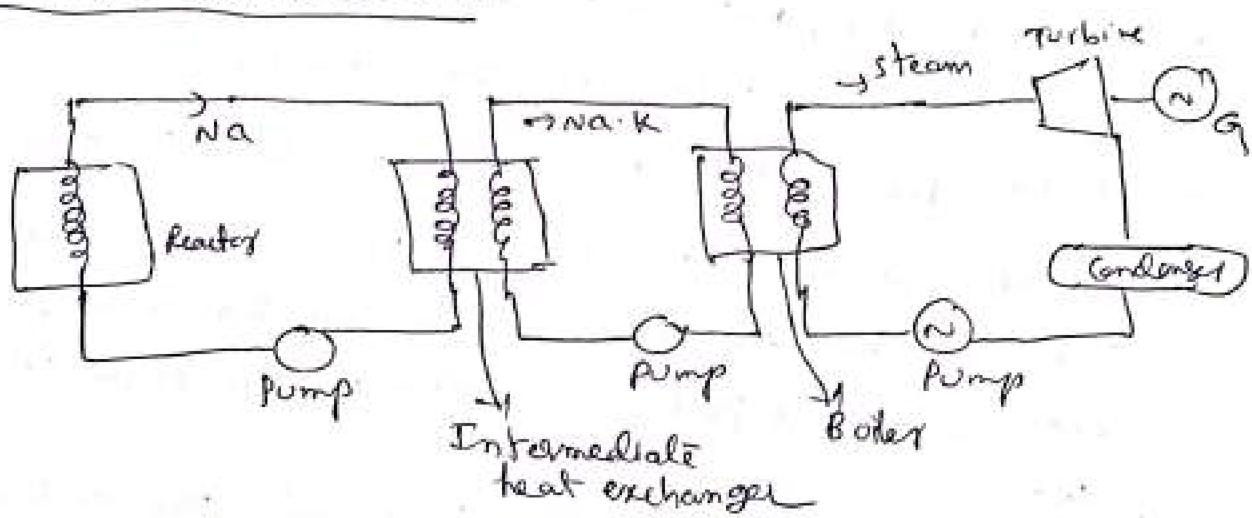
Advantages:

1. Since the pressure inside the vessel is small compared to PWR, so cost is lower.
2. Since, here this reactor does not require boiler, pressuriser & circulating pump hence cost is further reduced.
3. Thermal efficiency of this plant is higher (30 %) which is higher than PWR.

Disadvantages:

1. The steam leaving the reactor is radioactive and hence shielding of turbine & piping ckt is essential
2. The power density of this reactor is 50 % of PWR & hence the size of the vessel for the same capacity is more.

Liquid metal cooled Reactor:



- In this reactor, Fuel used is slightly enriched Uranium and moderator is graphite and coolant is sodium (Na) res.
- In order to have higher efficiency, the temperature should be high. and it is possible to have high temperature (540°C) with liquid metals at comparatively low pressure (7 kg/cm²) because of the excellent heat transfer capacity of these liquids when used as coolants.
- An Intermediate heat exchanger using Na-K is employed in

between the reactor & the boiler

- Na-K is the alloy of sodium and potassium.

Adv

① Higher thermal efficiency can be obtained as higher temperatures are possible

② Reactor size is comparatively very small

③ Pressure in the vessel is low as sodium need not be pressurised

Dis adv

① Incase of leakage of sodium, it may result in health hazard, as it comes out in high radioactive state

② Primary & secondary ~~ckt are~~ cooling ckts should be shield as sodium becomes highly radioactive due to neutron bombardment.

Canadian Deuterium Uranium (Candu) Reactor

- In this reactor, natural uranium as the ~~fuel~~ fuel and heavy water as both the coolant and the moderator.
- It has pressure tube construction and permits online refueling.
- The heavy water as a coolant is passed through the fuel pressure tubes and heat exchanger and is circulated in the primary ckt in exactly same as PWR. The steam is thus raised in the secondary ckt.
- Power out can be varied by varying the level of moderator in the reactor & hence control rods are not required.

Adv

① Natural uranium is used

② No control rods are required & hence control is simpler & cost is less

③ The moderator can be kept at low temperature there by its effectiveness in slowing down the neutrons is increased.

④ Plant can be constructed in relatively shorter time as compared to others

Dis adv

① Cost of heavy water is high

② The power density is low so reactor size for particular capacity is large

③ Design, ~~maint~~ manufacture & maintance are complex.

Solar power generation:

Role of solar energy

Solar technologies convert sunlight energy into solar energy through photovoltaic (pv) panels or through mirrors that concentrate solar radiation. This energy can be used to generate electricity or be stored in batteries or thermal storage.

Potential of solar energy

Based on the availability of land and solar radiation, the potential solar power in the country has been assessed to be around 750GWp

State wide details are shown below

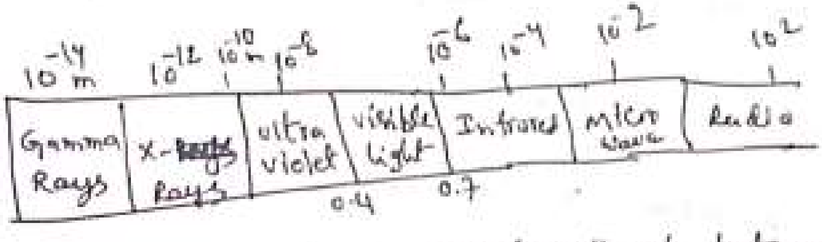
State	solar potential (GWp)
1. A.P	38.44
2. Aru. P	8.65
3. Assam	13.76
4. Bihar	11.20
5. chattisgarh	18.27
6. Goa	0.88
7. Jammu & Kashmir	111.05
8. Rajasthan	142.31

Solar capacity in mw (till march 2019)

1. Karnataka - 6095.55 mw
2. Telangana - 3592.09 mw
3. Rajasthan - 3226.79
4. Andra pradesh - 3055.68 mw
5. punjab - 905.62 mw

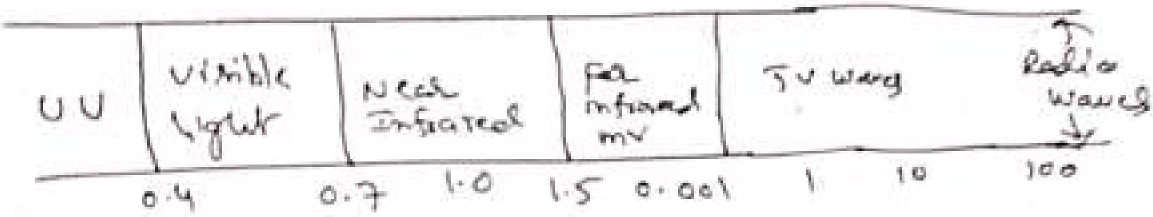
Principles of Solar radiation

- Sun is a sphere of hot gaseous matter with a diameter of 1.39×10^9 m. Due to its temperature, Sun emits energy in the form of electromagnetic waves, which is called radiation energy.
- The energy from the sun is transferred to the earth in the form of photons (small packet of energy) moving at a speed of 3×10^8 m/s.
- when photon energy absorption by metal called heat energy and when photon energy absorption by plant with O_2 called chemical energy.
- The heat energy received on the earth through photons is responsible for earth's temperature. The amount of solar radiation reaching different parts of the world is not the same. it varies from location to location and season to season
- There are many different types of radiation is defined by its wavelength. The electromagnetic radiation can vary widely



- visible light has a wavelength of between 0.4 to 0.71 micrometers (μm)
- The sun emits only a portion (44 %) of its radiation in this ~~radiation~~ range.

- Solar radiation spans a spectrum from 0.1 to 4 μm approximately.
- About 7 % of the sun's emission is in 0.1 to 0.4 μm wave-length band is UV.
- About 48 % of the sun's radiation falls in the region between 0.71 to 4 μm (near infrared : 0.71 to 1.5 μm, far infrared : 1.5 to 4 μm)



- Solar radiation incident outside the earth's atmosphere is called extraterrestrial radiation. On average the extraterrestrial irradiance is 1367 W/m^2.

Stephan - Boltzman Law

- The amount of electromagnetic radiation emitted by a body is directly related to its temparature.
  - If the body is a perfect ~~radi~~ emitter (black body), the amount of radiation is proportional to 4th power of its temparature.

$$E = \sigma T^4 \quad , \quad \sigma = 5.67 \times 10^{-8} \; W/m^2K^4.$$

Wein's Law

The wave length of maximum emission of any body is inversely proportional to its absolute temparature.

$$\lambda_{max} = \frac{C}{T} \quad , \quad C = 2897 \;, T\text{- Kelvin}$$

Inverse Square Law

The amount of radiation passing through a specific area is [illegible] square of the distance of that area

Solar energy collectors

Solar energy collector is a device that collect or concentrate Solar radiation from the sun. These devices are primarly used for active solar heating and allow for the heating of water for Personal use.

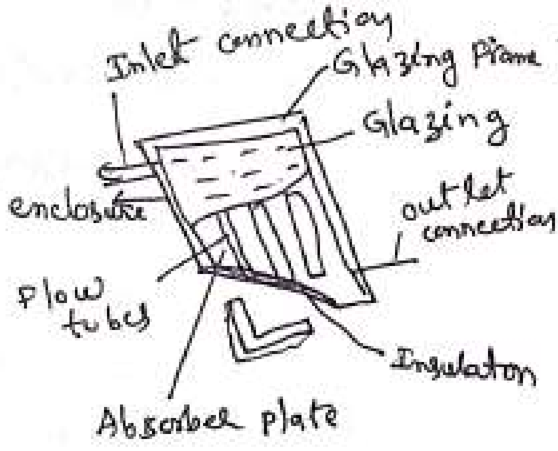
- These collectors are generally mounted on the roof and must be very sturdy as they are exposed to a variety of different weather conditions.
- a large number of these collectors can be combined in an array and is used to generate electricity in solar thermal power plants.

Types of Solar collectors

- There are many types of solar collectors but all of them are constructed with the same basic premise in mind.
- In general, there is some material that is used to collect and focus energy from the sun and use it to heat water.
- The simplest of these devices uses a black material surrounding pipes that water flows through. The black material absorbs the solar radiation very well and as the material heats up the water it surrounds.

The collectors are

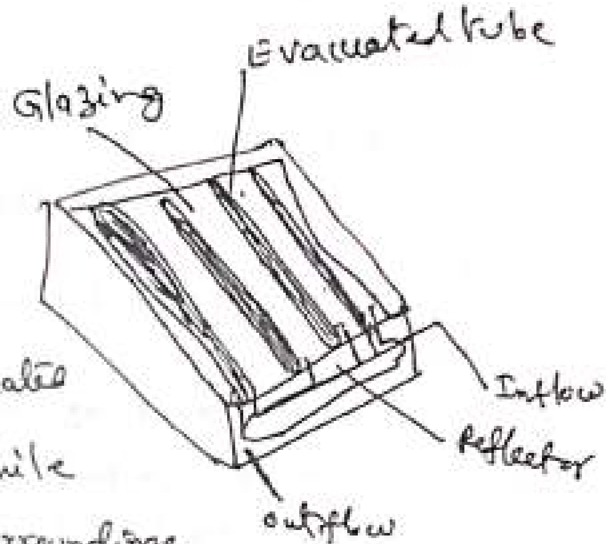
(1) Flat plate collectors :



- These collectors are simply metal boxes which have transparent glazing as a cover on top of a dark coloured absorber plate.

- The sides and bottom of the collector are covered with insulating to minimizes the heat losses to other parts of the collector.
- Solar radiation passes through the transparent glazing material and hits the absorber plate. This plate heats up, transferring the heat to either water or air between glazing and absorber plate.
- The absorber plate are made up with good conductor - usually copper or aluminium.

(2) Evacuated tube collectors

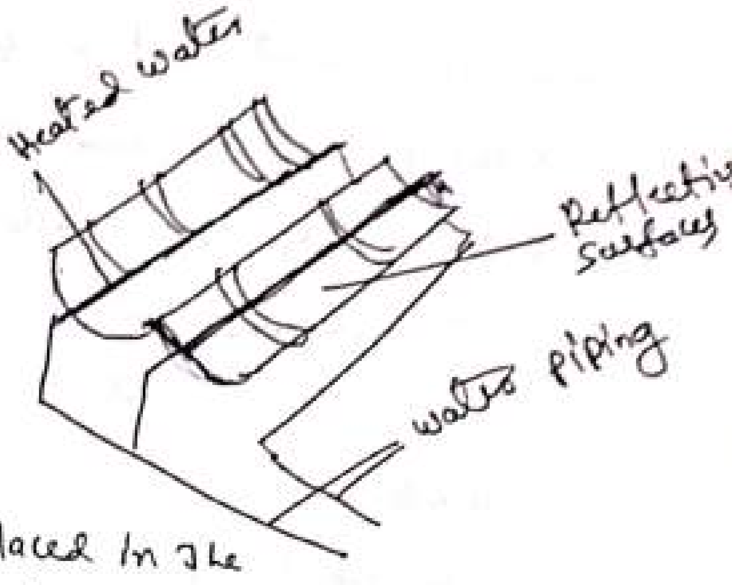


- This type of solar collector uses a series of evacuated tubes to heat water for use.
- These tubes utilize a vacuum or evacuated space, to capture the suns energy while minimizing the loss of heat to the surroundings.
- They have an inner ~~material~~ metal tube which acts as absorber plate, which is connected to a heat pipe to carry the heat collected from the sun to the water.

This heat pipe is a essentially pipe where the fluid contents are under a very particular pressure. At this pressure the hot end of the pipe has boiling liquid in it and cold end has condensing vapour.

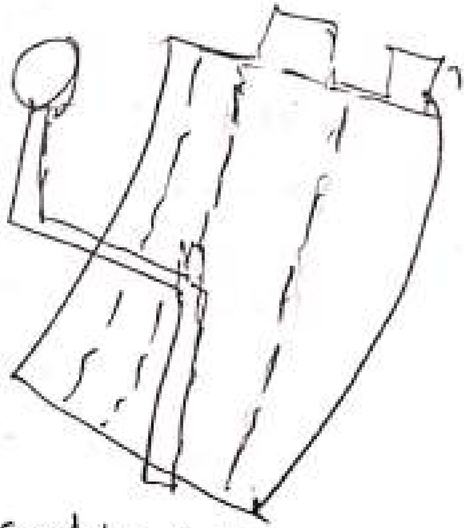
Once the heat from the sun moves from the hot end of the heat pipe to the condensing end, then the thermal energy is transported into water being heated for use.

(3) Line Focus collectors



- These collectors also called as Parabolic troughs, use highly reflective material to collect and concentrate the heat energy from solar radiation.
- A pipe that carries water is placed in the centre of this trough so that sunlight collected by the reflective material is focused onto the pipe, heating the contents.
- These are very powered collectors and so generally used to generate steam for solar thermal power plants and are not used in residential applications.

(4) Point Focus collectors



- These collectors are large parabolic dishes composed of some reflective material that focus the sun's energy on to a single point.
- The heat from these collectors are generally used for driving stirling engines.
- These dishes can be work alone or be combined into an array to gather more energy from the sun.

Different methods of energy storage

There are five types of energy storages

1. Batteries
2. Thermal
3. mechanical
4. Pumped hydro
5. Hydrogen

1. Batteries:

- Batteries, is oldest & most common form of storage and These are electro chemical technology comprised of one or more cells with two terminals namely cathode (+ve) and anode (-ve terminal).
- Batteries are used in portable electronic devices and vehicles are lithium-ion & lead acid. Other solid battery types are nickel-cadmium & sodium-sulphur.
- Another category is flow batteries with liquid electrolyte solutions including vanadium redox and iron chromium and Zinc-bromine chemistries.

(2) Thermal storage:

- Thermal storage is necessary which involves the capture & release of heat or cold in a solid, liquid or air and Potentially involving the changes of state of the storage medium

   Eg:- gas to liquid or solid to liquid

(3) mechanical storage:

- mechanical storage systems are simplest and which are drawing on the kinetic forces of rotation or gravitation to to store energy.

- The energy storage with flywheels and compressed air systems

4. pumped storage:

- Energy storage with pumped hydro systems based on the large water reservoirs has been widely implemented.
- such systems receive water cycling b/w two reservoirs at different levels with the Energy storage in the water in the upper reservoir which is released when the water released to the lower reservoir.

(5) Hydrogen:

- Energy storage with hydrogen, which is still emerging, which involve its conversion from electricity via electrolysis for storage in tanks. later it can be used to transport industry or residential as a replacement to gas.

Photo voltaic cell (Solar cell)

- A photo voltaic cell or solar cell is a electronic device that converts energy of light directly into electricity by photo voltaic effect.

- The photo voltaic effect is the production of electricity by a material when it is exposed to the light.

- Solar cells are made up of sillicon which is a p-type semicondu-ctor and which absorbs the photons (light) emitted by sun's rays.

- The photo voltaic cell was invented in Bell laboratories at 1954.

- Generally, the common material used for solar cell is sillicon semi conductor because of low weight volume ratio, extended life cycle, robustness and strength and increasing efficiency and lowering cost.

- unlike batteries or fuel cells, solar cells do not utilize chemical reactions or fuel to produce electrical power and unlike electric generators, they do not have any moving parts.

- solar cells can be arranged into large groupings called arrays. These arrays, composed of many thousands of individual cells, can function as, central electric power stations, converting sunlight into electrical energy for distribution to industrial, commercial and residencial users.

- Each solar cell generates 0.5 to 1 volts and produce current of 20–40 mA/cm² depending on the materials used and the conditions of sunlight.

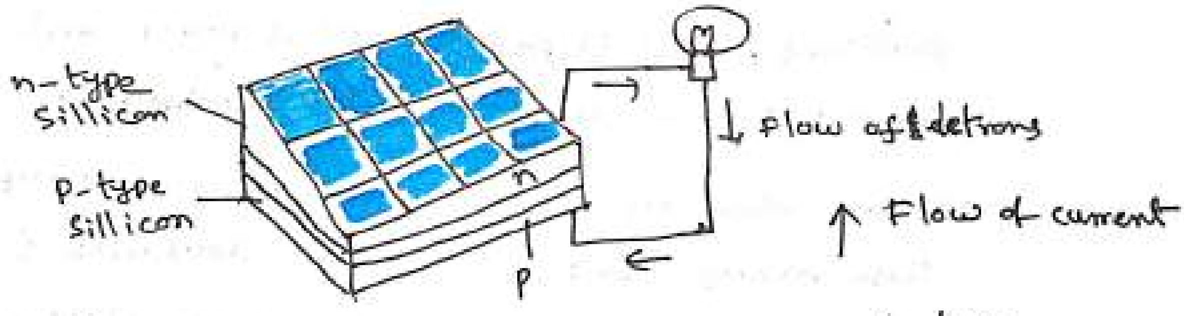
- The efficiency of solar cell is as low as 15%.. but solar energy is a basically a free of cost.

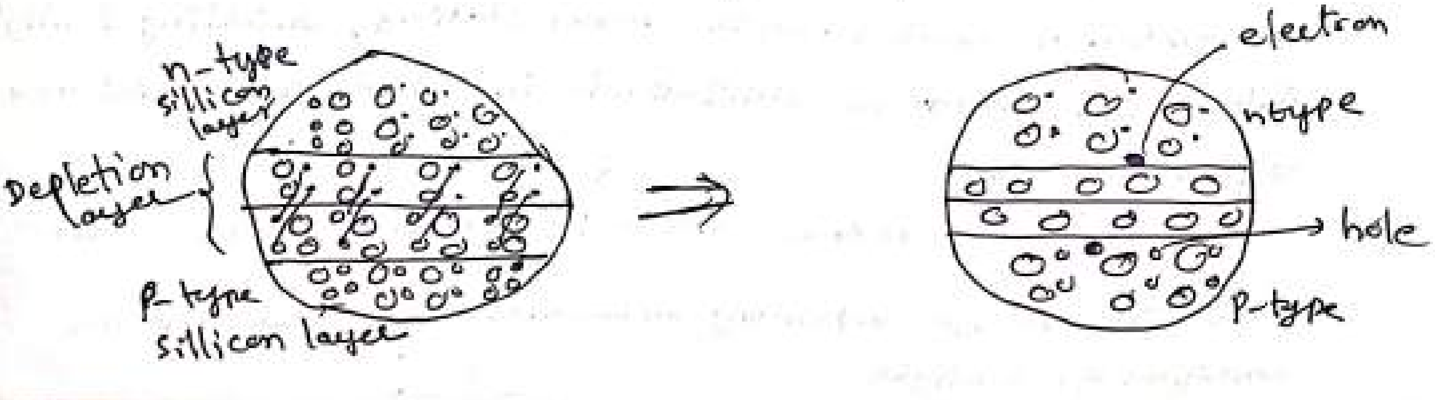
Construction & working of solar cell

- Solar cell is made up of two types of semiconductors, called P-type and N-type Sillicon. The P-type Sillicon is produced by adding atoms such as boron or gallium - that has one less electron in their outer energy level than does sillicon. It bonds with its sillicon atoms, ~~one electron it not involved in bonding~~ an hole is created.

Similarly, n-type sillicon is made by adding atoms that have one more electron in their outer level than does sillicon such a Phosphorus. Phosphorous have five electrons in its outer energy level, not four. it bons with its sillicon atoms, but one electron is not involved in bonding. Instead, it is free to move inside the sillicon structure

- A Solar cell consists of a layer of p-type Sillicon next to a layer of n-type Sillicon as shown in fig.





In the n-type layer, there is an excess of electrons and in the p-type layer, there is an excess of positely charged holes. Near the junction of the two layers, the electrons on one side of the junction i.e n-type layer move into the holes on the other side of the junction i.e p-type layer. This creates an area around the junction called the depletion zone, in which the electrons fill the holes.

- when all the holes are filled with electrons in the depletion zone the p-type side of the depletion zone (where holes were initially present) now contains negatively charged ions and the n-type of the depletion zone (where electrons were initially present) now contains positively charged ions.

The presence of these oppositely charged ions creates an internal electric field that prevents electrons in the n-type layer to fill holes in the p-type layer.

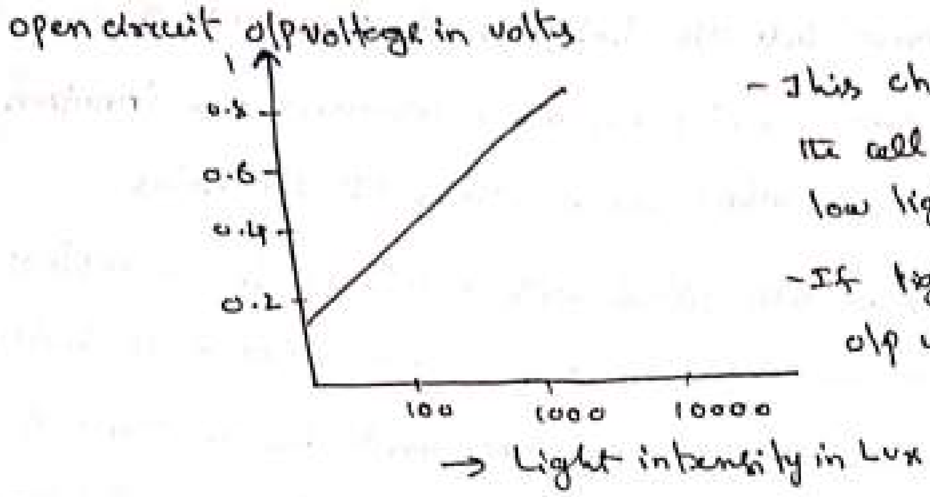
- when sunlight strikes a solar cell, electrons in the sillicon are ejected, which results in the formation of holes ~~by~~ left behind by the escaping electrons.

If this happens in the electric field, the field will move electrons to the n type layer and holes to the p type layer.

If you ~~sotto~~ connect the n-type and p-type layers with a metallic wire, the electrons will travel from the n-type layer to the p-type layer by crossing the depletion zone and then go through the external wire back of the n-type layer, creating a flow of eletricity.

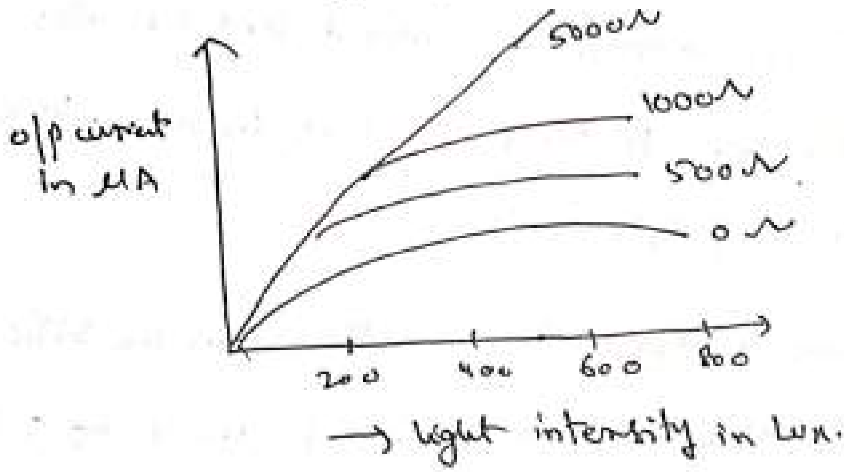
characteristics

- The open-ckt output voltage characteristics of a typical photo-voltaic cell is shown in fig.



- This characteristics shows that the cell is more sensitive for low light levels.
- If light intensity increases, the o/p voltage also increases.

- The output current characteristics of a solar cell for various load resistances are shown in fig



- o/p current increases with the increase in light intensity.
- Generally o/p current of a solar cell is very low and is measured in μA.

Advantages

1. It uses Renewable energy
2. No polution. so it is environmental friendly
3. It lasts for many years
4. No maintanance cost.

Dis advantages

1. Energy is not produced during rainy, cloudy days & during night times
2. cost of installation is high

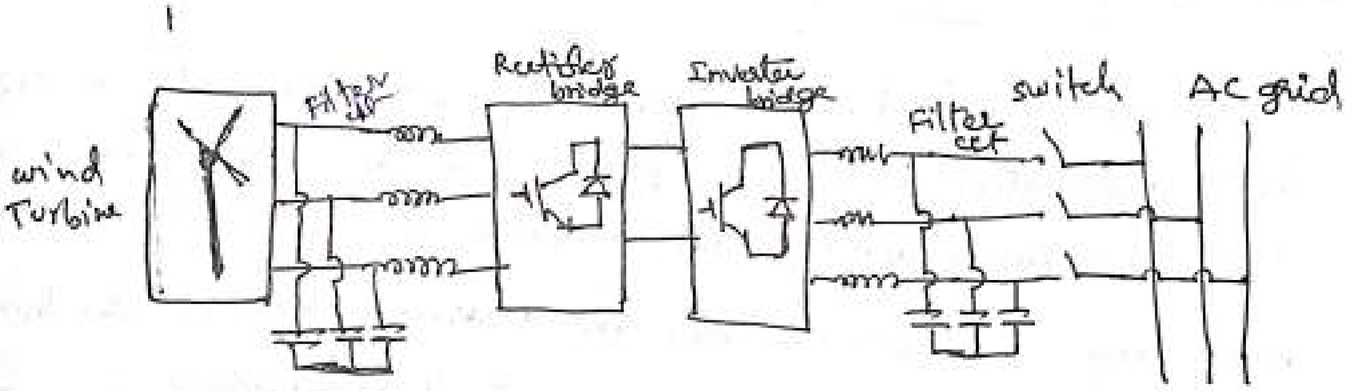
Applications

1. It is used in calculators and in wrist watches
2. used in storage batteries
3. street light
4. portable power supplies
5. Satellites.

Wind power Generation:

Def: wind power generation is power generation that converts wind energy into electric ~~ele~~ energy.

- The wind generating set absorbs wind energy with a specially designed blade and converts wind energy to mechanical energy, which further drives the generator rotating and realizes conversion of wind energy into electric energy.
- ~~commonly~~ The commonly used wind power generation systems are
  1. Direct driven wind generating set : It is connected to the grid through a full power converter
  2. Double fed wind power generating set : It is connected to the grid through double fed converter
- Fig shows direct driven permanent magnet synchronous wind power generation system.



For this system, wind energy drives the wind turbine rotating, which further drives the generator running, converting mechanical energy into electric energy. The stator of the permanent magnet synchronous generator outputs AC power with variable amplitude and frequency.

By passing through an AC/DC rectifier, the AC power will be converted into DC power and then with a DC/AC inverter, the output DC power will be inverted to AC power and connected to the AC grids. The power flows unidirectionally from the wind turbine to the AC grid. when it is only required to be connected to DC grids, the DC/AC inversion step can be omitted.

Role of wind energy

- wind turbines harness energy from the wind using mechanical power to spin a generator and create electricity.
- Not only is wind an abundant and inexhaustible resource, but it also provides electricity without burning any fuel or polluting the air.
- wind power is the most efficient technology to produce energy in a safe and environmentally sustainable manner.
- it is zero emissions, local, inexhaustible, competitive and it creates wealth & jobs

Potential of wind energy:

- wind energy potential is a great resource of renewable energy, which is the alternative resource of fossible fuel as well as shows great sign for reducing adverse environmental effects.
- According to ministry of New and Renewable energy, the india currently has the fourth highest wind installed capacity in the world with total installed capacity of 39.25 GW (as on 31st march 2021) and has generated around 60.149 billion units during 2020-21.
- The Government is promoting wind power projects in entire country through private sector investment by providing various financial incentives such as Accelerated Depreciation benefit, concessional custom duty exemption on certain components of wind electric generators.
- wind is an intermittent & site specific resource of energy and therefore, an extensive wind resource assessment is essential for the selection of potential sites.

- The Government through National institute of wind energy (NIWE), has installed over 800 wind monitoring stations all over country and issued wind potential maps at 50m, 80m, 100m and 120m above ground level.
- The recent assessment indicates a gross wind potential of 302 GW in the country at 100m and 695.50 GW at 120m above ground level.

The potentials of wind states are given below (as on 31st march 2021)

	wind potential at 100m (GW)	120m (GW)
Gujarat	84.43	142.56
Rajasthan	18.77	127.75
maharashtra	45.39	98.21
Tamil Nadu	33.79	68.75
madhya pradesh	10.48	15.40
Karnataka	55.85	124.15
Andhra pradesh	44.22	74.90
	292.97 GW	651.72 GW

Horizontal and vertical axis wind mills

There are two types of wind turbines. These are

1. Horizontal axis wind turbines
2. Vertical axis wind turbines

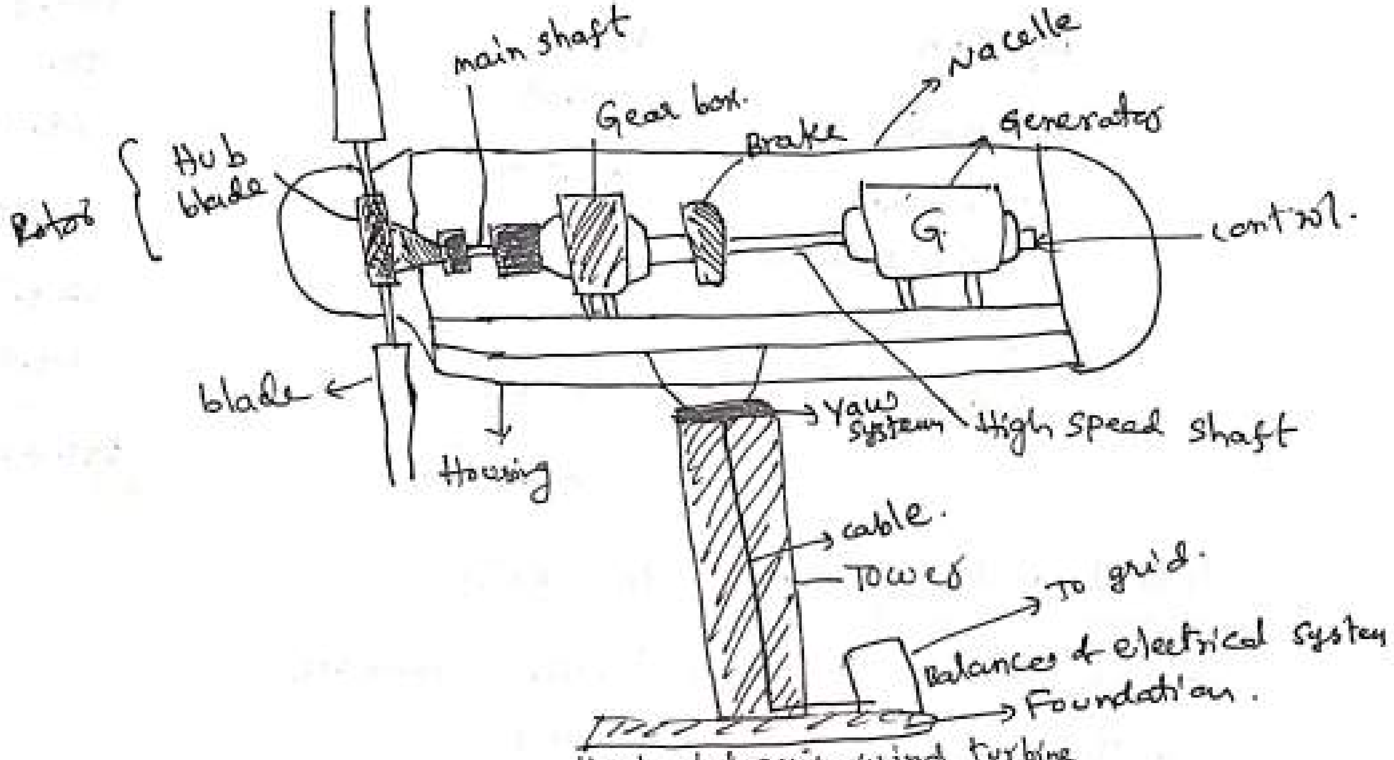
1. Horizontal axis wind turbine:

- Horizontal axis wind turbine dominates the majority of the wind industry.
- Horizontal axis means the rotating axis of the wind turbine is horizontal i.e parallel with the ground. In big wind application, these turbines are almost all you will ever see.
- The advantage of horizontal wind is that it is able to produce more electricity from a given amount of wind.

- The disadvantage of horizontal axis is that it is generally heavier and it does not produce well in turbulent winds.

Construction:

- Horizontal axis wind turbine consists of following components
  1. Foundation 2. Nacelle 3. Generator 4. tower 5. Rotor blades 6. Gear box
- For Horizontal axis wind turbine includes the rotor shaft and electric generator which are arranged at the top of the tower.



Horizontal axis wind turbine

1. Foundation:

For any wind turbine, the foundation gives support to the tower because wind turbine includes different parts which weigh in tonnes.

2. Tower:

- A tower is used to give support to the rotor hub and nacelle on the top of the wind turbine. The materials used to make this are concrete, tubular steel, or steel lattice.
- While designing this turbine, the height of the tower is very important because wind speed enhances with height. So taller towers allow these turbines to capture a huge amount of energy and produce more electricity.

different types of towers are available like tubular, lattice, guyed wind & etc.

3. wind turbine blades:

- These wind turbine blades are used to convert kinetic energy of wind to mechanical energy.
- This types of blades are designed with wood - epoxy or fibre glass - reinforced polyester.
- These turbines consists of minimum one and maximum multiple blades depending on the design.
- most of the Horizontal wind turbine includes 3 blades that are connected to the rotor hub.

4. Nacelle:

- The Nacelle includes different components which are used to operate the wind turbine efficiently like gear box, brakes, controller, low & high speed shafts and generator.
- It is arranged at the top of a tower and a wind ~~wane~~ vane is arranged on the Nacelle.

5. Hub:

- A Rotor hub is used to connect a shaft and rotor blade of the wind turbine.
- The hub includes blade bearings, bolts, internals and pitch system.
- These are designed with cast iron, welded sheet steel & forged steel.

6. Gear box:

- In wind turbines, a gear box is used to change high torque power with low speed which is received from a rotor blade to low torque power with high speed. This power is used for the generator.
- The Gearbox is generally connected in between the generator and the main shaft for enhancing rotational speeds from 30 - 60 rpm to 1000 - 1800 rpm.

- Gear boxes are made with different materials like superior quality alloys, aluminum cast iron, stainless steel etc.
- Three types of Gear boxes are available like, planetary, Helical & worm

7 - Generator:

- The rotating mechanical energy of the gearbox is given to the generator through the shaft.
- It converts mechanical energy to electrical.

working:

- once the wind blows, a wind turbine changes the kinetic energy from the motion of the wind into mechanical through the revolution of the rotor.

After that, this converted energy can be transmitted through the shaft and the gear train toward the generator. Further, this generator converts the energy from mechanical to the electrical to generate electricity.

Advantages

1. It produce high output power as compared to the vertical wind turbine
2. A tall tower gets stronger winds
3. High efficiency
4. it is not expensive as compared to vertical type turbine.
5. It has high reliability
6. It has a high rate of capacity
7. Its rotational speed is high.
8. it is more consistent.
9. these turbines are self starting.

Dis advantages

1. these are avaible in large size ~~self~~
2. weight is high
3. cannot move easily
4. Installation is difficult.

5. High noise.

6. to design this wind turbine, large machinery is needed.

7. Its maintenance is difficult

Applications

1. These type of wind turbines are mostly used for commercial and industrial purposes due to their large power output and high efficiency.

2. These are mostly used in wind farms.

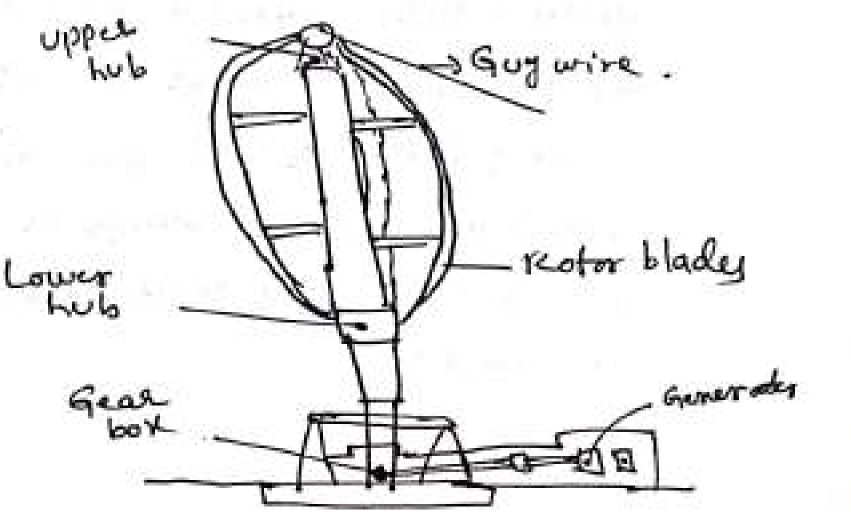
3. These are particularly used in large scale wind power plants and also for electricity generation.

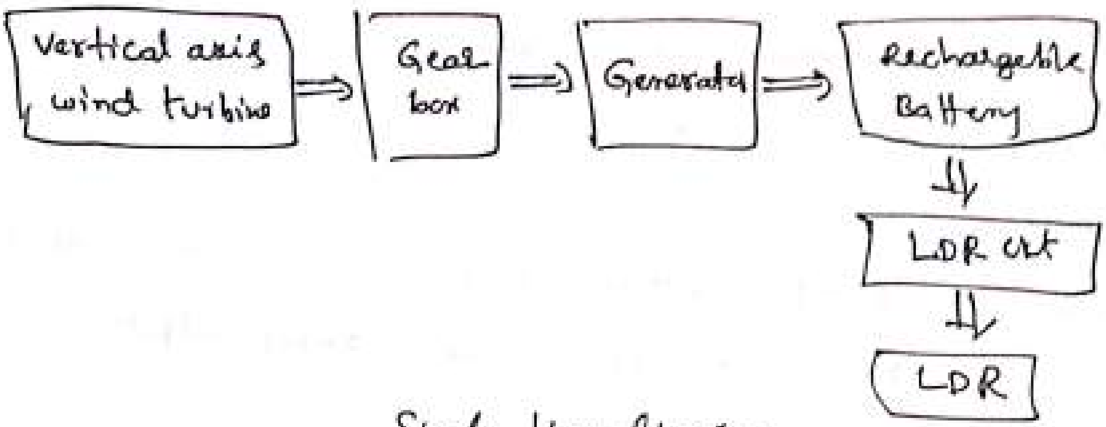
Vertical Axis wind turbine

- It is most freecuently used for residential purposes to povide renewable energy source to the home.
- this turbine includes the rotor shaft and 2-3 blades where the rotor shaft moves vertically
- So, this turbine movement is related to the spinning of coins on the edge.
- In this method, the generator is placed at the bottom of the tower ~~because~~ whereas the blades are covered around the shaft.

Construction

- the output energy generated from this can be used by any type of load.
- ~~the~~ It consists of
  - Gear box
  - Generator
  - Rechargeble battery
  - CDR ckt





Single line diagram

Gear box:

- This Gear box is used to enhance the rotating speed from low speed shaft to a high speed shaft connecting through an electric generator.

Generator:

The generator which converts mechanical energy to electrical.

Rechargeble Battery

The o/p electric energy generated by the generator will be stored in the rechargeble battery of the wind turbine

LDR ckt

The LDR ckt is used to turn on/off the light

working:

- This turbine works once the wind turns the turbine. once this turbine rotates, then the generator will get it as mechanical input and generate the output as electrical energy.
- This turbine is arranged on the dividers of the highway road.
- The shape of turbine wings is curved to get the wind for revolution from the 2-way road where the vehicle speed will make this turbine run.

Advantages

1. Safety for manpower
2. Scalability
3. They can generate electricity in any direction of the wind.
4. It doesn't require a strong supporting tower because the gearbox, generator & other components are arranged on the ground.
5. As compared to horizontal axis wind turbine, these are cheaper to design.
6. Installation is easy
7. These are portable so we can simply move from one location to other.
8. These turbines have less blades to reduce the risk to birds & people.
9. It can work in all weather conditions like variable wind & mountain conditions.
10. Taller structures are not allowed.
11. Its operation is simple so they don't bother people in residential areas.
12. These turbines can be arranged close to earth so that, maintenance, the cost of construction can be reduced.

Dis adv

1. As compared to Horizontal axis, the efficiency level will be decreased
2. These are very hard to arrange on towers because they are connected ~~to~~ on bases like buildings or ground.
3. The efficiency of rotation is low
4. Lower wind speed
5. Lower efficiency
6. Noise pollution

applications: ① It can be used in small wind projects ~~...~~ is
② used in residential applications.

Pitch and Yaw controls

Pitch control

- The purpose of pitch control is to maintain the optimum blade angle to achieve certain rotor speeds or power output.

pitch adjustment

- There are two types of pitch controls
  1. stall
  2. Furl

→ By stalling a wind turbine, you can increase the angle of attack, which causes the flat side of the blade to face further into the wind.

- Furling decreases the angle of attack, causing the edge of the blade to face the oncoming wind.

- Pitch angle adjustment is the most effective way to limit output power by changing aerodynamic force on the blade at high wind speed

Yaw control

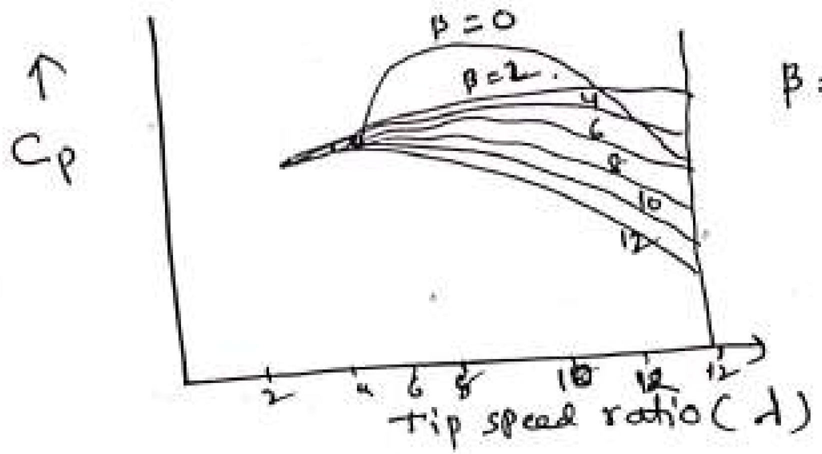
- Yaw control refers to the rotation of the entire wind turbine in the horizontal axis.

- Yaw control ensures that the turbine is constantly facing into the wind to maximize the effective rotor area as a result power.
- Because wind direction can vary quickly, the turbine may misalign with the oncoming wind and cause power output loss. The approximate loss with the following equation

$\Delta P = \alpha \cos(\varepsilon)$, ΔP - lost of power , $\varepsilon \rightarrow$ Yaw error angle.

Performance characteristics of wind turbine

— The performance characteristics of the wind turbine is relationship between the coefficients of power vs tip speed ratio.



β = Pitch angle of blade

- here, Increasing the pitch angle of blade, the coefficient of power is gradually decreasing. This indicates, coefficient of power depends on the pitch angle and tip speed ratio.
- The tip speed ratio is increases, coefficient of power also increases upto certain points.
- The maximum coefficient of power is 0.41 at tip speed ratio 8 then cp decreasing gradually.

$$\text{Power coefficient} = \frac{\text{Power o/p of the turbine}}{\text{power available in the wind}}$$

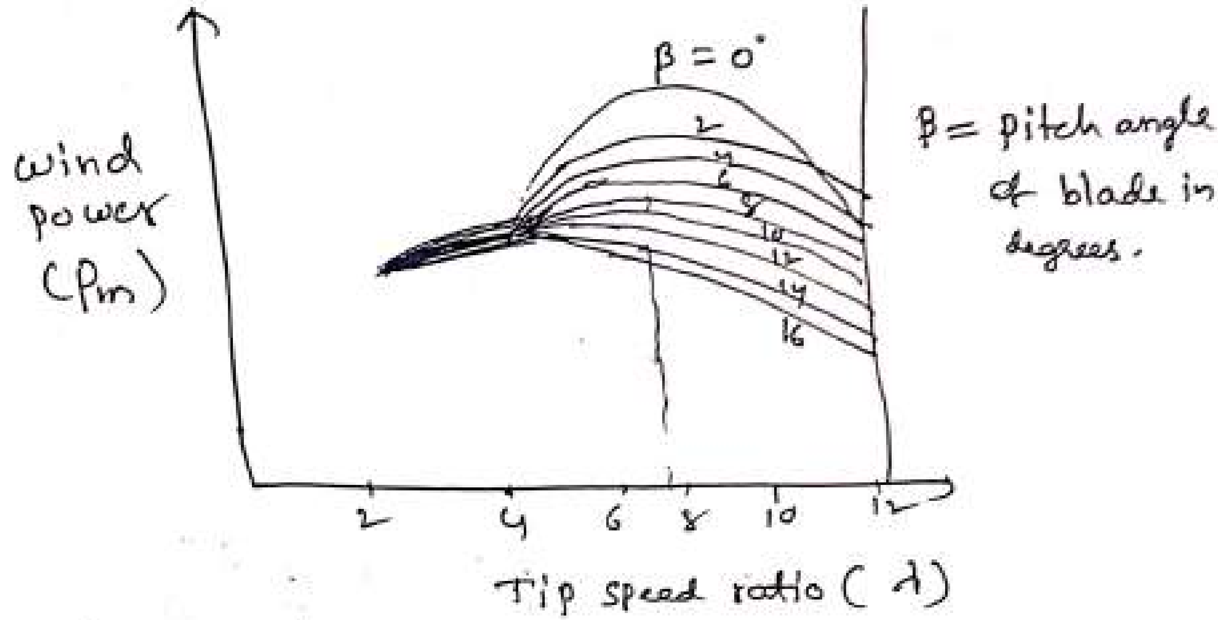
$$\text{Tip speed ratio } (\lambda) = \frac{\text{Tangential speed of the tip of a blade}}{\text{actual speed of the wind}}$$

recomended is 6 to 8

→ The performance characteristic of the wind turbine is relationship between the wind power vs tip speed ratio.

- Increasing the pitch angle, the wind power is gradually decreasing.
- Tip speed increases, then the wind power also increases upto certain points. The maximum wind power is 1.86mw at tip speed ratio is 8.

Then wind power is decreasing gradually.



Economic aspects of wind turbines

→ wind power projects can help diversity, strengthen & stabilises the local economies at the ~~municipal~~ municipal, country & state level.

- Increased economic diversification helps improve economic stability by minimising high & low financial cycles associated with a specific industry.

- wind turbines may also reduce the amount of electricity generation from fuels which results in lower total air pollution and carbon dioxide emissions.

- For 2-3 mw wind power,
  - Turbine cost is 2-4 million dollers range.
  - operation & maintance cost 42K to 48K dollers per year

Power System Architecture

Unit-2

Dr. A. Hema Sekhar

Transmission line parameters

Types of conductors – calculation of Resistance for solid conductors – Bundle conductors, Skin effect, proximity effect, concept of GMR & GMD – Transposition of power lines – calculation of inductance for single phase and three phase, single and double ckt lines, symmetrical & asymmetrical conductor configuration with and without transposition. calculation of capacitance for 2 wire and 3 wire systems, effect of ground on capacitance, capacitance calculation for symmetrical and asymmetrical single and three phase, single and double ckt lines, Numerical problems.

Introduction:

Generally Electrical power can be transmitted or distributed either by underground cables or by overhead lines. The underground cables are rarely used because of two reasons. Firstly, power is generally transmitted over long distances so insulation costs for underground cables will be very heavy. Secondly, Transmission voltages are at higher voltages so proper insulation is required. Therefore, power transmitted over long distance is carried out by using overhead line.

main components of overhead lines

An overhead line may be used to transmit or distribute electrical power. The successful operation of an overhead line depends upon the mechanical design of the line. This mechanical strength of the line is provided against most probably weather conditions.

In general, the main components are

(1) conductors : which carry electric power from one place to other place.

(2) Supports : which may be poles or towers and keep the conductors at a suitable level above the ground.

(3) Insulators : which are attached to supports and insulate conductors from ground.

(4) cross arms : which provide supports to the insulators

(5) miscellaneous items : such as phase plates, danger plates, ~~etc~~ lightning arresters etc.

Types of conductors

Generally, the conductor is one of the important items as most of the capital cost is invested for it. Therefore, paper choice of material and size of conductor is very importance.

The conductor material used for transmission and distributio[n] should have following properties.

(a) High electrical conductivity

(b) high tensile strength in order to withstand mechanical stre[sses]

(c) Low cost so that it can be used for long distances.

(d) Low specific gravity so that weight per unit volume is small.

commonly used conductor materials are

copper, Aluminium, steel cored aluminium, Galvanized steel and cadmium copper.

(1) Copper :

- Copper is ideal material for overhead lines and it has high electrical conductivity and greater tensile strength.

- It always used hard drawn form as stranded conductor.

- Copper has high current density i.e current carrying capacity per unit cross sectional area is quite large. This leads two advantages
  - Firstly, smaller cross section of conductor is required
  - area affected by conductor to wind loads is reduced.

- But due to high cost and non availability, It is rarely used for transmission of power.

(2) Aluminium :

- Aluminium is cheap and light in weight as compared to copper.

- The conductivity of aluminium is 60 % of that of copper. The smaller conductivity means for a particular transmission efficiency, the x-sectional area of conductor must be larger in aluminium as that of copper. and for the same resistance, the diameter of aluminium is 1.26 times diameter of copper conductor.

  The increased cross section of conductor leads to greater wind pressure and require. greater ~~strength strength of~~ strength of supports.

- The specific gravity of aluminium is 2.71 gm/cc and for copper is 8.9 gm/cc. so specific gravity of Al is

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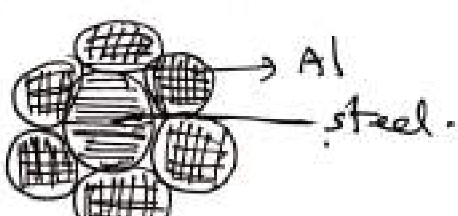
- The specific gravity of aluminium is 2.71 gm/cc and for copper is 8.9 gm/cc. so specific gravity of Al is less than copper conductor. i.e the aluminium conductor has one half of the weight of copper conductor. So supporting structures need not be strong.

- Aluminium conductor, being light, liable to greater swings, hence larger cross are required.
- Due to low tensile strength, the sag is greater in aluminium conductors.

(3) Steel cored aluminium:

- Due to low tensile strength, aluminium conductor produce greater sag. This prohibits use for long spans for power transmission.
- In order to increase the tensile strength, the aluminium conductor is reinforced with galvanized steel wires. The conductor is called steel cored aluminium and it is abbreviated as ACSR (Aluminium conductor steel reinforced) conductor.
- Steel cored aluminium consists of central core of galvanized steel wires surrounded by a number of aluminium strands.
- The diameter of both wires are same and the two metals are generally in the ratio of 1:4 or 1:6



(4) Galvanized steel:

- Steel has very high tensile strength. Therefore, it can be used for long spans or for short spans.
- These are very suitable for rural areas where cheapness is main consideration.
- Due to it's poor conductivity & high resistance, these are not used for long distance transmission.
- It can be used for transmitting small power over a small distance where size of copper is very small.

(5) cadmium copper:

- In certain cases conductor material with copper alloyed with cadmium.
- An addition of 1% or 2% of cadmium, increases tensile strength by 50% and the conductivity is only reduced by 15% of that of pure copper.
- It can be used for long spans. However, due to high cost of cadmium, such conductors are economical only for lines of small cross section.

Bundled conductors :

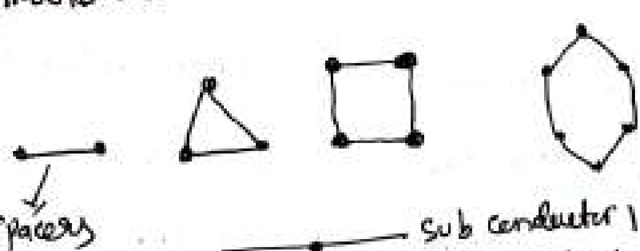
Def : Bundled conductor is a conductor made up of two or more sub conductors and is used as one phase conductor.

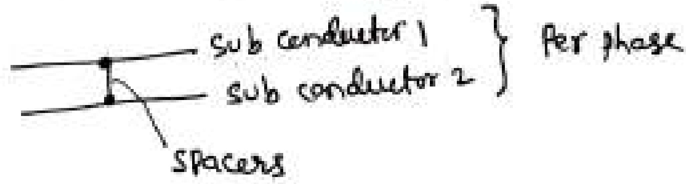
- Generally, for voltages greater than 220 KV, it is preferable to use more than one conductor per phase.
- By using Bundled conductors instead of the single conductor in the transmission line increases the GMR (Geometrical mean radius) of the conductors.

$$L = 4\times10^{-7}\frac{GMD}{GMR}$$

- Increase GMR means reduce inductance & hence reactance and hence to get more current carrying capacity.
- GMR↑ L↓ XL↓

- Hence, by using bundled conductors, it helps in obtaining better voltage regulation and efficiency by reducing inductance and skin effect. and to reduce corona loss and radio interface.
  - Also reduces voltage gradient.
- The symbols are





Advantages

① Increase current carrying capacity

② ~~KKP~~ Increase GMR of conductor, Therefore, inductance becomes reduces then reduces the inductive reactance of line.

(3) It also reduces voltage gradient

(4) Reduces corona power loss

(5) Reduces Radio & audio interface

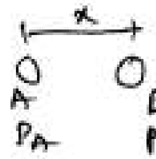
(6) Reduces surge impedance $\left(Z_0 = \sqrt{\frac{L}{C}}\right)$ & hence increases surge impedance loading of the line and hence Transmission capacity of the system is more.

(7) it increases the capacitance of line

$$C = \frac{\pi \epsilon_0}{\ln\left(\frac{GMD}{GMR}\right)} \Rightarrow C \propto \ln(GMR)$$

Note: (1) Voltage gradient : It is a difference in electrical potential across a distance or space

(2) suppose if two conductors A & B then



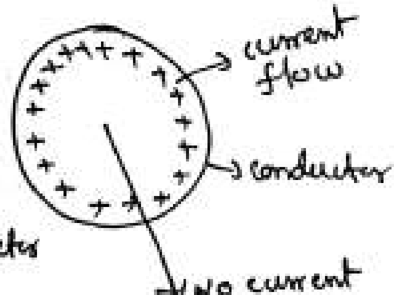
voltage gradient = ~~potential diff~~

$$\frac{(P_B - P_A)}{x_B - x_A} = \frac{\Delta P}{\Delta x} \quad \text{or} \quad V = \frac{Q}{4\pi\epsilon_0 r}$$

$x_B - x_A$ → distance; V → potential; r → distance

Skin effect

Def: The tendency of alternating current to concentrate near the surface of the conductor is known as skin effect.

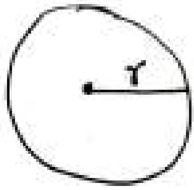


when a conductor is carrying dc, this current is uniformly distributed over the whole cross section of the conductor. However, an alternating current flowing through the conductor does not distribute uniformly, rather it has the tendency to concentrate near the surface of the conductor. So it is called skin effect.

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

Explanation

- Suppose take one stranded conductor. Then inductance is varying its position.



- inductance is

$$L = 4 \times 10^{-7} \ln \frac{d}{r} \quad \text{or} \quad 4 \times 10^{-7} \ln \frac{GMD}{GMR}$$

- At centre, $r = 0$, hence inductance is large, then reactance is more and hence no current flow.
- At the surface, radius is r, then inductance is very low, then inductive reactance is very low hence high current flow.

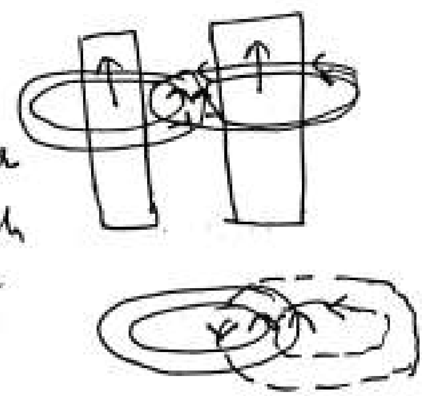
- Skin effect depends on
  - Nature of material
  - Diametre of wire : it increase with increase in diameter of wire
  - Frequency : it increases with increase in frequency
  - Shape of wire : For stranded conductor skin effect is less as compared to solid conductor

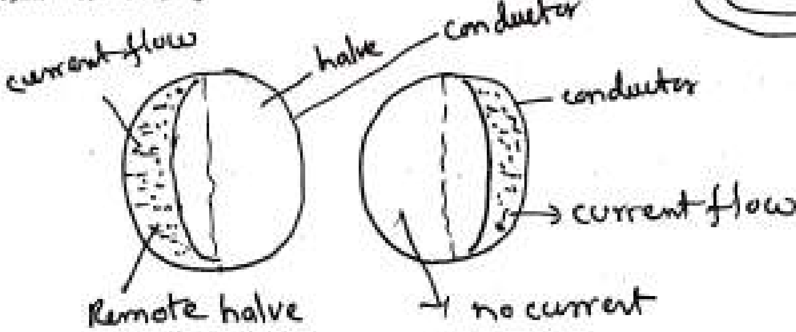
Proximity effect

Def: when two or more nearby conductors carry alternating current then the currents are non uniformly distributed on the cross sectional area of the conductor. This effect is called proximity effect.

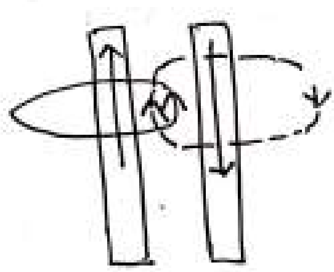
- When two or more conductors are placed near to each other. Then their electro magnetic fields interact with each other. Due to this interaction, then current in each of them is re distributed such that greater current density is concentrated in the part of the strand most remote from the interfacing conductor.

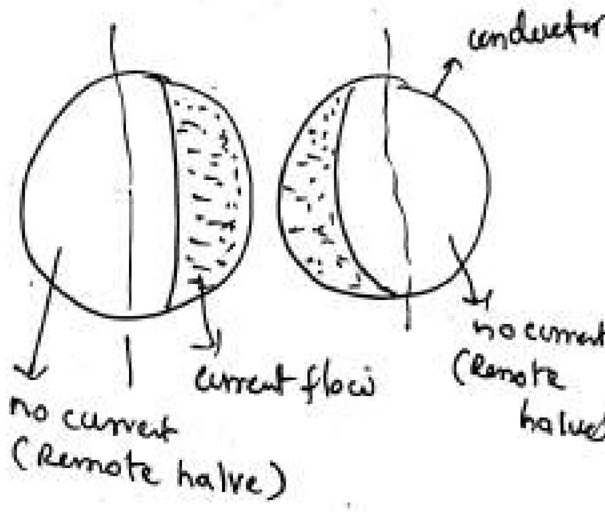
- when conductors carrying current in the same direction, then magnetic field of the halves of the conductors which are close to each other is cancelling each other and hence no current flow through that halves portion of the conductor





- when conductors carrying current in the opposite direction, then close part of the conductor carries, and no current in the furthest end.





– Proximity effect depends on

- Frequency : it increases with increases in the frequency
- Diameter : it increases with increase of the diameter
- Shape of wire : it is less in ACSR & more in solid conduct
- Nature of material : High ferromagnetic material, the Proximity effect is more on the surface.

Resistance of Transmission line

The resistance of transmission line is the most important cause of power loss in a transmission line.

The resistance 'R' of a line conductor having resistivity ρ, length 'l' and area of cross section 'a' is given by

$$\boxed{R = \rho \frac{l}{a}}$$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation.

Suppose R_1 & R_2 are the resistances of a conductor at t_1°c and t_2°c $(t_2 > t_1)$

Then if α_1 is the temperature coefficient at t_1°c then

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

where $\alpha_1 = \frac{\alpha_0}{1+\alpha_0 t_1}$, α_0 = temp coefficient at 0°c

note:

(i) In a 1-ϕ or 2-wire dc, the total resistance is equal to double the resistance of either conductor.

(ii) In case of a 3-phase transmission line, resistance per phase is resistance of one conductor.

Inductance:

When alternating current flows through a conductor, a changing flux is setup which links the conductor. Due to these flux linkages, the conductor possess inductance.

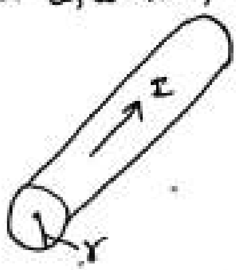
$$\boxed{L = \frac{\psi}{I}}$$

$\psi \rightarrow$ flux linkages in wb turns

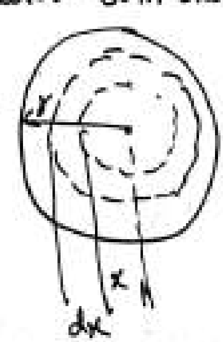
$I \rightarrow$ current in Amperes.

Flux linkages due to single current carrying conductor

Consider a long straight cylindrical conductor of radius 'r' m and carrying a current 'I' amp (rms) as shown in fig (i). This current will setup magnetic field. The magnetic lines of force will exist inside the conductor as well as outside the conductor. Both the fluxes will contribute inductance



(i)



(ii)

(a) Flux linkages due to internal flux:

Fig (ii) shows a conductor of radius 'r'. The magnetic field intensity (H_x) at a point 'x' metres from centre is given by

$$H_x = \frac{I_x}{2\pi x} \text{ AT/m} \quad \text{—(1)}$$

[According to Ampere's law
$mmF = I_x$
$H_x \cdot 2\pi x = I_x$]

here Assuming uniform current density

$$I_x = \frac{\pi x^2}{\pi r^2} I = \frac{x^2}{r^2} I \quad \text{—(2)}$$

Sub eq (2) in eq (1)

$$H_x = \frac{x^{\cancel{2}}}{r^2} \cdot I \times \frac{1}{2\pi \cancel{x}} = \frac{x}{2\pi r^2} I \text{ AT/m} \quad \text{—(3)}$$

If $\mu (\mu = \mu_0 \mu_r)$ is the permeability of the conductor, then flux density at the point 'x' is given by

$$B_x = \mu H_x$$

$$B_x = \mu_0 \mu_r H_x$$

for non-magnetic material $\mu_r = 1$

$$B_x = \mu_0 H_x \quad -(4)$$

Sub eq (4) in eq (3)

$$B_x = \mu_0 . \frac{x}{2\pi r^2} I \quad wb/m^2 \quad -(5)$$

Now, flux $d\phi$ of radial thickness dx & axial length 1m is given by

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

$$d\phi = \frac{\mu_0 x I}{2\pi r^2} . dx \quad wb \quad -(6)$$

This changing flux links with current $\left(I_x = \frac{\pi x^2}{\pi r^2} I \right)$ only

Therefore, flux linkages per metre length of the conductor is

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

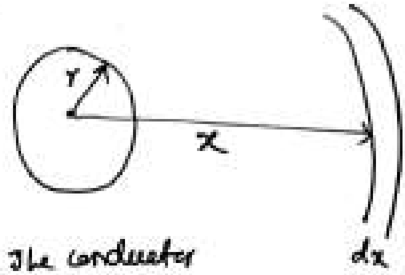
Total flux linkages from centre upto conductor surface is

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

$$\psi_{int} = \frac{\mu_0 I}{8\pi} \quad wb\text{-turns per metre length.}$$

(b) Flux linkages due to external flux :

The external flux extends from the surface of the conductor to infinity.



The magnetic field intensity at a distance 'x' m from centre to outside the conductor

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

Flux density $B_x = \mu_0 H_x = \frac{\mu_0 I}{2\pi x}$ wb/m²

now, $d\phi$ due to cylindrical shell of thickness dx and axial length of 1m is

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

Now flux linkages

$$d\psi = d\phi = B_x \cdot dx$$

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

Total flux linkages of the conductor from surface to infinity

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

∴ overall flux linkages

$$\psi = \psi_{int} + \psi_{ext} = \frac{\mu_0 I}{8\pi} + \int_r^{\infty} \frac{\mu_0 I}{2\pi x} \cdot dx$$

$$\boxed{\psi = \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \int_r^{\infty} \frac{dx}{x}\right]}$$

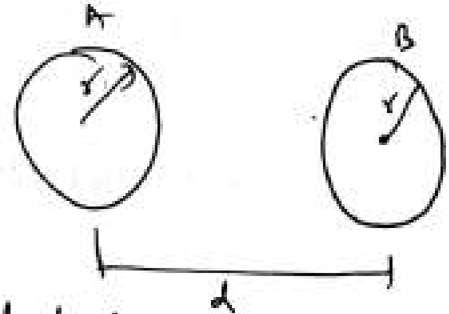
Inductance of a single phase two wire line

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

When alternating current flows through such a loop, a changing magnetic flux is setup. The changing flux links the loop and hence loop possess inductance.

→ consider a single phase overhead line consists of two parallel conductors A & B spaced 'd' metres apart. conductors A & B carry same current ($I_A = I_B$), but in the opposite direction because one forms return ckt of the other.

$$\boxed{I_A + I_B = 0}$$



In order to find inductance of conductor A or B, we shall consider flux linkages with it.

There will be flux linkages with conductor 'A' due to its own current I_A and also due to the mutual inductance effect of current I_B in the conductor B.

The flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^{\alpha} \frac{dx}{x}\right] \quad -①$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_d^{\alpha} \frac{dx}{x} \quad -(2)$$

Total flux linkages with conductor 'A'

$$\psi_A = eq(1) + eq(2)$$

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

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

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

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

$$= \frac{\mu_0}{2\pi}\left[\frac{I_A}{4} - I_A \log_e r - I_B \log_e d\right] \quad -(3)$$

Since we know $I_A + I_B = 0 \Rightarrow I_A = -I_B$ and

put in eq (3)

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

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

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

Inductance of conductor A, L_A

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

$$= \frac{\overset{2}{\cancel{4}}\cancel{\pi} \times 10^{-7}}{\cancel{2}\cancel{\pi}}\left(\frac{1}{4} + \ln\frac{d}{r}\right) \quad \text{H/m}$$

$$= 10^{-7}\left(\frac{1}{2} + 2\ln\frac{d}{r}\right) \text{ H/m}$$

Loop Inductance $= 2L_A$ H/m

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

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

<u>concise form</u>

The eq of inductance of a conductor can be put in a concise form

$$L_A = 10^{-7}\left(\frac{1}{2}+2\ln\frac{d}{r}\right) \text{ H/m}$$

$$= 2\times10^{-7}\left(\frac{1}{4}+\ln\frac{d}{r}\right) \text{ H/m}$$

$$L = 2\times10^{-7}\left[\ln e^{1/4}+\ln\frac{d}{r}\right]$$

$$L = 2\times10^{-7}\ln\left[\frac{d}{r e^{-1/4}}\right]$$

If we put $re^{-1/4} = r'$

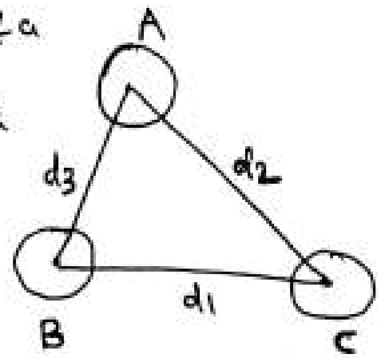
$$\boxed{L_A = 2\times10^{-7}\ln\frac{d}{r'} \text{ H/m}}$$

$$\text{Loop inductance } L = 4\times10^{-7}\ln\frac{d}{r'}$$

here $r' = re^{-1/4} = 0.7788r$. is called Geometric mean radius (GMR) of the wire.

Inductance of a 3-phase overhead line

Fig shows three conductors A, B & C of a 3-phase line carrying currents I_A, I_B & I_C resp.



Let d_1, d_2, d_3 be the spacing b/w the conductors.

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

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

Flux linkages of conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4} + \int_r^\alpha \frac{dx}{x}\right] \quad —(1)$$

Flux linkages with conductor A due to current I_B

$$= \frac{\mu_0 I_B}{2\pi}\int_{d_3}^\alpha \frac{dx}{x} \quad —(2)$$

Flux linkages with conductor 'A' due to current I_C

$$= \frac{\mu_0 I_C}{2\pi}\int_{d_2}^\alpha \frac{dx}{x} \quad —(3)$$

Total flux linkages with conductor A is

$$\psi = eq(1) + eq(2) + eq(3)$$

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

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

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \ln d_3 - I_C \ln d_2\right] + \frac{\mu_0}{2\pi}\left[\ln\alpha\,\underbrace{(I_A + I_B + I_C)}_{0}\right]$$

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

(i) Symmetrical spacing:

If three conductors A, B & C are placed symmetrically at the corners of an equilateral traingle of side 'd' then $d_1 = d_2 = d_3 = d$

under this conditions, flux linkages with conductor A

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

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

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} \cdot I_A - I_A \ln r + I_A \ln d\right] \quad \left[\because I_B + I_C = -I_A\right]$$

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

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

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

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

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

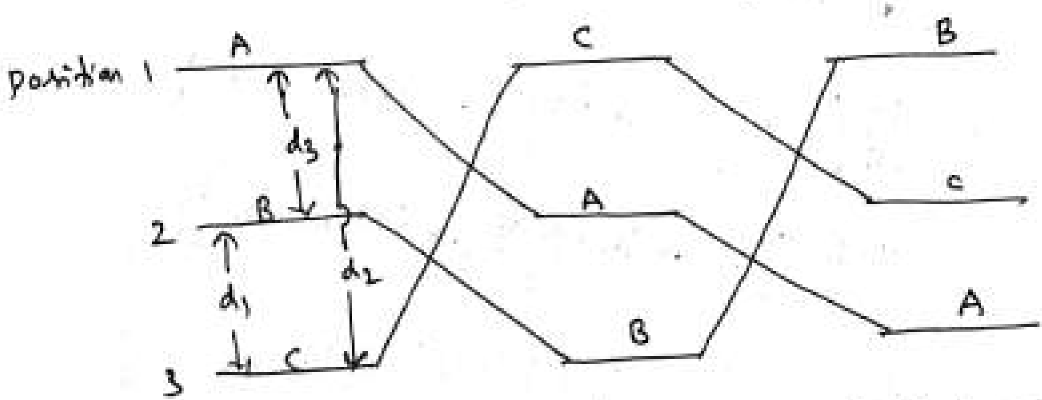
Unsymmetrical spacing :

When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, flux linkages and inductance of each phase are not the same.

A different inductance in each phase results in unequal voltage drops in the three phases even if the currents are balanced in the conductors. Therefore, the voltage at the receiving end will not be the same in all phases.

In order to make voltage drops are equal in all three conductors, we generally interchange the positions of the conductors at regular intervals along the line so that each conductor occupies the original position of every other conductor over the equal distance. It is known as transposition.

Fig shows transposed line



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

Fig shows a 3-phase transposed line having unsymmetrical spacing. ~~The~~ Let us assume that each of the three sections is 1m length. also assumed that balanced conditions $I_A + I_B + I_C = 0$

Let the line currents be

$$I_A = I\,(1 + j0)$$

$$I_B = I\,(-0.5 - j0.866)$$

$$I_C = I\,(-0.5 + j0.866)$$

The total flux linkages per m of conductor A is

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

putting the values of I_A, I_B & I_C

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

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

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

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

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

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

$$L_A = \frac{\psi_A}{I_A} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \ln\frac{\sqrt{d_2 d_3}}{I} + j0.866\ln\frac{d_3}{d_2}\right]$$

$$L_A = \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \ln\frac{\sqrt{d_2 d_3}}{r} + j\,0.866 \ln\frac{d_3}{d_2}\right] \text{ H/m}$$

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

$||^{ly}$ Inductance of conductors B & C

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

1.23

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

Inductance of each line conductor

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

$$\boxed{L = \frac{1}{2} + 2\ln\frac{\sqrt[3]{d_1 d_2 d_3}}{r}\Bigg] \times 10^{-7} \text{ H/m}}$$

Inductance of 3-ϕ lines with more than one ckt (or) Inductance of 3-ϕ line with Double ckt line:

Generally to run 3-ϕ transmission lines with more than one ckt in parallel on the same towers, because it gives greater reliability and a higher transmission capacity also cost of extra towers will be saved, cheaper and requires less land and maintanance also increases.

If such ckts are widely separated that the mutual inductance b/w them ~~in~~ is negligible and the inductance of equivalent single ckt would be half of the each of individual ckts considered alone.

But in actual practice, the separation is not very wide and the mutual inductance is not neglizible.

Here GMD method is used for determination of inductance per phase by considering various conductors connected in parallel so provides minimum inductance so as to have maximum transmission capacity. This is only possible with low GMD & high GMR.

In this case, individual conductors of a phase are widely separated to provide high GMR and distance b/w phases are small to give low GMD.

Arrangement of double ckt lines

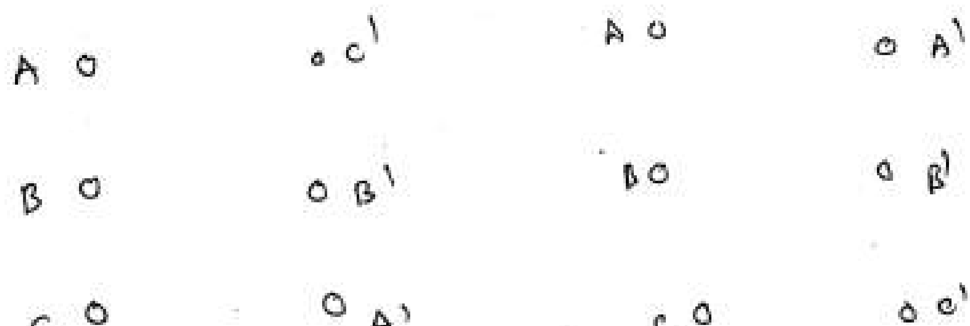


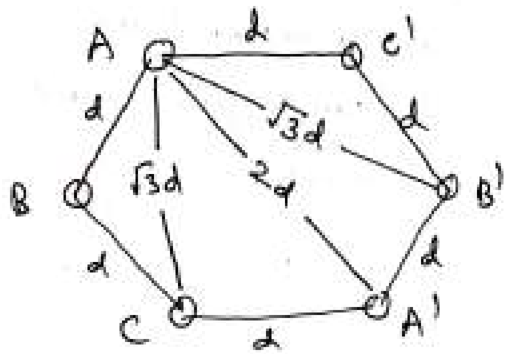
Fig (a) Fig (b)

Fig (a) have low inductance as compared to Fig (b).

Inductance of a 3-φ double ckt with symmetrical spacing

consider 3-φ double ckt connected in parallel.

conductors A, B, C forming one ckt and conductors A', B', C' forming the other ckt.



Flux linkages of phase A conductors

$$\psi_A = \frac{\mu_0}{2\pi}\left[\left(\left(\frac{1}{4}+\int_r^{\alpha}\frac{dx}{x}\right)+\int_{2d}^{\alpha}\frac{dx}{x}\right)I_A + I_B\int_d^{\alpha}\frac{dx}{x} + I_B\int_{\sqrt{3}d}^{\alpha}\frac{dx}{x} + \right.$$

$$\left. I_C\left[\int_d^{\alpha}\frac{dx}{x}+\int_{\sqrt{3}d}^{\alpha}\frac{dx}{x}\right]\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\ln r-\ln 2d\right)I_A + I_B\left(-\ln d-\ln\sqrt{3}d\right)+I_C\left(-\ln d-\ln\sqrt{3}d\right)\right.$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\ln 2dr\right)I_A - I_B\left(\ln\sqrt{3}d^2\right)-I_C\ln\sqrt{3}d^2\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\ln 2dr\right)I_A - \ln\sqrt{3}d^2\left(I_B+I_C\right)\right]$$

$$= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4}-\ln 2dr\right)I_A + I_A\ln\sqrt{3}d^2\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\ln\frac{\sqrt{3}d^2}{2dr}+\frac{1}{4}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\frac{1}{4}+\ln\frac{\sqrt{3}d}{2r}\right]$$

$$= \frac{\mu_0 I_A}{2\pi}\left[\ln\frac{\sqrt{3}d}{2r'}\right]$$

$$L_A = \frac{\mu_0}{2\pi}\left[\ln\frac{\sqrt{3}d}{2r'}\right] = \frac{4\pi\times10^{-7}}{2\pi}\ln\frac{\sqrt{3}d}{2r'}$$

$$\boxed{L_A = 2\times10^{-7}\ln\frac{\sqrt{3}d}{2r'}}$$

PSA
Unit-3

Dr. A. Hema Sekhar

Modelling of Transmission lines

Classification of Transmission lines - short, medium and long lines and their models - representations - Nominal-T, Nominal π and A, B, C, D constants, mathematical solutions to estimate regulation and efficiency of all types of lines. long transmission line - Rigorous solution, evaluation of A, B, C, D constants, Interpretation of the long line equations - Representation of long lines - equivalent T and Equivalent - π, Numerical problems - Surge Impedance and Surge impedance loading - Types of system transients - Travelling or propagation of Surges - attenuation, Distortion, Reflection and Refraction coefficients. Termination of lines with different types of condition - wavelengths and its velocity of propagation - Ferranti effect - charging current, Need of shunt compensation.

Introduction:

The main objective of modelling of transmission line is to analyse the performance and characteristics of the lines.

~~characteristics : Analyze the voltage and current in the line~~

Performance : performance includes the calculation of sending end voltage, sending end current, sending end power factor, power loss in the lines, efficiency of transmission, regulation and limits of power flows during steady state and transient conditions.

characteristics : Transmission lines are characterized by a series resistance, inductance and shunt capacitance per unit length.

These values determining the power carrying capacity of the transmission line and the voltage drop across it at full load.

Classification of Transmission lines

A Transmission line has Three constants R, L, C distributed uniformly along the whole length of the line. The R & L form the series impedance. The capacitance existing b/w conductors for 1-ϕ line or from a conductor to neutral for a 3-ϕ line forms a shunt path throughout the length of the line. Therefore, capacitance has introduces some complications in transmission line calculations.

Depending upon the manner in which capacitance is taken into account, the overhead transmission line are classified as

1. Short transmission lines
2. medium transmission lines
3. Long transmission lines

(1) Short transmission lines:

- when the length of the overhead transmission line is about upto 50 km or span below 80m and the operating voltage is < 20 kV. Then this type of transmission line is called short transmission line.
- Due to smaller length and lower voltage, the capacitance effects are very small & hence neglected.
- So, In this short transmission lines, only R & L of the line are taken into account.
- R & L are lumped not distributed.

(2) Medium transmission lines:

- when the length of the transmission line is about 50 km – 150 km (or) span between 80 m – 150 m and

and the operating voltage is in between 20KV - 100KV. Then this type of transmission lines are represented as medium transmission lines.

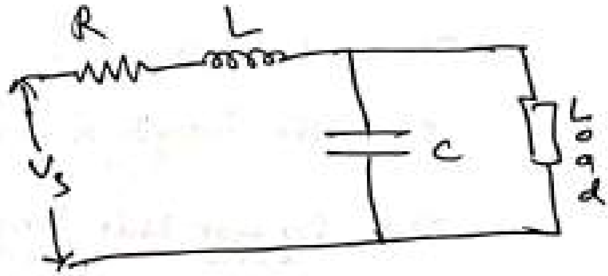
- Due to sufficient length & voltage of the line, capacitance effects are taken into account.

- In medium transmission line, the line parameters are lumped only.

- Based on the location of the capacitance, the medium transmission lines have three different configurations. These configurations shows the different ways in which the effect of capacitance is taken into account. These are

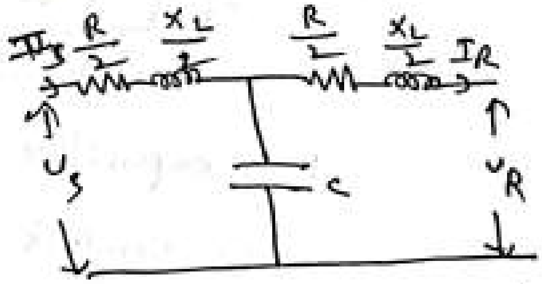
(A) End condensor method:

In this configuration, the total capacitance of the line is assumed to be concentrated at the receiving end of the line.



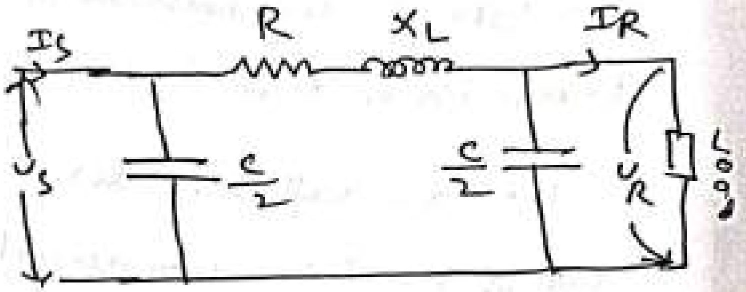
(B) Nominal-T

In this configuration, the total capacitance of the line is assumed to be concentrated at the centre of the line. Hence R & L are assumed to be divided into two halves on either side of the line.



(c) Nominal – π

In this configuration, the total capacitance of the line is assumed to be divided into two halves, one is near sending end and other near receiving end as shown in fig.

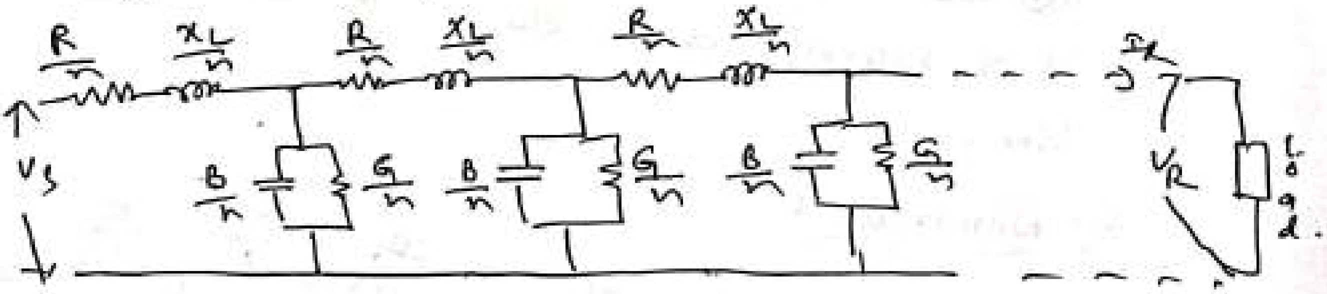


Long transmission lines

– when the length of the overhead transmission line is >150km or span ~~set~~ above 150 m and the operating voltage is >100kV then this type of transmission lines are represented as Long transmission lines.

– In this lines, the line constants are uniformly distributed over the lengths of the line.

– The fig for this long tr||ssion line is



B → capacitive Susceptance

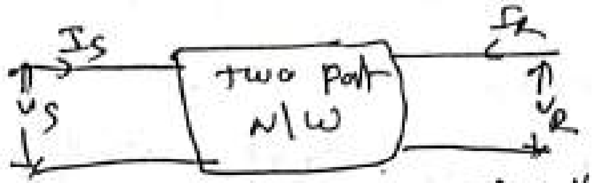
G → Conductance.

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

$$Z = \sqrt{R^2+X_L^2}$$

ABCD constants of Transmission line

We know the ABCD parameter of a line are



$V_S = AV_R - BI_R$ —(1)

$I_S = CV_R - DI_R$ —(2)

$\Rightarrow \begin{pmatrix} V_S \\ I_S \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_R \\ -I_R \end{pmatrix}$ '-' indicate direction

Properties : (1) A & D are dimensionless $\left[A = \frac{V_S}{V_R},\ D = -\frac{I_S}{I_R}\right]$

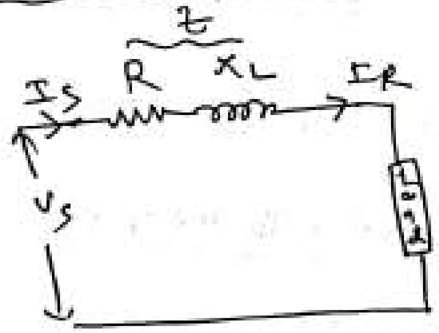
(2) B is impedance & C is admittance.

(3) condition for symmetry $A = D$

(4) condition for reciprocity $AD - BC = 1$.

(1) ABCD parameters of short transmission line

From the fig,



$\bar{I}_S = \bar{I}_R$

$\bar{V}_S = \bar{V}_R + \bar{I}_S \bar{Z}$

$V_S = \bar{V}_R + \bar{I}_R Z$ —(3)

$I_S = 0V_R + I_R$ —(4)

comparing eq (1) & (2) with eq (3) & (4)

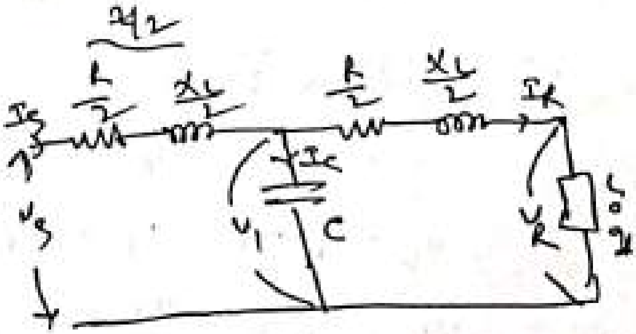
$A = 1,\ B = Z,\ C = 0,\ D = 1$

$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix}$

2. Medium Transmission lines

(a) Nominal-T method

From fig,



$\bar{V}_S = \bar{V}_1 + \bar{I}_S\left(\frac{Z}{2}\right)$ —(3)

$V_1 = \bar{V}_R + \bar{I}_R\left(\frac{Z}{2}\right)$ —(4)

$I_S = I_R + I_C$ —(5)

where $I_C = Y \cdot V_1 = Y \cdot \left[\bar{V}_R + \bar{I}_R \cdot \frac{Z}{2}\right]$ —(6)

$$I_s = \bar{I_R} + Y\bar{V_R} + \bar{Y}\cdot\frac{\bar{I_R}}{2}\cdot Z$$

$$I_s = \bar{Y}\cdot\bar{V_R} + \left(1+\frac{YZ}{2}\right)\bar{I_R} \quad -(7)$$

from eq (3)

$$\bar{V_s} = \bar{V_R} + \bar{I_R}\left(\frac{Z}{2}\right) + \left(\frac{Z}{2}\right)\left[\bar{Y}\cdot V_R + \bar{I_R}\left(1+\frac{YZ}{2}\right)\right]$$

$$= \bar{V_R}\left(1+\frac{YZ}{2}\right) + \bar{I_R}\left(Z + \frac{YZ^2}{4}\right)$$

$$V_s = V_R\left(1+\frac{YZ}{2}\right) + I_R\cdot Z\left(1+\frac{YZ}{4}\right) \quad -(8)$$

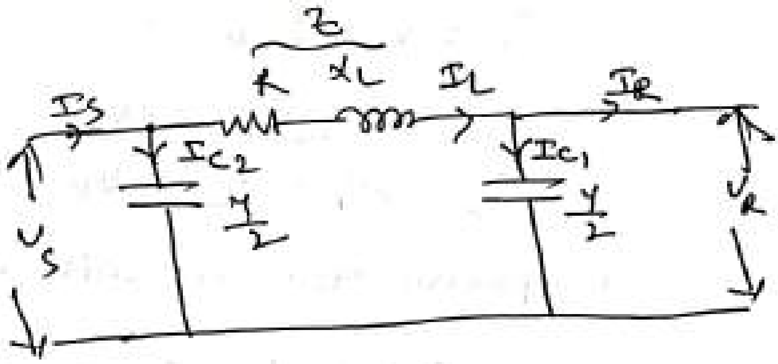
compare eq 7 & 8 with eq (1) & (2)

$$A = 1+\frac{YZ}{2}, \quad B = Z\left(1+\frac{YZ}{4}\right)$$

$$C = Y, \quad D = 1+\frac{YZ}{2}$$

Note: (1) $A = D$ (2) $AD - BC = 1$

(B) Nominal-π method



from fig,

$$\bar{I_s} = \bar{I_L} + \bar{I_{C2}}$$

$$\bar{I_s} = \bar{I_L} + V_s\cdot\frac{Y}{2} \quad -(3)$$

Also, $\bar{I_L} = \bar{I_R} + \bar{I_{C1}}$

$$I_L = I_R + \bar{V_R}\cdot\frac{Y}{2} \quad -(4)$$ where $I_{C1} = V_R\cdot\frac{Y}{2}$

$$\bar{V_S} = \bar{V_R} + \bar{I_L}\bar{Z}$$

$$= \bar{V_R} + Z(\bar{I_R} + \bar{I_{C1}})$$

$$V_s = V_R + Z\left(\bar{I_R} + \bar{V_R}\cdot\frac{Y}{2}\right)$$

$$V_s = \bar{V_R}\left(1+\frac{YZ}{2}\right) + I_R\cdot Z \quad -(5)$$

Then

$$\bar{I_S} = I_L + V_S \cdot \frac{Y}{2}$$

$$= \bar{I_R} + \bar{V_R} \cdot \frac{Y}{2} + \frac{Y}{2}\left[\bar{V_R}\left(1+\frac{YZ}{2}\right) + \bar{I_R} Z\right]$$

$$I_S = \bar{V_R}\, Y\left(1+\frac{YZ}{4}\right) + \bar{I_R}\left(1+\frac{YZ}{2}\right) \quad -(6)$$

compare eq (5) & (6) with eq (1) & (2)

$$A = 1+\frac{YZ}{2}, \quad B = Z$$

$$C = Y\left(1+\frac{YZ}{4}\right), \quad D = 1+\frac{YZ}{2}$$

Note: $A = D$, $AD - BC = 1$ (Reciprocity)
↓
symmetry.

Performance of Transmission lines

Performance of Transmission lines i.e it is desirable to determine voltage regulation and Transmission efficiency.

Voltage Regulation:

when Transmission line is carrying current, there is a voltage drop in the line due to resistance and inductance of the line. This results that the receiving end voltage (V_R) is less than sending end voltage (V_S).

This voltage drop ($V_S - V_R$) in the line is expressed as a percentage of receiving end voltage is called voltage regulation

Def: The difference in voltage at the receiving end of the Trn line from no load to full load is called voltage regulation

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

Note: It is desirable that V.R should be low i.e increase in load current should make very little difference $(V_S - V_R)$.

Transmission efficiency:

"The Ratio of receiving end power to the sending end power of a transmission line is known as the transmission efficiency".

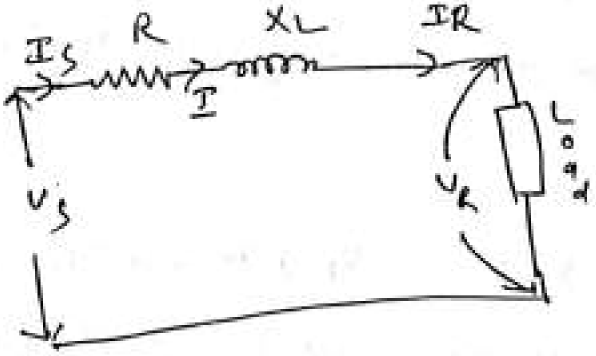
$$\% \text{ Transmission efficiency} = \frac{\text{Receiving end power}}{\text{Sending end power}} \times 100$$

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

Performance of Short Transmission lines

- For short transmission line, the effect of capacitances are neglected. So the performance of this line is studying by only R & L are taken into account.

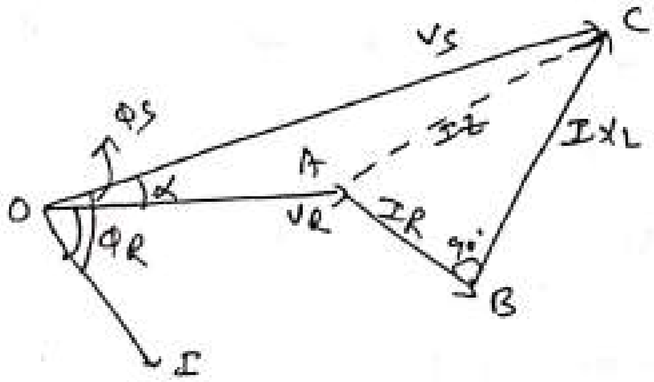
- The equivalent ckt is



here I_S = Sending end current
I_R = receiving end current
V_S = sending end voltage
V_R = Receiving end voltage.

Phasor diagram is

Taking $\bar{V_R}$ as the reference phasor,



From the phasor diagram

$$\bar{V_R} = V_R + j0$$

$$I = I\angle -\phi_R = I(\cos\phi_R - j\sin\phi_R)$$

$$Z = R + jX_L$$

$$\bar{V_s} = \bar{V_R} + \bar{I}\bar{Z}$$

$$= (V_R + j0) + I(\cos\phi_R - j\sin\phi_R)(R + jX_L)$$

$$\bar{V_s} = V_R + (IR\cos\phi_R + IX_L\sin\phi_R) + j(IX_L\cos\phi_R - IR\sin\phi_R)$$

$$V_s = \sqrt{(V_R + IR\cos\phi_R + IX_L\sin\phi_R)^2 + (IX_L\cos\phi_R - IR\sin\phi_R)^2}$$

The second term under root is very small and hence it is negligible

$$V_s = \sqrt{(V_R + I_R\cos\phi_R + IX_L\sin\phi_R)^2}$$

$$\boxed{V_s = V_R + I\cos\phi_R + IX_L\sin\phi_R}$$

(ii) percentage voltage regulation $= \frac{V_S - V_R}{V_R} \times 100$

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

(iv) Line losses $= I^2R$

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

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

Note: For Analyzing the performance of 3-ϕ short transmission lines, as a matter of convenience, we generally analyse 3-ϕ system by considering single phase only. So, the expression for regulation, efficiency etc derived for a 1-ϕ line can also be applied to a 3-ϕ system.

Effect of Load pf on Regulation & efficiency

The Regulation and efficiency of a transmission line depends on power factor of the load.

1. % voltage Regulation = $\frac{IR\cos\phi_R + IX_L\sin\phi_R}{V_R} \times 100$ — For lagging pf

% voltage Regulation = $\frac{IR\cos\phi_R - IX_L\sin\phi_R}{V_R} \times 100$ — For leading pf

- From the above equation it is clear that,
  (i) when the load pf is lagging or unity, $IR\cos\phi_R > IX_L\sin\phi_R$ then V.R is positive i.e $V_R < V_S$
  (ii) For a given V_R & I, the VR of the line increases with the decrease in pf for lagging loads.
  (iii) when load pf is leading to this extent that $IX_L\sin\phi_R > IR\cos\phi_R$, then V.R is -ve i.e $V_R > V_S$.
  (iv) For given V_R & I, the V.R of the line decreases with the decrease in pf for leading loads.

2. Transmission efficiency = $\frac{\text{Power Delivered}}{\text{Power Sent out}} \times 100$

Power delivered $= V_R I_R \cos\phi_R = V_R I \cos\phi_R$ (For Single phase)
$= 3 V_R I \cos\phi_R$ (For 3-ϕ)

Problems

① 1-ϕ overhead transmission line delivers 1100 kW at 33 kV at 0.8 pf 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 (iii) Transmission efficiency

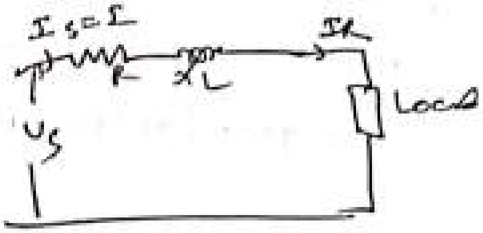
Sol)

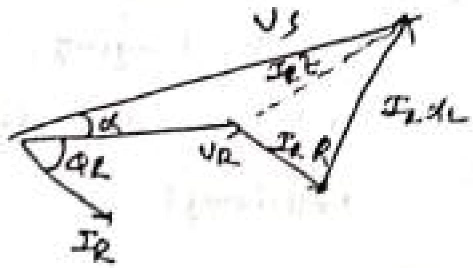
Load pf $= \cos\phi_R = 0.8$ lagging

$Z = R + jX_L = 10 + j15\ \Omega$

$V_R = 33\ kV$

Load current $I = \frac{P}{V_R \cos\phi_R} = \frac{1100 \times 10^3}{33 \times 10^3 \times 0.8} = 41.67\ A.$





Taking V_R as reference phasor

$\bar{V_R} = V_R + j0 = 33000\ V$

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

$= 41.67\ (0.8 - j0.6)$

$\bar{I} = 33.33 - j25$

(i) Sending end voltage $V_s = \bar{V_R} + \bar{I}\bar{Z}$

$= 33000 + (33.33 - j25)(10 + j15)$

$= 33000 + 333.3 - j250 + j500 + 375$

$= 33708.3 + j250$

magnitude of $V_S = \sqrt{33708.3^2 + 250^2} = 33709\ V$

(ii) Angle b/w V_S & V_R is α

$\alpha = \tan^{-1}\frac{250}{33708.3} = 0.42°$

Sending end power factor angle

$\phi_s = \phi_R + \alpha = 36.87 + 0.42 = 37.29°$

(iii) line losses $= I^2R = (41.67)^2 \times 10$

$= 17364\ W$

$= 17.364\ kW$

power o/p $= 1100\ kW$

power sent out $= 1100 + 17.364 = 1117.364\ kW$

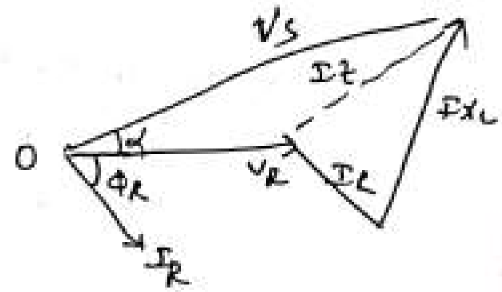
$$\text{Transmission efficiency} = \frac{\text{power delivered}}{\text{power sent out}} \times 100$$

$$= \frac{1100}{1117.364} \times 100$$

$= 98.44\ \%$.

(2) An overhead 3-φ Transmission line delivers 5000 kW at 22kV at 0.8 pf lagging. The resistance & reactance of each conductor is 4 Ω & 6 Ω resp. determine (i) V_s (ii) % Regulation (iii) Transmission efficiency.

Sol: Load pf = 0.8 lagging



V_R per phase $= \dfrac{22000}{\sqrt{3}} = 12700\ V$

Impedance per phase $= \bar{Z} = 4 + j6$

Line current $I = \dfrac{P}{3V_R \cos\phi_R} = \dfrac{5000 \times 10^3}{3 \times 12700 \times 0.8} = 164\ A$.

Taking $\bar{V_R}$ as reference vector

$\bar{V_R} = V_R + j0 = 12700\ V$

$\bar{I} = I(\cos\phi_R - j\sin\phi_R) = 164(0.8 - j0.6) = 131.2 - j98.4$

(i) Sending end voltage

$V_s = \bar{V_R} + \bar{I}\bar{Z} = 12700 + (131.2 - j98.4)(4 + j6)$

$= 12700 + 524.8 + j787.2 - j393.6 + 590.4$

$= 13815.2 + j393.6$

magnitude of $V_s = |V_s| = \sqrt{13815.2^2 + 393.6^2} = 13820.8\ V$

Line value of $V_s = \sqrt{3} \times$ single phase value

$= \sqrt{3} \times 13820.8 = 23938\,V = 23.938\,kV.$

(ii) % voltage regulation $= \dfrac{V_s - V_R}{V_R} \times 100$

$= \dfrac{13820.8 - 12700}{12700} \times 100$

$= 8.825\ \%$

(iii) Line losses $= 3I^2R = 3 \times 164^2 \times 4 = 322.752\,kW$

Transmission efficiency $= \dfrac{5000}{5000 + 322.752} \times 100 = 93.94\,\%.$

(3) A 3-ϕ, 50Hz 16 km long overhead line supplies 1000 kW at 11kV, 0.8 pf lagging. The line resistance is 0.03 Ω per phase per km and line inductance is 0.7 mH per phase per km. calculate sending end voltage, vol. regulation & efficiency of transmission.

Sol)

$R = 0.03 \times 16 = 0.48\,\Omega$

$X_L = 2\pi f L \times 16 = 2\pi \times 50 \times 0.7 \times 10^{-3} \times 16 = 3.52\,\Omega$

$V_R/\text{phase} = \dfrac{11000}{\sqrt{3}} = 6351\,V$

$\cos\phi_R = 0.8$ lagging

Line current $I = \dfrac{P}{3 V_R \cos\phi_R} = \dfrac{1000 \times 10^3}{3 \times 6351 \times 0.8} = 65.6\,A.$

(i) sending end voltage

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

$= 6351 + 65.6 \times 0.48 \times 0.8 + 65.6 \times 3.52 \times 0.6$

$= 6515\,V.$

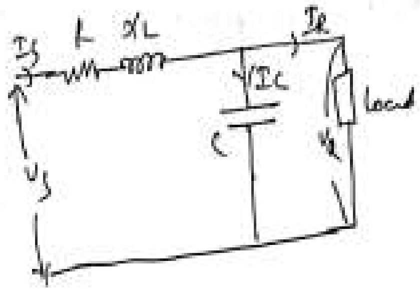
(2) Voltage Regulation $= \dfrac{V_S - V_R}{V_R} \times 100 = \dfrac{6515 - 6351}{6351} \times 100 = 2.58\,\%.$

(3) Line losses $= 3I^2R = 3 \times 65.6^2 \times 0.48 = 6.2\,kW$

Transmission efficiency $= \dfrac{\text{o/p power}}{\text{Input power}} \times 100 = \dfrac{1000}{1000 + 6.2} \times 100 = 99.38\,\%.$

medium Transmission lines

(1) End condenser method



The equivalent ckt is shown in fig.

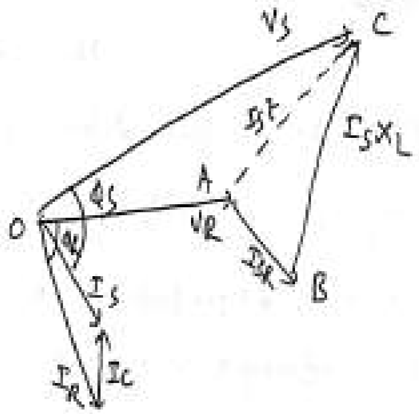
I_s = Sending end current

I_R = Receiving end current

I_c = capacitive current.

Phasor diagram is

Taking V_R as reference phasor



From phasor diagram

$$\bar{V_R} = V_R + j0$$

Load current $\bar{I_L} = I_R(\cos\phi_R - j\sin\phi_R)$

capacitive current $\bar{I_c} = \frac{V_R}{-jX_c} = jV_R\omega C$

$$= j2\pi f C\bar{V_R}$$

(i) $\bar{I_s} = \bar{I_R} + \bar{I_c}$

$$= I_R(\cos\phi_R - j\sin\phi_R) + j2\pi f C\bar{V_R}$$

$$I_s = I_R\cos\phi_R + j(-I_R\sin\phi_R + 2\pi f C V_R)$$

(2) Sending end voltage

$$V_s = \bar{V_R} + \bar{I_s}\bar{Z} = \bar{V_R} + \bar{I_s}(R + jX_L)$$

(3) $\% V.R = \frac{V_s - V_R}{V_R} \times 100$

(4) Transmission efficiency $= \frac{\text{Power delivered/phase}}{\text{Power delivered/phase} + \text{losses/ph}} \times 100$

$I_s^2 R$

Problems

① A medium single phase transmission line 100 km long has the following

const

$R/km = 0.25\Omega$, $X/km = 0.8\Omega$

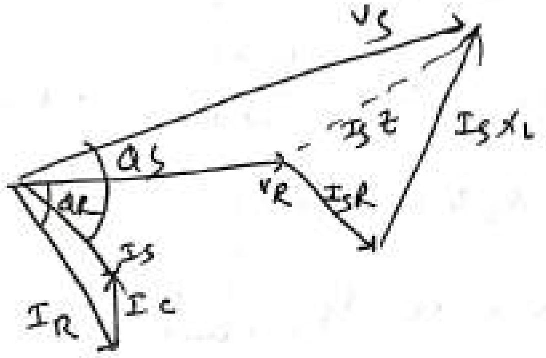
V_R(line vol) = 66000 V.

susceptance/km = 14×10^{-6} S

assuming that the total capacitance of the line is localized at the receiving end alone. Determine

(i) I_S (2) V_S (3) Regulation (4) $\cos\phi_S$. The line is delivering 15000 kW at 0.8 pf lagging

Sol



Given

$R = 0.25 \times 100 = 25\Omega$, $X_L = 0.8 \times 100 = 80\Omega$

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

$V_R = 66000$ V.

Load current $I_R = \frac{P}{V_R \cos\phi_R} = \frac{15000 \times 10^3}{66000 \times 0.8} = 284$ A.

$\cos\phi_R = 0.8$, $\sin\phi_R = 0.6$

$\bar{V_R} = V_R + j0 = 66000$ V

$\bar{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 284(0.8 - j0.6) = 227 - j170$

$I_C = jY \cdot V_R = j14 \times 10^{-4} \times 66000 = j92$

(i) $I_S = I_R + I_C = 227 - j170 + j92 = 227 - j78$

$|I_S| = \sqrt{227^2 + 78^2} = 240$ A.

(ii) $\bar{V_S} = \bar{V_R} + \bar{I_S}\bar{Z}$

$= 66000 + (227 - j78)(25 + j80)$

$= 77915 + j16210$

$|V_S| = 79583$ V.

(3) $\% VR = \frac{V_S - V_R}{V_R} \times 100 = \frac{79583 - 66000}{66000} \times 100 = 20.58\%$

(4) sending end power factor ϕ_s = Angle b/w V_s & I_s

Angle b/w V_s & I_s = Angle b/w V_R & I_s + Angle b/w V_s & V_R

Angle b/w V_R & I_s (θ_1)

using eq I_s $[\because I_s = 227 - j78]$

$$\theta_1 = \tan^{-1}\frac{(-78)}{227} = -18.96^\circ$$

Angle b/w V_S & V_R (θ_2)

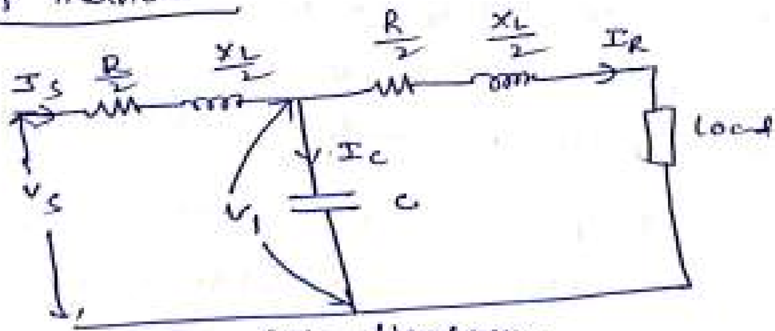
using eq V_s $[\because V_s = 77915 + j16210]$

$$\theta_2 = \tan^{-1}\left(\frac{16210}{77915}\right) = 11.50^\circ$$

$$|\phi_s| = 18.96 + 11.50 = 30.46^\circ$$

$$\cos\phi_s = \cos 30.46 = 0.86 \text{ lag.}$$

(B) Nominal-T method



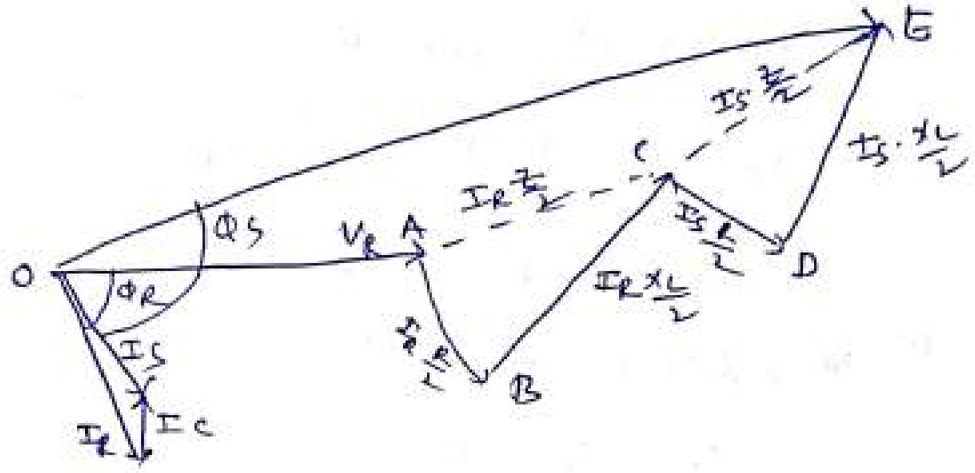
Ckt diagram.

Taking $\bar{V_R}$ as reference vector.

$\bar{V_R} = V_R + j0$

$\bar{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$

Phasor diagram is



From the phasor diagram

$$\bar{V_1} = \bar{V_R} + \bar{I_R}\frac{Z}{2}$$

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

capacitive current $\bar{I_c} = j\omega c\bar{V_1} = j2\pi f c\bar{V_1}$

sending end current $I_s = I_R + I_C$.

sending end voltage $V_s = V_1 + I_s \cdot \frac{Z}{2}$

$$= V_1 + I_s\left(\frac{R}{2} + j\frac{X_L}{2}\right)$$

Problems

① A 3-ϕ, 50Hz overhead transmission line 100 km long has the following constants

R/km/phase = 0.1Ω, Inductive reactance/km/phase = 0.2Ω

capacitive susceptance/km/phase = 0.04 x 10^{-4} siemen

Determine

(a) sending end current (b) V_s (c) sending end power factor

(d) Transmission efficiency when supplying a balanced load of 10000kW at 66kV, pf 0.8 lagging. Use nominal T-method

10)

Given

line length = 100 km

total Resistance = 0.1 x 100 = 10Ω

total reactance = X_L = 0.2 x 100 = 20Ω capacitive susceptance $Y = 0.04 \times 10^{-4} \times 100$

$= 4 \times 10^{-4}$ S

$V_R/_{ph} = \frac{66000}{\sqrt{3}} = 38105$ V

Load current $I_R = \frac{P}{\sqrt{3} V_R \cos\phi} = \frac{10000 \times 10^3}{\sqrt{3} \times 66 \times 10^3 \times 0.8} = 109$ A

Impedance $Z = R + jX_L = 10 + j20$

(1) Sending end current (I_s)

$I_s = I_R + I_C$

$= I_R(\cos\phi_R - j\sin\phi_R) + jYV_1$

$= 109(0.8 - j0.6) + j \times 4 \times 10^{-4} (\bar{V}_R + I_R \frac{Z}{2})$

$= 87.2 - j65.4 + j \times 4 \times 10^{-4} [38105 + 109(5 + j10)]$

$= 87 - j49.8 = 100 \angle -29.47^\circ$ A.

$|I_s| = 100$ A

(2) $V_s = V_1 + I_s \frac{Z}{2}$

$= \bar{V}_R + I_R \frac{Z}{2} + I_s (\frac{Z}{2})$

$= 38105 + 109(0.8 - j0.6)(5 + j10) + (87 - j49.8)(5 + j1$

$= 40128 + j1170 = 40145 \angle 1^\circ 40'$ V

$|V_s| = 40145$ V.

Line vol (V_s) $= \sqrt{3} \times 40145 = 69533$ V $= 69.533$ kV

(3) ϕ_s (sending end pf)

ϕ_s = Angle b/w V_s & I_s

= Angle b/w V_R & I_s + Angle b/w V_R & V_s.

$= \theta_1 + \theta_2$

θ_1 = Angle b/w V_R & I_S = 29.47

~~= tan⁻¹(~~

$\theta_2 = 1'40'$

$\theta_S = 1^\circ 40 + 29'47' = 31.27^\circ$

Sending end pf $\cos\phi_S = \cos 31.27 = 0.853$ lag.

(4) Sending end power $= 3 V_S I_S \cos\phi_S$

$= 3 \times 40145 \times 100 \times 0.853$

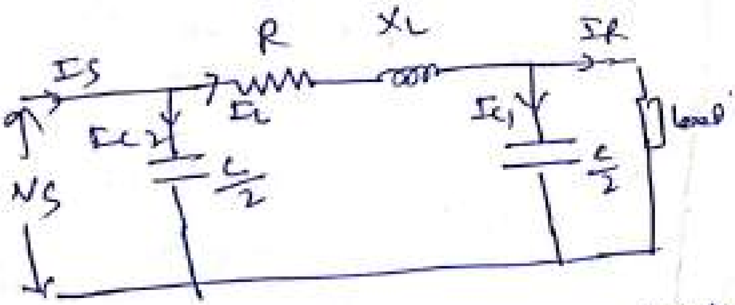
$= 10273.105$ kW

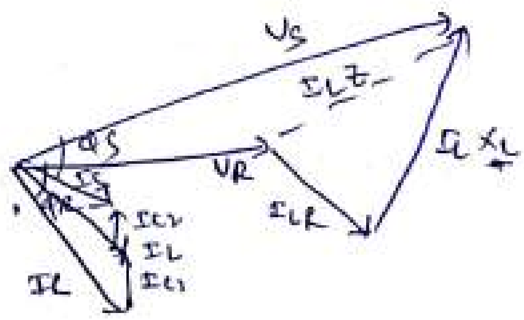
power delivered = 10000 kw

Transmission efficiency $= \dfrac{10,000}{10273.105} \times 100 = 97.34\%$

<u>Nominal – π method</u>

– In this method, the capacitance is devided into two halfs, one half being lumped at the sending end and other half at the receiving end.





Taking $\bar{V_R}$ as reference vector,

$\bar{V_R} = V_R + j0$

$\bar{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$

$I_{c1} = j\omega\left(\frac{C}{2}\right)\bar{V_R} = j\pi f C \bar{V_R}$

Line current $\bar{I_L} = \bar{I_R} + \bar{I_{c1}}$

Sending end voltage (V_S) = $V_R + I_L Z$

$= V_R + I_R(R + jX_L)$

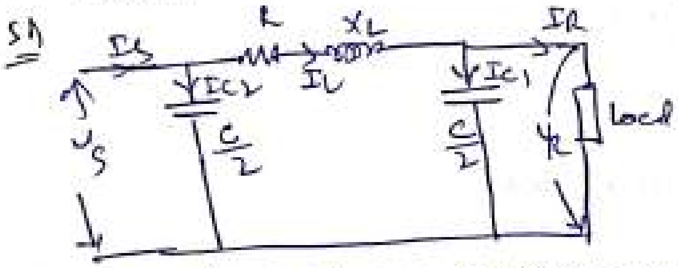
Charging current $I_{C_2} = j\omega \frac{C}{2} V_S$

$= j\pi f V_S \cdot C$

Sending end current (I_S) = $I_L + I_{C_2}$

Problem: A 3-phase, 50Hz, 150 km long line has a resistance, inductive reactance and capacitive shunt admittance of 0.1Ω, 0.5Ω and 3×10^{-6} S per km per phase. If the line delivers 50 MW at 110 kV and 0.8 pf lagging. Determine the V_S, I_S. Assuming nominal-π ckt for the line.

Sol:



Total resistance/phase = $0.1\times150 = 15\Omega$

total reactance/phase $X_L = 0.5\times150 = 75\Omega$

capacitive admittance/phase

$Y = 3\times10^{-6}\times150 = 45\times10^{-6}$ S

Receiving end voltage/phase

$V_R = \frac{110\times10^3}{\sqrt{3}} = 63508$ V

Load current $I_R = \frac{P}{\sqrt{3} V_R \cos\phi_R}$

$= \frac{50\times10^6}{\sqrt{3}\times110\times10^3\times0.8}$

$= 328$ A.

$\bar{I_R} = I_R(\cos\phi_R - j\sin\phi_R)$

$= 328(0.8 - j0.6)$

$= 262.4 - j196.8$

① Sending end voltage (V_S)

$\bar{V_S} = \bar{V_R} + \bar{I_L}\bar{Z}$

$\bar{V_S} = \bar{V_R} + \bar{I_L}(R + jX_L)$

where $\bar{I_L} = \bar{I_R} + \bar{I_{C_1}}$

$= \bar{I_R} + j\frac{Y}{2}V_R$

~~$= 262.4 - j182.5$~~

$= (262.4 - j196.8) + j\frac{45\times10^{-5}}{2}\times63508$

$= 262.4 - j196.8 + j14.3$

$= 262.4 - j182.5$

∴ Now $\bar{V_S} = \bar{V_R} + \bar{I_L}(R + jX_L)$

$= 63508 + (262.4 - j182.5)(15 + j75)$

$\boxed{\bar{V_S} = 81131 + j16942.5} = 82881 \angle 11.7$

Line voltage of $\bar{V_S} = 82881\times\sqrt{3}$

$= 143.55$ kV

lly

$I_S = I_L + I_{C_2} = (262.4 - j182.5) + j\frac{Y}{2}V_S$

$= (262.4 - j182.5) + (81131 + j16942)\cdot j\times\frac{45\times10^{-5}}{2}$

$= (262.4 - j182.5) + (-3.81 + j18.25)$

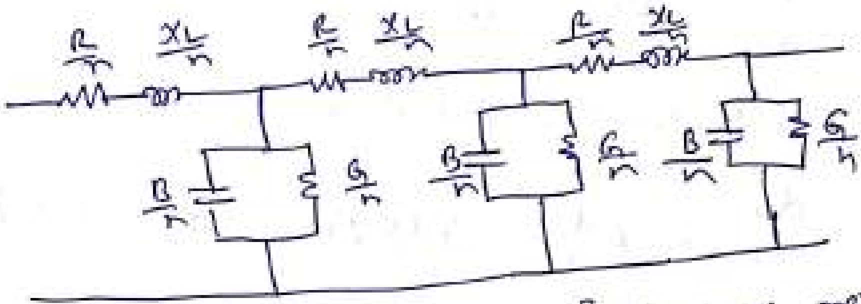
$= 258.6 - j164.25$

$\boxed{\bar{I_S} = 306.4 \angle -32.4^\circ \text{ A}}$

$\boxed{|I_S| = 306.4 \text{ A}}$

Long Transmission lines

- In long Transmission lines, All the parameters (R, L, C) are distributed along the length of the line. Rigorous mathematical treatment is required for the solution of these lines.



Analysis of long transmission lines [Rigorous method]

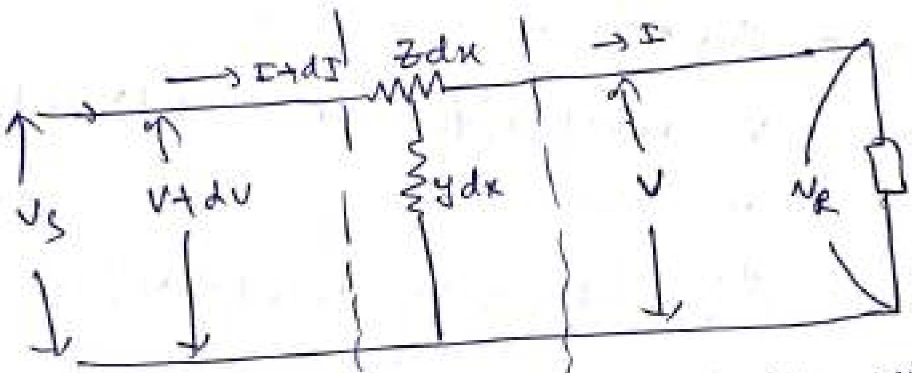


Fig shows one phase to neutral of a 3-ϕ line with Impedance and shunt admittance of the line uniformly distributed. To analyze the long line, consider a small element in the line of length dx situated at a distance 'x' from receiving end.

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 in the element dx

I → current leaving the element dx.

Then, for small element dx,

$Z\,dx$ = series impedance

$y\,dx$ = Shunt admittance

$dV = IZdx$

$$\frac{dV}{dx} = IZ \quad -①$$

$dI \rightarrow$ current passing through shunt admittance of the element.

$dI = Vy\,dx$

$$\frac{dI}{dx} = Vy \quad -②$$

differentiating eq (1) w.r.t 'x'

$$\frac{d^2V}{dx^2} = Z\frac{dI}{dx} = Z(Vy) \quad \text{(from eq (2))}$$

$$\frac{d^2V}{dx^2} = yZV \quad -(3)$$

Solution for this differential equation is

$$V = K_1\cosh(x\sqrt{YZ}) + K_2\sinh(x\sqrt{YZ}) \quad -(4)$$

differentiating w.r.t 'x'

$$\frac{dV}{dx} = K_1\sqrt{YZ}\sinh(x\sqrt{YZ}) + K_2\sqrt{YZ}\cosh(x\sqrt{YZ})$$

But $\frac{dV}{dx} = IZ$ (from eq (1))

$$IZ = K_1\sqrt{YZ}\sinh(x\sqrt{YZ}) + K_2\sqrt{YZ}\cosh(x\sqrt{YZ})$$

$$I = K_1\cdot\sqrt{\frac{Y}{Z}}\sinh(x\sqrt{YZ}) + K_2\sqrt{\frac{Y}{Z}}\cosh(x\sqrt{YZ})$$

$$I = \sqrt{\frac{Y}{Z}}\left[K_1\sinh(x\sqrt{YZ}) + K_2\cosh(x\sqrt{YZ})\right] \quad -(5)$$

To find K_1 & K_2, apply end conditions.

At $x = 0$, $V = V_R$, $I = I_R$

eq (4) gives,

$V_R = K_1\cosh 0 + K_2\sinh 0 \Rightarrow K_1$

$$\boxed{V_R = K_1}$$

eq (5) gives

$$I_R = \sqrt{\frac{Y}{Z}}\left[K_1\sinh 0 + K_2\cosh 0\right] = \sqrt{\frac{Y}{Z}}\left[0 + K_2\right]$$

$$\boxed{K_2 = \sqrt{\frac{Z}{Y}}\, I_R}$$

Substitute K_1, K_2 in eq (4) & (5), we get

$$V = V_R \cosh(x\sqrt{YZ}) + \sqrt{\frac{Z}{Y}}\, I_R \sinh(x\sqrt{YZ})$$

$$I = \sqrt{\frac{Y}{Z}}\, V_R \sinh(x\sqrt{YZ}) + I_R \cosh(x\sqrt{YZ})$$

V_S, I_S are obtained by putting $x = l$ in the above equations

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

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

Now $l\sqrt{YZ} = \sqrt{lY \cdot lZ} = \sqrt{YZ}$

$$\sqrt{\frac{Y}{Z}} = \sqrt{\frac{Y \cdot l}{Z \cdot l}} = \sqrt{\frac{Y}{Z}}$$

where Z = total series impedance of the line

Y = total shunt admittance of the line

$\therefore$

$$\boxed{\begin{aligned} V_S &= V_R \cosh\sqrt{YZ} + I_R \sqrt{\frac{Z}{Y}} \sinh\sqrt{YZ} \\ I_S &= V_R \cdot \sqrt{\frac{Y}{Z}} \sinh\sqrt{YZ} + I_R \cosh\sqrt{YZ} \end{aligned}}$$

Problem A 3-φ transmission line 200 km long has the following constants resistance/ph/km = 0.16 Ω, Reactance/ph/km = 0.25 Ω, shunt admittance/ph/km = 1.5×10^{-6} S. calculate the rigorous method, the sending end voltage & current when the line is delivering a load of 20 MW at 0.8 pf lagging. The receiving end voltage is kept const at 110 kV.

Sol

Total resistance/phase (R) $= 0.16 \times 200 = 32\,\Omega$

Total reactance/ph $X_L = 0.25 \times 200 = 50\,\Omega$

Total shunt admittance $Y = j1.5 \times 10^{-6} \times 200 = j0.0003$

$= 0.0003\angle 90°$

total series impedance/phase $= Z = R + jX_L = 32 + j50$

$= 59.4\angle 58°$

Sending end voltage V_s per phase is

$$V_s = V_R \cosh\sqrt{YZ} + I_R\sqrt{\frac{Z}{Y}} \sinh\sqrt{YZ} \quad \text{---(1)}$$

$$\sqrt{YZ} = \sqrt{59.4\angle 58^\circ \times 0.0003\angle 90^\circ} = 0.133\angle 74^\circ$$

$$ZY = 0.0178\angle 148^\circ$$

$$Z^2Y^2 = 0.00032\angle 296^\circ$$

$$\sqrt{\frac{Z}{Y}} = \sqrt{\frac{59.4\angle 58^\circ}{0.0003\angle 90^\circ}} = 445\angle -16^\circ$$

$$\sqrt{\frac{Y}{Z}} = \sqrt{\frac{0.0003\angle 90^\circ}{59.4\angle 58^\circ}} = 0.00224\angle 16^\circ$$

$$\therefore \cosh\sqrt{YZ} = 1 + \frac{ZY}{2} + \frac{Z^2Y^2}{24} = 1 + \frac{0.0178\angle 148^\circ}{2} + \frac{0.00032\angle 296^\circ}{24}$$

$$= 1 + 0.0089\angle 148^\circ + 0.0000133\angle 296^\circ$$

$$= 1 + 0.0089(-0.848 + j0.529) + 0.00000133(0.438 - j09)$$

$$= 0.992 + j0.00469$$

$$= 0.992\angle 0.26^\circ$$

$$\sin\sqrt{YZ} = \sqrt{YZ} + \frac{(YZ)^{3/2}}{6}$$

$$= 0.133\angle 74^\circ + \frac{0.0024\angle 222^\circ}{6}$$

$$= 0.133\angle 74^\circ + 0.0004\angle 222^\circ$$

$$= 0.133(0.275 + j0.96) + 0.0004(-0.743 - j0.67)$$

$$= 0.0362 + j0.1275$$

$$= 0.1325\angle 74.6$$

$$V_R = \frac{110\times 10^3}{\sqrt{3}} = 63508\,V$$

$$I_R = \frac{20\times 10^6}{\sqrt{3}\times 110\times 10^3 \times 0.8} = 131A$$

Then

$$V_s = 63508 \times 0.992\angle 0.26 + 131 \times 445 \angle{-16} \times 0.1325 \angle 74.6$$

$$= 63000\angle 0.26 + 7724\angle 58.6$$

$$= 63000(0.999 + j0.0045) + 7724(0.5284 + j0.8489)$$

$$= 67018 + j6840$$

$$= 67366\angle 5.50 \text{ V}$$

Sending end line voltage $= 67366 \times \sqrt{3} = 116.67 \times 10^3$ V
$= 116.67$ kV

Sending end current (I_s) is

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

$$= 63508 \times 0.00224\angle 16^\circ \times 0.1325\angle 74.6^\circ + 131 \times 0.992\angle 0.26$$

$$= 18.85\angle 90.6 + 130\angle 0.26$$

$$= 18.85(-0.0017 + j0.999) + 130(0.999 + j0.0045)$$

$$= 129.83 + j19.42$$

$$= 131.1\angle 8^\circ \text{ A.}$$

$$|I_s| = 131.1\text{A}$$

ABCD constants of long lines

$$V_s = V_R\cosh\sqrt{YZ} + I_R\sqrt{\frac{Z}{Y}}\sinh\sqrt{ZY} \quad -①$$

$$I_s = V_R\sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} + I_R\cosh\sqrt{YZ} \quad -②$$

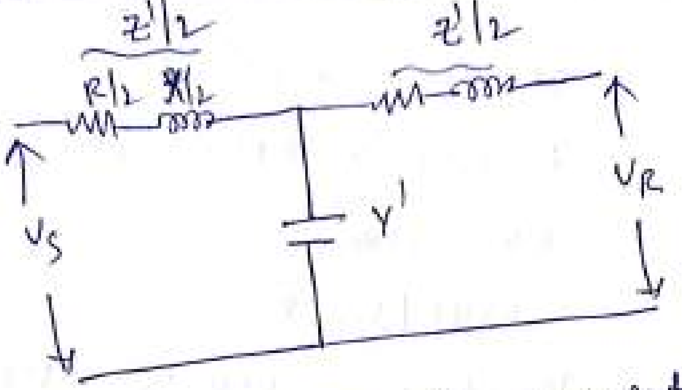
Then $A = \cosh\sqrt{YZ}$, $B = \sqrt{\frac{Z}{Y}}\sinh\sqrt{ZY}$

$C = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ}$, $D = \cosh\sqrt{YZ}$

Note: ① $A = D = \cosh\sqrt{YZ}$

② $AD - BC = 1$ $\quad [\cosh^2\sqrt{YZ} - \sinh^2\sqrt{YZ} = 1]$

Equivalent - T circuit of long lines



Equivalent-T ckt of long lines is a representation of the line in which the distributed parameters are assumed to be lumped parameters. Hence the series Impedance, Z is assumed to be divided into two equal halves & shunt admittance is at the centre of the line. V_S & I_S for T n/w can be written as

$$V_S = \left(1+\frac{Y'Z'}{2}\right)V_R + Z'\left(1+\frac{Y'Z'}{4}\right)I_R \quad -(1)$$

$$I_S = Y'V_R + \left(1+\frac{Y'Z'}{2}\right)I_R \quad -(2)$$

V_S & I_S for long transmission lines are

$$V_S = V_R\cosh\sqrt{YZ} + \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ}\cdot I_R \quad -(3)$$

$$I_S = V_R\cdot\sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} + \cosh\sqrt{YZ}\cdot I_R \quad -(4)$$

Compare eq (1) & (2) with (3) & (4)

$$1+\frac{Y'Z'}{2} = \cosh\sqrt{YZ} \quad -(5)$$

$$Z'\left(1+\frac{Y'Z'}{4}\right) = \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ} \quad -(6)$$

$$Y' = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} \quad -(7)$$

$$1+\frac{Y'Z'}{2} = \cosh\sqrt{YZ} \quad -(8)$$

From eq (7)

$$Y' = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} \times \frac{\sqrt{ZY}}{\sqrt{ZY}} = Y\,\frac{\sinh\sqrt{YZ}}{\sqrt{YZ}}$$

$$\boxed{Y' = Y\,\frac{\sinh\sqrt{YZ}}{\sqrt{YZ}}}$$

From eq(5) $1+\frac{Y'Z'}{2} = \cosh\sqrt{YZ}$

$$1+\frac{Z'}{2}\cdot Y' = \cosh\sqrt{YZ}$$

$$1+\frac{Z'}{2}\left[Y\,\frac{\sinh\sqrt{YZ}}{\sqrt{YZ}}\right] = \cosh\sqrt{YZ}$$

$$1+\frac{Z'}{2}\cdot\sqrt{\frac{Y}{Z}}\,\sinh\sqrt{YZ} = \cosh\sqrt{YZ}$$

$$\frac{Z'}{2}\sqrt{\frac{Y}{Z}}\,\sinh\sqrt{YZ} = \cosh\sqrt{YZ}-1$$

$$\frac{Z'}{2} = \frac{\cosh\sqrt{YZ}-1}{\sqrt{\frac{Y}{Z}}\,\sinh\sqrt{YZ}}$$

$$= \sqrt{\frac{Z}{Y}}\left(\frac{\cosh\sqrt{YZ}-1}{\sinh\sqrt{YZ}}\right)$$

$$= \sqrt{\frac{Z}{Y}}\ \cancel{\tan}\ \frac{2\cosh^2\frac{\sqrt{YZ}}{2}-1-1}{2\sinh\frac{\sqrt{YZ}}{2}\cosh\frac{\sqrt{YZ}}{2}}$$

$\boxed{\begin{matrix}\cosh^2 x-\sinh^2 x=1\\ \cosh^2 x-1=\sinh^2 x\end{matrix}}$

$$= \sqrt{\frac{Z}{Y}}\ \frac{2\cosh^2\frac{\sqrt{YZ}}{2}-2}{2\sinh\frac{\sqrt{YZ}}{2}\cosh\frac{\sqrt{YZ}}{2}}$$

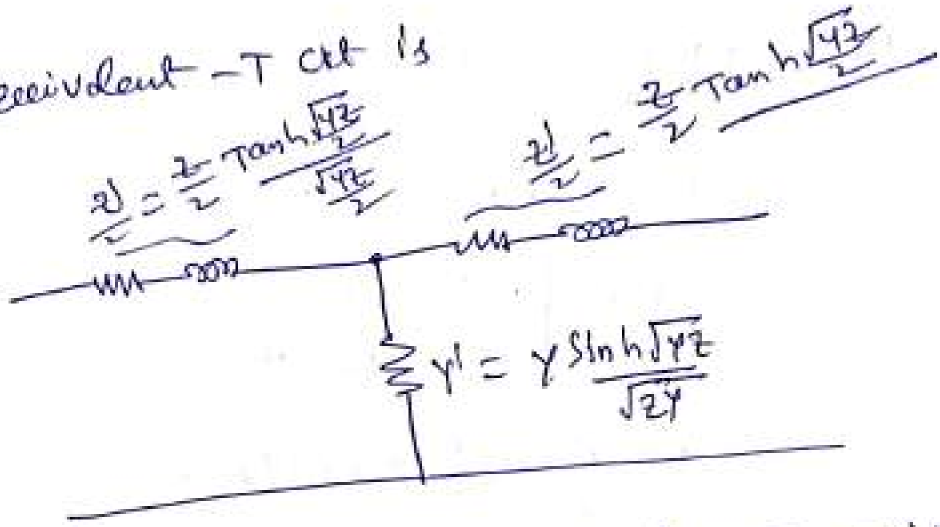
$$= \sqrt{\frac{Z}{Y}}\cdot\frac{\sinh^2\frac{\sqrt{YZ}}{2}}{\sinh\frac{\sqrt{YZ}}{2}\cosh\frac{\sqrt{YZ}}{2}}$$

$$= \sqrt{\frac{Z}{Y}}\times\tanh\frac{\sqrt{YZ}}{2}$$

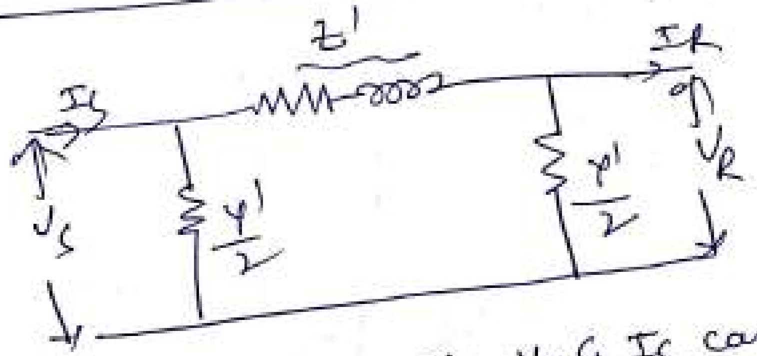
$$= \sqrt{\frac{Z}{Y}}\times\tanh\frac{\sqrt{YZ}}{2}\times\frac{\frac{\sqrt{YZ}}{2}}{\frac{\sqrt{YZ}}{2}}$$

$$\boxed{\frac{Z'}{2} = \frac{Z}{2}\times\frac{\tanh\frac{\sqrt{YZ}}{2}}{\frac{\sqrt{YZ}}{2}}}$$

The equivalent -T ckt is



Equivalent -π representation of long Transmission lines



From Nominal-π, the V_S & I_S can be written as

$$V_S = \left(1+\frac{Y'Z'}{2}\right)V_R + Z'I_R \quad -(1)$$

$$I_S = Y'\left(1+\frac{Y'Z'}{4}\right)V_R + \left(1+\frac{Y'Z'}{2}\right)I_R \quad -(2)$$

For long Transmission line

$$V_S = \cosh\sqrt{YZ}\cdot V_R + \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ}\cdot I_R \quad -(3)$$

$$I_S = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ}\cdot V_R + \cosh\sqrt{YZ}\cdot I_R \quad -(4)$$

comparing eq (1) (2) with eq (3) & (4).

$$1+\frac{Y'Z'}{2} = \cosh\sqrt{YZ} \quad -(5)$$

$$Z' = \sqrt{\frac{Z}{Y}}\sinh\sqrt{YZ} \quad -(6)$$

$$Y'\left(1+\frac{Y'Z'}{4}\right) = \sqrt{\frac{Y}{Z}}\sinh\sqrt{YZ} \quad -(7)$$

$$1+\frac{Y'Z'}{2} = \cosh\sqrt{YZ} \quad -(8)$$

From eq (6)

$$z' = \sqrt{\frac{Z}{Y}} \sinh\sqrt{YZ} \times \frac{\sqrt{YZ}}{\sqrt{YZ}}$$

$$\boxed{z' = Z \frac{\sinh\sqrt{YZ}}{\sqrt{YZ}}}$$

From eq (5),

$$1 + \frac{Y'Z'}{2} = \cosh\sqrt{YZ}$$

$$1 + \frac{Y'}{2}(Z') = \cosh\sqrt{YZ}$$

$$1 + \frac{Y'}{2}\left[Z \frac{\sinh\sqrt{YZ}}{\sqrt{YZ}}\right] = \cosh\sqrt{YZ}$$

$$1 + \frac{Y'}{2}\left[\sqrt{\frac{Z}{Y}} \sinh\sqrt{YZ}\right] = \cosh\sqrt{YZ}$$

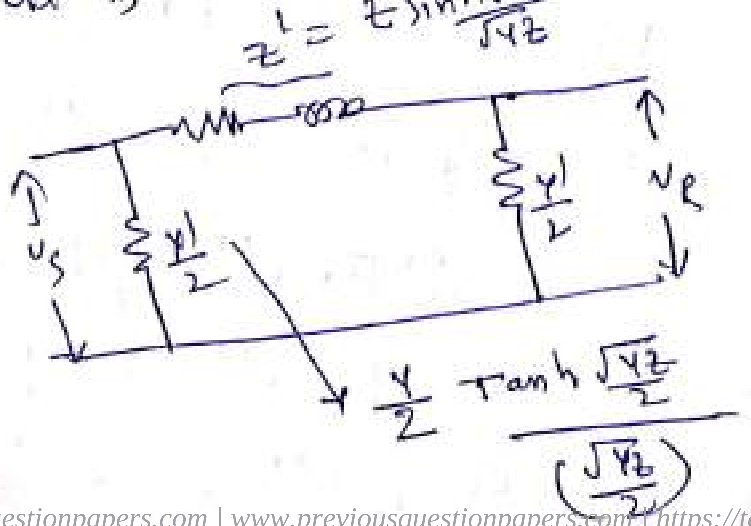
$$\frac{Y'}{2}\left[\sqrt{\frac{Z}{Y}} \sinh\sqrt{YZ}\right] = \cosh\sqrt{YZ} - 1$$

$$\frac{Y'}{2} = \sqrt{\frac{Y}{Z}}\left(\frac{\cosh\sqrt{YZ} - 1}{\sinh\sqrt{YZ}}\right)$$

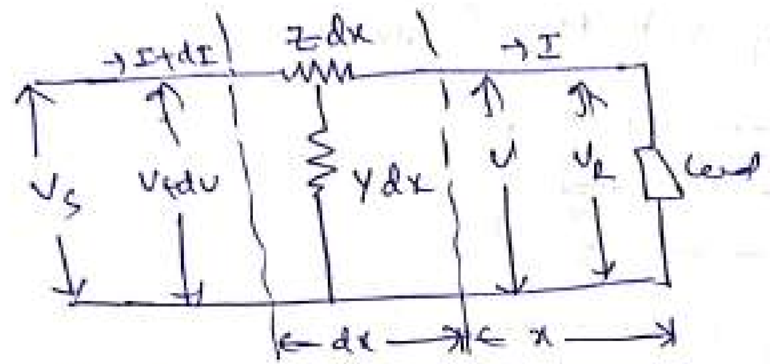
$$= \sqrt{\frac{Y}{Z}} \tanh\frac{\sqrt{YZ}}{2} \times \frac{\frac{\sqrt{YZ}}{2}}{\frac{\sqrt{YZ}}{2}}$$

$$\boxed{\frac{Y'}{2} = \frac{Y}{2} \cdot \frac{\tanh\frac{\sqrt{YZ}}{2}}{\frac{\sqrt{YZ}}{2}}}$$

The equivalent ckt is



Interpretation of the long line equations



From the above ckt,

$$dV = IZ\,dx \qquad dI = YV\,dx$$

$$\frac{dV}{dx} = IZ \quad -(1) \qquad \frac{dI}{dx} = YV \quad -(2)$$

differentiating eq (1)

$$\frac{d^2V}{dx^2} = Z\frac{dI}{dx} = Z \cdot Y \cdot V \quad -(3)$$

This is a linear differential eq. The solution of the equation is

$$V = C_1 e^{x\sqrt{YZ}} + C_2 e^{-x\sqrt{YZ}} \quad -(4)$$

put $\gamma = \sqrt{YZ}$

$$V = C_1 e^{\gamma x} + C_2 e^{-\gamma x} \quad -(5)$$

differentiating eq(5) wrt 'x'

$$\frac{dV}{dx} = C_1 \cdot \gamma \cdot e^{\gamma x} - C_2 \gamma e^{-\gamma x}$$

$$IZ = C_1 \gamma e^{\gamma x} - C_2 \gamma e^{-\gamma x}$$

$$I = \frac{C_1}{Z} \gamma e^{\gamma x} - \frac{C_2}{Z} \gamma e^{-\gamma x}$$

$$= \frac{C_1}{Z}\sqrt{YZ}\, e^{\gamma x} - \frac{C_2}{Z}\sqrt{YZ}\, e^{-\gamma x}$$

$$= C_1\sqrt{\frac{Y}{Z}}\, e^{\gamma x} - C_2\sqrt{\frac{Y}{Z}}\, e^{-\gamma x}$$

$$I = C_1 \times \frac{1}{Z_c} e^{\gamma x} - \frac{C_2}{Z_c} e^{-\gamma x} \quad -(6)$$

$$Z_c = \sqrt{\frac{Z}{Y}}, \qquad \frac{1}{Z_c} = \sqrt{\frac{Y}{Z}}$$

Ferranti effect

To find c_1 & c_2

Apply end conditions

At $x=0$, $V=V_R$, $I=I_R$

From eq (3), $V_R = c_1 + c_2$ — (7)

From eq (4), $I_R = \frac{c_1 - c_2}{Z_c}$ — (8)

by solving eq (7) & (8)

$$c_1 = \frac{1}{2}(V_R + Z_c I_R)$$

$$c_2 = \frac{1}{2}(V_R - Z_c I_R)$$

$c_1 + c_2 = V_R$
$c_1 - c_2 = Z_c I_R$
$2c_1 = V_R + Z_c I_R$
$c_1 = \frac{V_R + Z_c I_R}{2}$

Substitute c_1 & c_2 in eq (3) & (4)

$$V = V_R = \left(\frac{V_R + Z_c I_R}{2}\right) e^{\gamma x} + \left(\frac{V_R - Z_c I_R}{2}\right) e^{-\gamma x}$$

$$I = I_R = \left(\frac{1}{2}\left(\frac{V_R}{Z_c} + I_R\right)\right) e^{\gamma x} - \left(\frac{\frac{V_R}{Z_c} - I_R}{2}\right) e^{-\gamma x}$$

here γ = propagation constant

$$\gamma = \sqrt{YZ}$$

$$\alpha + j\beta = \sqrt{YZ}$$

α — attenuation constant

β → phase constant

Surge Impedance

- Surge Impedance is the characteristic impedance of a lossless transmission line.
- It is also called as Natural Impedance because this impedance has nothing to do with load impedance.
- Since the line is assumed to be lossless; i.e R & $G = 0$

Characteristic Impedance $Z_c = \sqrt{\frac{Z}{Y}}$

$$= \sqrt{\frac{R + j\omega L}{G + j\omega C}}$$

$$\boxed{Z_c = \sqrt{\frac{L}{C}}} \ \Omega.$$

Note:- The value of Surge Impedance for overhead transmission line is 400Ω. where as for underground cable is 40Ω.

Surge Impedance loading (SIL)

⇒ Surge Impedance loading is defined as the maximum load (at upf) that can be delivered by the transmission line when the loads terminates with the value equal to surge impedance (Z_S) of line.

⇒ If any line terminates with surge impedance then corresponding loading in MW is called SIL.

⇒ It is very essential parameter in power systems as it is used in the prediction of maximum loading of Transmission line.

⇒ SIL for 1-φ line

$$(SIL)_{1-\phi} = V_{ph} I_{ph} \cos\phi$$

If $\cos\phi = 1$

Ferranti effect:

Def: "At noload or lightly loaded conditions, the voltage at the receiving end of the transmission line is more than the Sending end voltage is known as Ferranti effect."

- Ferranti effect is mainly due to the charging current of the line.

⇒ when alternating voltage is applied, the current that flows into the capacitor is called charging current. This charging current is also known as capacitive current.

This charging current increases in the line increases when receiving end vol of the line is larger than the Sending end.

Reason for occurs

Generally L & C are main parameters of the lines having length of 240 km & above. on this transmission lines, when the voltage is applied at the sending end, the current drawn by the capacitance of the line is more than the current associated with the load. Thus, at noload or lightly load, voltage at receiving end side is more than the sending end.

⇒ Ferranti effect is more in short transmission line cables because their capacitance is high.

How to reduce Ferranti effect

Generally Electrical devices are designed to work at some particular voltage. If the voltages are higher, the equipments at end users get damaged.

$$(SIL)_{1-\phi} = V_{ph} I_{ph}$$

$$= V_{ph} \cdot \frac{V_{ph}}{Z_0}$$

$$\boxed{P_0 = (SIL)_{1-\phi} = \frac{V_{ph}^2}{Z_0}} \text{ W/phase}$$

Similarly

$$(SIL)_{3-\phi} = 3P_0 = \frac{3V_{ph}^2}{Z_0} = \frac{V_L^2}{Z_0} \text{ W}$$

$$(SIL)_{3-\phi} = \frac{(kV_L)^2}{Z_0} \text{ MW}$$

Significance

1. It is used to find max. permissible power transfer capacity for any transmission line
2. Surge impedance loading depends on the voltage of the transmission line
3. Practically SIL is always less than the max. loading capacity of the line
4. If the load is less than SIL, then reactive volt-amp is generated and voltage at the receiving end is greater than sending end.
5. If the load is more than SIL, then the reactive power consumed and voltage at the receiving end is small.
6. If the shunt conductance and resistance are neglected, and SIL is equal to the load than the voltage at both the end will be equal.
7. If loading = SIL, the V & I are uniform along the line
8. Power factor is unity for SIL

and their windings burn because of high voltage.

→ To reduce the ferranti effect, by placing the shunt reactors at the receiving end the lines.

- Shunt reactor is a inductive current element connected b/w line & neutral to compensate the capacitive current from the transmission lines, therefore voltage is regulated within the limits.

UNIT IV INSULATORS, CORONA AND MECHANICAL DESIGN OF LINES AND CABLES

Types of Insulators, String efficiency and Methods for improvement, Numerical Problems – Voltage Distribution, Calculation of string efficiency, Capacitance grading and Static shielding. Corona - Description of the phenomenon, factors affecting corona, critical voltages and power loss, Radio Interference. Sag and Tension Calculations with equal and unequal heights of towers, Effect of Wind and Ice on weight of Conductor, Numerical Problems - Stringing chart and sag template and its applications. Types of Cables, Construction, Types of Insulating materials, Calculations of Insulation resistance and stress in insulation, Numerical Problems.

Introduction

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports *i.e.*, line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of **insulators**. The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth.

Properties of Insulators

The insulators should have the following desirable properties

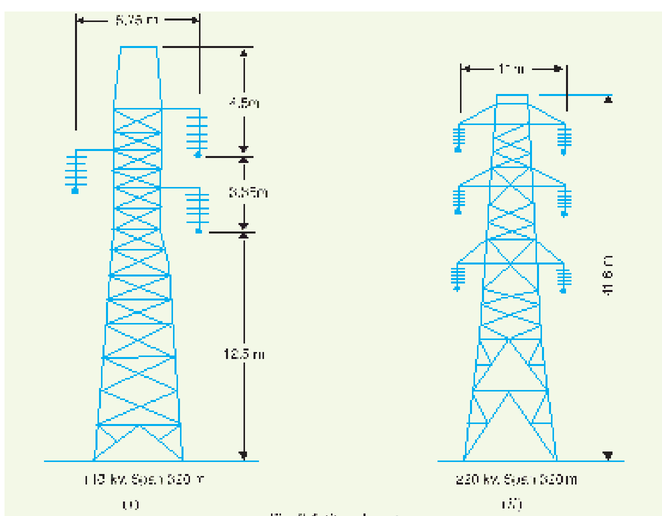
(i) High mechanical strength in order to withstand conductor load, wind load etc.

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

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

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

(v) High ratio of puncture strength to flashover.



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

Types of Insulators

There are several types of insulators but the most commonly used are pin type, suspension type, strain insulator and shackle insulator.

1. Pin Type Insulator:

Fig shows Pin type insulator

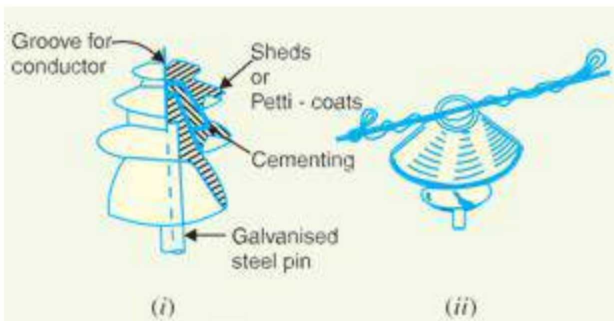


Fig. . Pin-type insulator

The pin type insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor.

Pin type insulators are used for transmission and distribution of elec- tric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical,

Causes of insulator failure.

Insulators are required to withstand both mechanical and electrical stresses. The latter type is pirmarily due to line voltage and may cause the breakdown of the insulator. The electrical break- down of the insulator can occur either by flash-over or puncture.

In flash- over, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the *air gaps, following shortest dis- tance. Fig. shows the arcing distance (i.e. a + b + c) for the insula- tor. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator.

In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat.

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

Safety factor of insulator = Puncture strength / Flash - over voltage

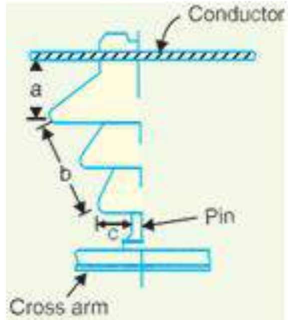
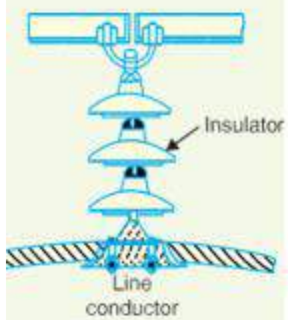


Fig. 8.6



2 Suspension type insulators.

The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators.

Suspension type insulators consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working volt- age is 66 kV, then six discs in series will be provided on the string.

Advantages

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

(ii) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in se- ries.

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

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

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

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

3. Strain insulators.

When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used.

For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Fig.

The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.

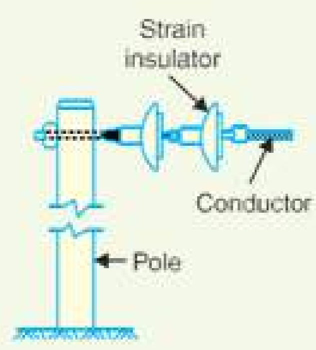


Fig. Strain insulator.

4.Shackle insulators.

In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm. Fig. shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

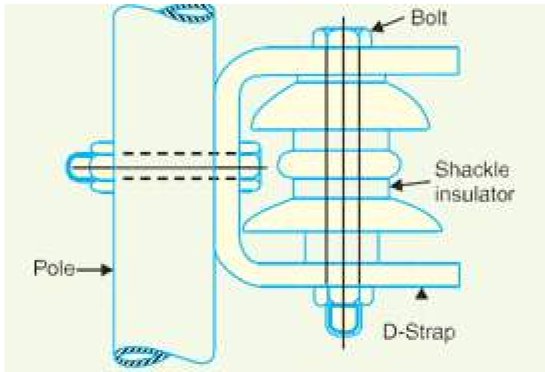


Fig.

Potential Distribution over Suspension Insulator String

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links.

Fig. (i) shows 3-disc string of suspension insulators.

The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor C as shown in Fig. (ii). This is known as mutual capacitance or self-capacitance. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same i.e., V/3 as shown in Fig (ii).

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

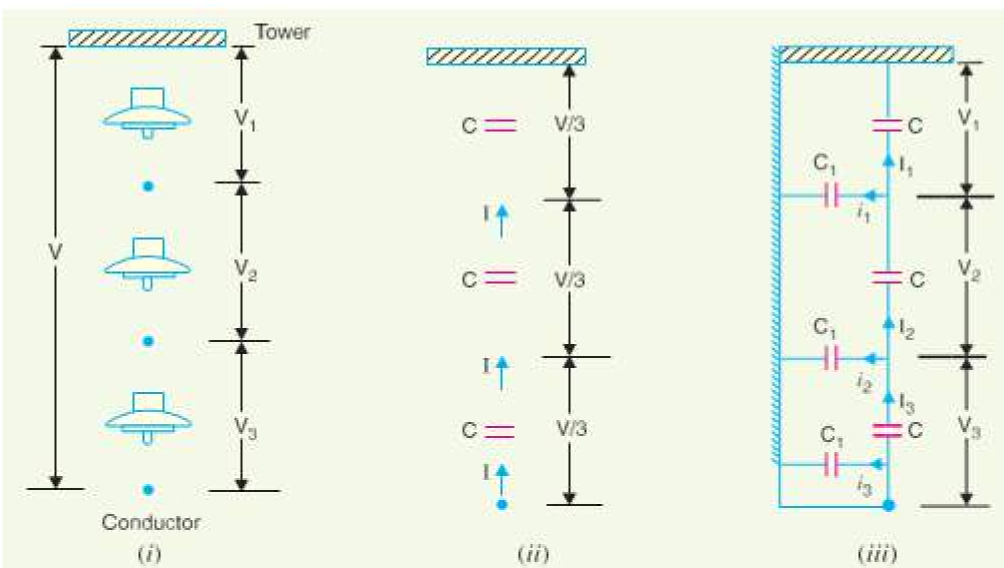


Fig. _

String Efficiency

The voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs.

This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

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

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

$$n = \text{number of discs in the string.}$$

Mathematical expression.

Fig. shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C1 is some fraction K of self- capacitance i.e., C1 = KC. Starting from the cross-arm or tower, the volt- age across each unit is V1,V2 and V3 respectively as shown

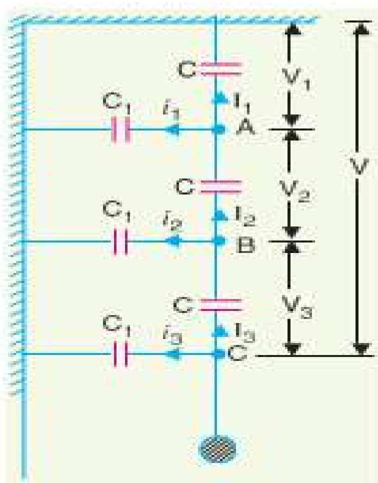


Fig. :

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

$$I_2 = I_1 + i_1$$

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

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

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

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

$$I_3 = I_2 + i_2$$

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

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

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= K V_1 + V_2 (1 + K)$$

$$= KV_1 + V_1 (1+K)^2 \qquad [\because V_2 = V_1 (1+K)]$$

$$= V_1 [K + (1+K)^2]$$

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

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

$$V = V_1 + V_2 + V_3$$

$$= V_1 + V_1(1+K) + V_1 (1 + 3K + K^2)$$

$$= V_1 (3 + 4K + K^2)$$

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

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

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

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

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

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

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

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

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

(*i*) If $K = 0{\cdot}2$ (Say), then from exp. (*iv*), we get, $V_2 = 1{\cdot}2\ V_1$ and $V_3 = 1{\cdot}64\ V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(*ii*) The greater the value of K ($= C_1/C$), the more non-uniform is the potential across the discs and lesser is the string efficiency.

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

Methods of Improving String Efficiency

Generally Potential distribution in a string of suspension insulators is not uniform.

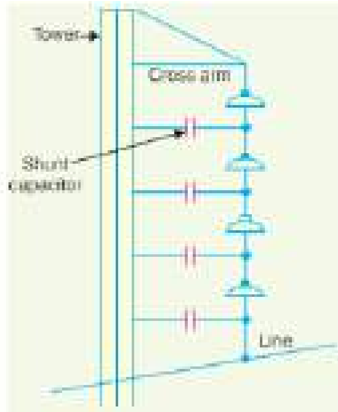
The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross-arm is approached.

If the insulation of the highest stressed insulator (i.e. nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates to equalize the potential across the various units of the string i.e. to improve the string efficiency. The various methods for this purpose are :

(i) By using longer cross-arms.

The value of string efficiency depends upon the value of K i.e., ratio of shunt capacitance to mutual capacitance. The lesser the value of K, the greater is the string efficiency and more uniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance.

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



(ii) By grading the insulators.

In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded i.e. they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (i.e., nearest to conductor) is reached.

Since voltage is inversely proportional to capacitance, this method tends to equalize the potential distribution across the units in the string.

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

(iii) By using a guard ring.

The potential across each unit in a string can be equalized by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig.

The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i1, i2 etc. are equal to metal fitting line capacitance currents i1, i2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

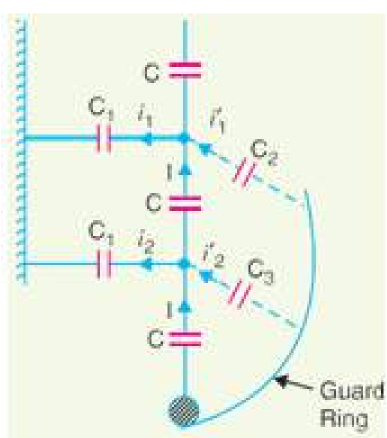


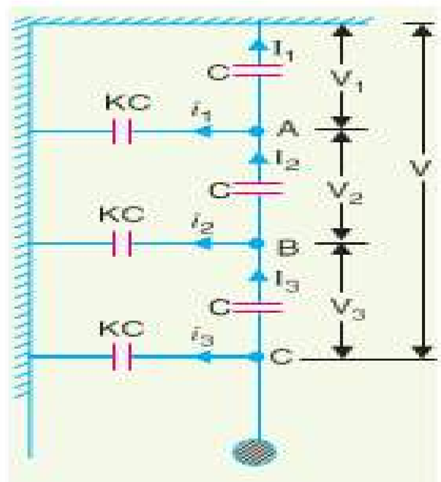
Fig.

Problems

1. In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency.

Fig shows the equivalent circuit of string insulators.

Let V1, V2 and V3 be the voltage across top, middle and bottom unit respectively. If C is the self-capacitance of each unit, then KC will be the shunt capacitance.



$$K = \frac{\text{Shunt Capacitance}}{\text{Self - capacitance}} = 0.11$$

$$\text{Voltage across string, } V = 33/\sqrt{3} = 19{\cdot}05 \text{ kV}$$

At Junction A

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1(1+K) = V_1(1+0{\cdot}11)$$

or $$V_2 = 1{\cdot}11\ V_1 \qquad ...(i)$$

At Junction B

$$I_3 = I_2 + i_2$$

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

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= 1{\cdot}11 V_1 + (V_1 + 1{\cdot}11\ V_1)\ 0{\cdot}11$$

$\therefore$ $$V_3 = 1{\cdot}342\ V_1$$

(*i*) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1{\cdot}11\ V_1 + 1{\cdot}342\ V_1 = 3{\cdot}452\ V_1$$

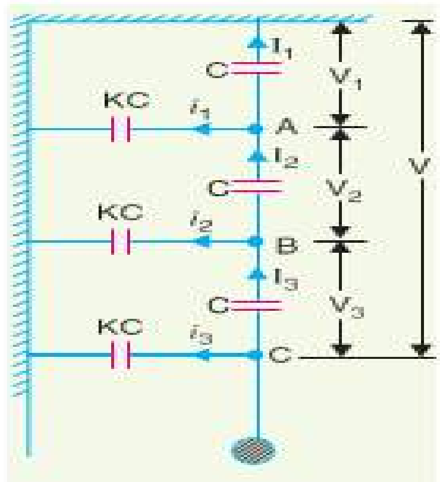
or $$19{\cdot}05 = 3{\cdot}452\ V_1$$

$\therefore$ Voltage across top unit, $V_1 = 19{\cdot}05/3{\cdot}452 =$ **5·52 kV**

Voltage across middle unit, $V_2 = 1{\cdot}11\ V_1 = 1{\cdot}11 \times 5{\cdot}52 =$ **6.13 kV**

Voltage across bottom unit, $V_3 = 1{\cdot}342\ V_1 = 1{\cdot}342 \times 5{\cdot}52 =$ **7.4 kV** (*ii*) String efficiency $= \dfrac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \dfrac{19 \cdot 05}{3 \times 7 \cdot 4} \times 100 =$ **85.8%**

2. A 3-phase transmission line is being supported by three disc insulators. The potentials across top unit (i.e., near to the tower) and middle unit are 8 kV and 11 kV respectively. Calculate (i) the ratio of capacitance between pin and earth to the self-capacitance of each unit (ii)the line voltage and (iii) string efficiency.



$V_1 = 8$ kV and $V_2 = 11$ kV.

(*i*) Let K be the ratio of capacitance between pin and earth to self capacitance. If C farad is the self capacitance of each unit, then capacitance between pin and earth $= KC$.

Applying Kirchoff's current law to Junction A,

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1 (1 + K)$$

$$\therefore \quad K = \frac{V_2 - V_1}{V_1} = \frac{11-8}{8} = 0{\cdot}375$$

(*ii*) Applying Kirchoff's current law to Junction B,

$$I_3 = I_2 + i_2$$

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

or $$V_3 = V_2 + (V_1 + V_2) K = 11 + (8 + 11) \times 0{\cdot}375 = 18{\cdot}12 \text{ kV}$$

Voltage between line and earth $= V_1 + V_2 + V_3 = 8 + 11 + 18{\cdot}12 = 37{\cdot}12$ kV

$\therefore$ Line Voltage $= \sqrt{3} \times 37{\cdot}12 =$ **64·28 kV**

(*iii*) String efficiency $= \dfrac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \dfrac{37 \cdot 12}{3 \times 18 \cdot 12} \times 100 =$ **68.28%**

3. Each line of a 3-phase system is suspended by a string of 3 similar insulators. If the voltage across the line unit is 17•5 kV, calculate the line to neutral voltage. Assume that the shunt capacitance betwen each insulator and earth is 1/8th of the capacitance of the insulator itself. Also find the string efficiency.

Solution

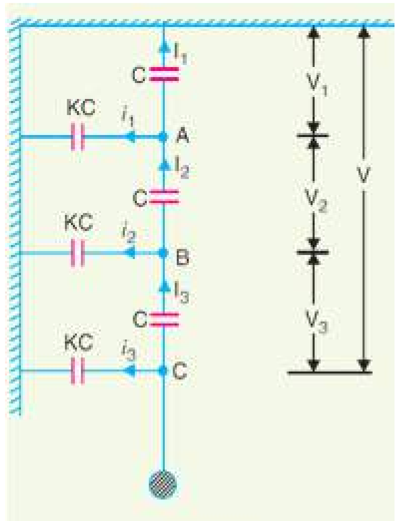


Fig. .

Fig. shows the equivalent circuit of string insulators. If C is the self capacitance of each unit, then KC will be the shunt capacitance where K = 1/8 = 0•125.

Voltage across line unit, V3 = 17•5 kV

At Junction A

$$I_2 = I_1 + i_1$$

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

or $$V_2 = V_1(1+K) = V_1(1+0.125)$$

∴ $$V_2 = 1{\cdot}125\ V_1$$

At Junction B

$$I_3 = I_2 + i_2$$

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

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= 1{\cdot}125\ V_1 + (V_1 + 1{\cdot}125\ V_1) \times 0.125$$

∴ $$V_3 = 1{\cdot}39\ V_1$$

Voltage across top unit, $V_1 = V_3/1{\cdot}39 = 17{\cdot}5/1{\cdot}39$

$= 12{\cdot}59$ kV

Voltage across middle unit, $V_2 = 1{\cdot}125\ V_1 = 1{\cdot}125 \times 12{\cdot}59 = 14{\cdot}16$ kV

∴ Voltage between line and earth (*i.e.,* line to neutral)

$$= V_1 + V_2 + V_3 = 12{\cdot}59 + 14{\cdot}16 + 17{\cdot}5 = \mathbf{44.25\ kV}$$

$$\text{String efficiency} = \frac{44{\cdot}25}{3 \times 17{\cdot}5} \times 100 = \mathbf{84{\cdot}28\%}$$

4. A string of 4 insulators has a self-capacitance equal to 10 times the pin to earth capacitance. Find (i) the voltage distribution across various units expressed as a percentage of total voltage across the string and (ii) string efficiency.

When the number of insulators in a string exceeds 3, the nodal equation method becomes laborious.

Under such circumstances, there is a simple method to solve the problem.

In this method, shunt capacitance (C1) and self capacitance (C) of each insulator are represented by their equivalent reactances. As it is only the ratio of capacitances which determines the voltage distribution, therefore, the problem can be simplified by assigning unity value to XC i.e., assuming XC = 1 ohm.

If ratio of C/C1 = 10, then we have XC = 1 ohm and XC1 = 10 ohm .

(i) Suppose XC = 1 Ω. As the ratio of self-capacitance to shunt capacitance (i.e., C/C1) is 10, therefore, XC1 = 10 Ω as shown in Fig. (i).

Suppose that potential V across the string is such that 1 A current flows in the top insulator. Now the potential across each insulator can be easily determined. Thus :

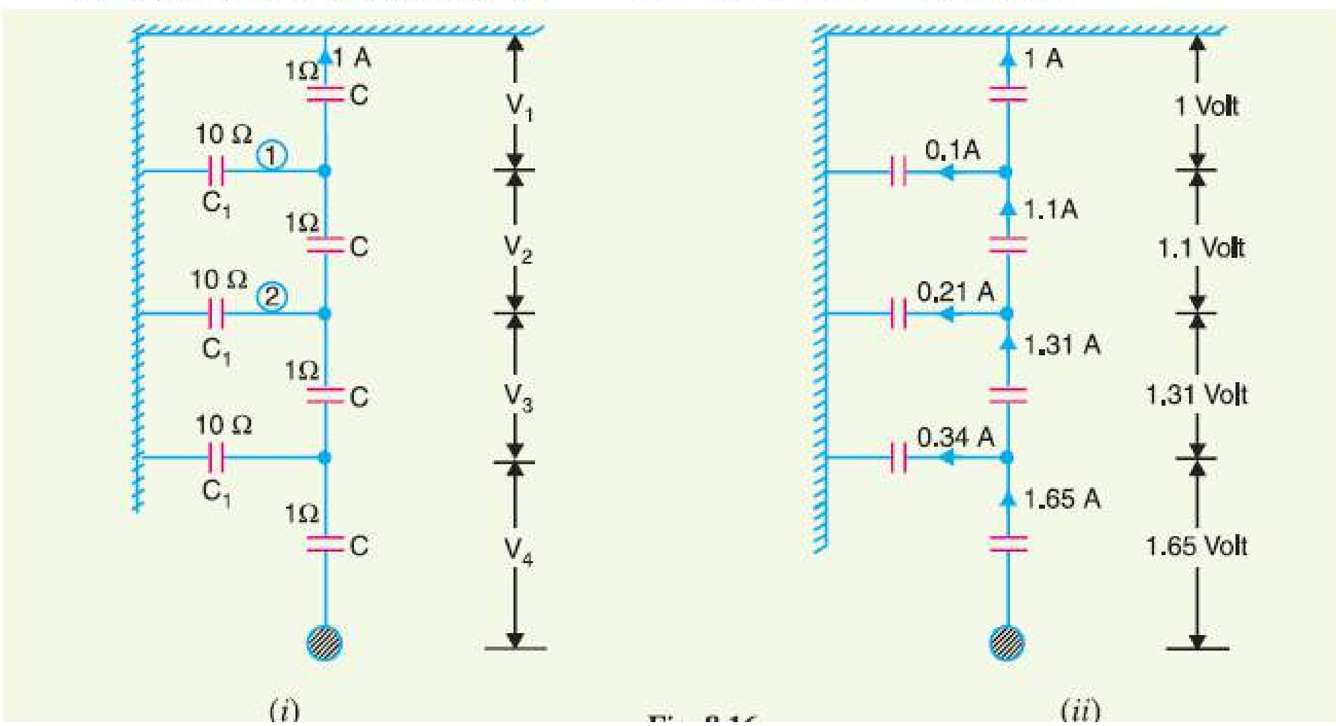
Voltage across top unit, $V_1 = 1\ \Omega \times 1\ \text{A} = 1$ volt

Voltage across **2nd unit, $V_2 = 1\ \Omega \times 1{\cdot}1\ \text{A} = 1{\cdot}1$ volts

Voltage across †3rd unit, $V_3 = 1\ \Omega \times 1{\cdot}31\ \text{A} = 1{\cdot}31$ volts

Voltage across 4th unit, $V_4 = 1\ \Omega \times 1{\cdot}65\ \text{A} = 1{\cdot}65$ volts

Voltage obtained across the string, $V = 1 + 1{\cdot}1 + 1{\cdot}31 + 1{\cdot}65 = 5{\cdot}06$ volts



The voltage across each unit expressed as a percentage of V (*i.e.*, 5·06 volts) becomes :

Top unit $= (1/5{\cdot}06) \times 100 = \mathbf{19{\cdot}76\%}$

Second from top $= (1{\cdot}1/5{\cdot}06) \times 100 = \mathbf{21{\cdot}74\%}$

Third from top $= (1{\cdot}31/5{\cdot}06) \times 100 = \mathbf{25{\cdot}9\%}$

Fourth from top $= (1{\cdot}65/5{\cdot}06) \times 100 = \mathbf{32{\cdot}6\%}$

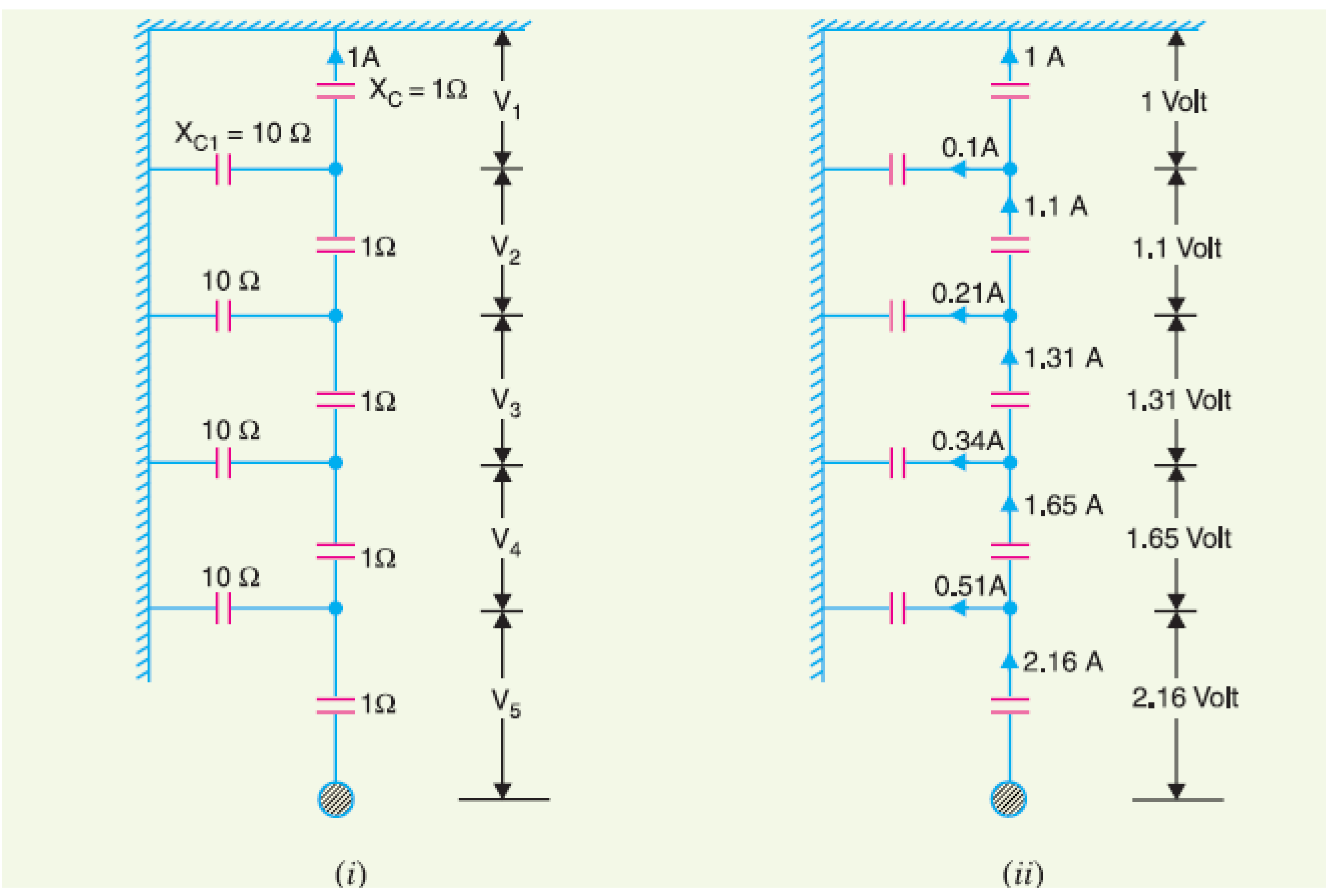
(*ii*) String efficiency $= \dfrac{V}{4 \times V_4} \times 100 = \dfrac{5 \cdot 06}{4 \times 1 \cdot 65} \times 100 = \mathbf{76{\cdot}6\%}$

5. A string of 5 insulators is connected across a 100 kV line. If the capacitance of each disc to earth is 0•1 of the capacitance of the insulator, calculate (i) the distribution of voltage on the insulator discs and (ii) the string efficiency.

Solution

Suppose $X_C = 1\ \Omega$. As the ratio of self capacitance to shunt capacitance is 10, there- fore, $X_{C1} = 10\ \Omega$ as shown in Fig (i).

Suppose that potential V across the string is such that 1A current flows in the top insulator. Then potential across each insulator will be as shown in Fig. (ii).



The value obtained for $V = 1 + 1{\cdot}1 + 1{\cdot}31 + 1{\cdot}65 + 2{\cdot}16 = 7{\cdot}22$ volts and starting from top, the percentage of V (*i.e.,* 7·22 volts) across various units are :

*13·8 %, 15·2 %, 18·2 %, 22·8 % and 30%

Voltage across string = $100/\sqrt{3} = 57{\cdot}7$ kV

(*i*) Voltage across top insulator, $V_1 = 0{\cdot}138 \times 57{\cdot}7 = \mathbf{7{\cdot}96\ kV}$

Voltage across 2nd from top, $V_2 = 0{\cdot}152 \times 57{\cdot}7 = \mathbf{8{\cdot}77\ kV}$

Voltage across 3rd from top, $V_3 = 0{\cdot}182 \times 57{\cdot}7 = \mathbf{10{\cdot}5\ kV}$

Voltage across 4th from top, $V_4 = 0{\cdot}228 \times 57{\cdot}7 = \mathbf{13{\cdot}16\ kV}$

Voltage across 5th from top, $V_5 = 0{\cdot}3 \times 57{\cdot}7 = \mathbf{17{\cdot}3\ kV}$

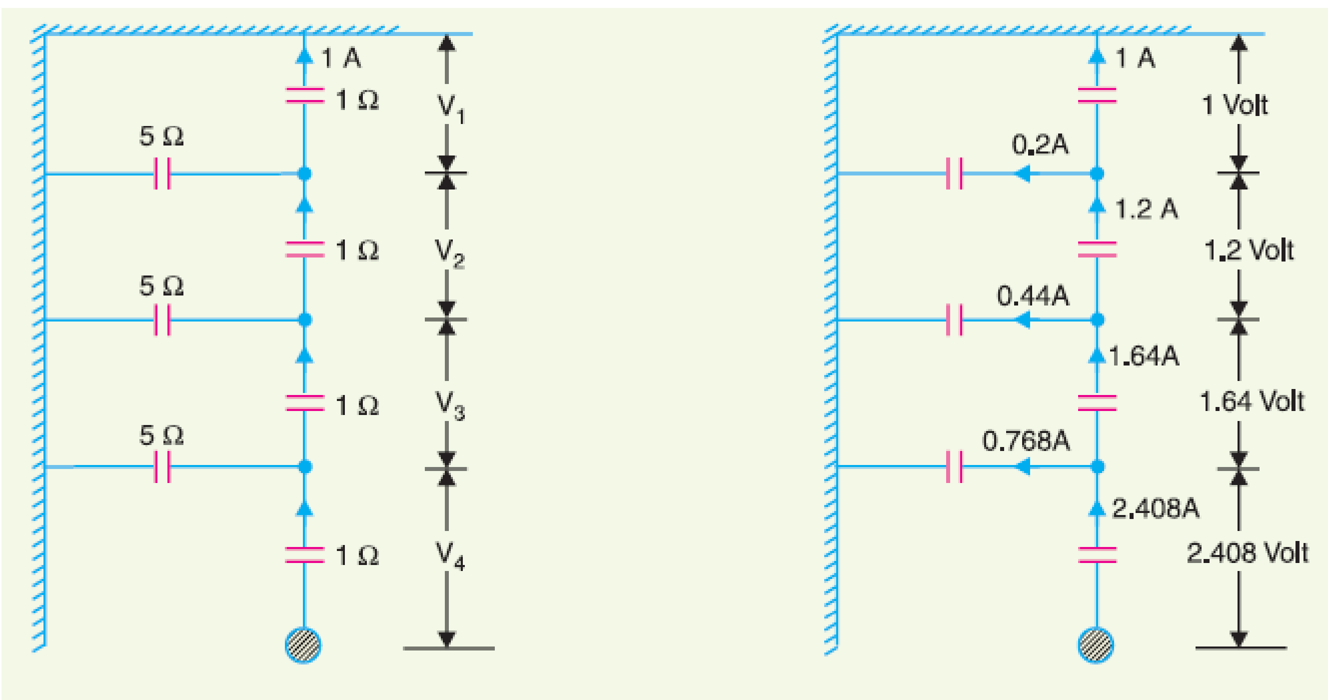
(*ii*) String efficiency $= \dfrac{57{\cdot}7}{5 \times 17{\cdot}3} \times 100 = \mathbf{66{\cdot}7\%}$

6. A string of four insulators has a self-capacitance equal to 5 times pin to earth capacitance. Find (i) the voltage distribution across various units as a percentage of total voltage across the string and (ii) string efficiency.

Solution

The ratio of self-capacitance (C) to pin-earth capacitance (C1) is C/C1 = 5. Suppose

XC = 1 ohm. Then XC1 = 5 ohm. Suppose the voltage V across string is such that current in the top insulator is 1A as shown in Fig. (i). The potential across various insulators will be as shown in Fig. (ii).



(*i*) (*ii*)

The voltage obtained across the string is given by ;

$$V = 1 + 1{\cdot}2 + 1{\cdot}64 + 2{\cdot}408 = 6{\cdot}248 \text{ volts}$$

(*i*) The voltage across each unit expressed as a percentage of V (*i.e.*, 6·248 volts) is given by :

Top Unit	=	$(1/6{\cdot}248) \times 100 =$ **16%**
Second from top	=	$(1{\cdot}2/6{\cdot}248) \times 100 =$ **19·2%**
Third from top	=	$(1{\cdot}64/6{\cdot}248) \times 100 =$ **26·3%**
Fourth from top	=	$(2{\cdot}408/6{\cdot}248) \times 100 =$ **38·5%**

(*ii*) String efficiency $= \dfrac{6\cdot 248}{4 \times 2\cdot 408} \times 100 =$ **64·86%**

Corona

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

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

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

If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductors, otherwise the rough points will appear brighter. With d.c. voltage, there is

difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation.

Some ionization is always present in air due to cosmic rays, ultra- violet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionized particles (i.e., free electrons and +ve ions) and neutral molecules.

When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons.

When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions.

Thus, the process of ionisation is cummulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors

Factors Affecting Corona

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

(i) Atmosphere.

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

(ii) Conductor size.

The corona effect depends upon the shape and conditions of the conduc- tors. The rough and irregular surface will give rise to more corona because unevenness of the surface decreases the value of breakdown voltage. Thus a stranded conductor has ir- regular surface and hence gives rise to more corona that a solid conductor.

(iii) Spacing between conductors.

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

(iv) Line voltage.

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

Important Terms

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

(i) Critical disruptive voltage.

It is the minimum phase-neutral voltage at which corona occurs.

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

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

In order that corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25ºC is 30 kV/cm (max) or 21.2 kV/cm (r.m.s.) and is denoted by go. If Vc is the phase-neutral potential required under these conditions, then,

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

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

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

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

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

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

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

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

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

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

(ii) Visual critical voltage.

It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors.

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

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

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

(iii) Power loss due to corona.

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

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

where f = supply frequency in Hz

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

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

Advantages and Disadvantages of Corona

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

Advantages

(i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electro- static stresses between the conductors.

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

Disadvantages

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

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

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

Methods of Reducing Corona Effect

The corona effects can be reduced by the following methods :

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

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

1. A 3-phase line has conductors 2 cm in diameter spaced equilaterally 1 m apart.If the dielectric strength of air is 30 kV (max) per cm, find the disruptive critical voltage for the line. Take air density factor = 0•952 and irregularity factor mo = 0•9.

Solution

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

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

Dielectric strength of air, g_o = 30 kV/cm (*max.*) = 21·2 kV (*r.m.s.*) per cm

Disruptive critical voltage, $V_c = m_o g_o \delta r \log_e (d/r)$ kV*/phase (*r.m.s.* value)

$= 0{\cdot}9 \times 21{\cdot}2 \times 0{\cdot}952 \times 1 \times \log_e 100/1 = 83{\cdot}64$ kV/phase

$\therefore$ Line voltage (*r.m.s.*) $= \sqrt{3} \times 83{\cdot}64 =$ **144·8 kV**

2. A 132 kV line with 1•956 cm dia. conductors is built so that corona takes place if the line voltage exceeds 210 kV (r.m.s.). If the value of potential gradient at which ionization occurs can be taken as 30 kV per cm, find the spacing between the conductors.

Solution

Assume the line is 3-phase.

Conductor radius, $r = 1{\cdot}956/2 = 0{\cdot}978$ cm

Dielectric strength of air, $g_o = 30/\sqrt{2} = 21{\cdot}2$ kV (*r.m.s.*) per cm

Disruptive voltage/phase, $V_c = 210/\sqrt{3} = 121{\cdot}25$ kV

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

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

$$V_c = m_o g_o \delta r \log_e (d/r) \text{ kV}$$

$$= 1 \times 21{\cdot}2 \times 1 \times 0{\cdot}978 \times \log_e (d/r)$$

or $$121{\cdot}25 = 20{\cdot}733 \log_e (d/r)$$

or $$\log_e \frac{d}{r} = \frac{121{\cdot}25}{20{\cdot}733} = 5{\cdot}848$$

or $$2{\cdot}3 \log_{10} d/r = 5{\cdot}848$$

or $$\log_{10} d/r = 5{\cdot}848/2{\cdot}3 = 2{\cdot}5426$$

or $$d/r = \text{Antilog } 2{\cdot}5426$$

or $$d/r = 348{\cdot}8$$

$\therefore$ Conductor spacing, $d = 348{\cdot}8 \times r = 348{\cdot}8 \times 0{\cdot}978 =$ **341 cm**

3. A 3-phase, 220 kV, 50 Hz transmission line consists of 1•5 cm radius conductor spaced 2 metres apart in equilateral triangular formation. If the temperature is 40ºC and atmospheric pressure is 76 cm, calculate the corona loss per km of the line. Take mo = 0•85.

Solution

The corona loss is given by

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

Now, $$\delta = \frac{3{\cdot}92\, b}{273 + t} = \frac{3{\cdot}92 \times 76}{273 + 40} = 0{\cdot}952$$

Assuming $$g_o = 21{\cdot}2 \text{ kV/cm } (r.m.s.)$$

∴ Critical disruptive voltage per phase is

$$V_c = m_o g_o \delta r \log_e d/r \text{ kV}$$
$$= 0{\cdot}85 \times 21{\cdot}2 \times 0{\cdot}952 \times 1{\cdot}5 \times \log_e 200/1{\cdot}5 = 125{\cdot}9 \text{ kV}$$

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

Substituting the above values, we have corona loss as:

$$P = \frac{242 \cdot 2}{0 \cdot 952}(50 + 25) \times \sqrt{\frac{1 \cdot 5}{200}} \times (127 - 125 \cdot 9)^2 \times 10^{-5} \text{ kW/phase/km}$$
$$= \frac{242 \cdot 2}{0 \cdot 952} \times 75 \times 0 \cdot 0866 \times 1 \cdot 21 \times 10^{-5} \text{ kW/km/phase}$$
$$= 0{\cdot}01999 \text{ kW/km/phase}$$

∴ Total corona loss per km for three phases

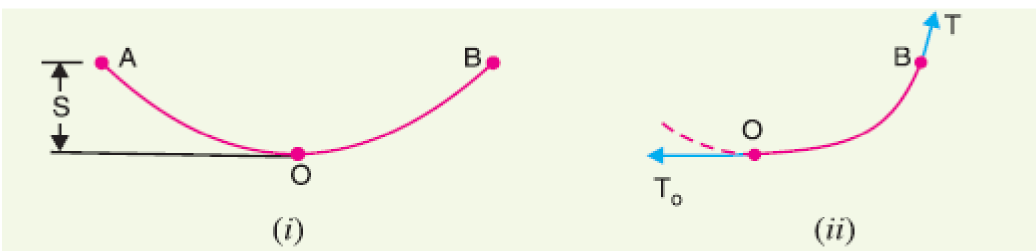
$$= 3 \times 0{\cdot}01999 \text{ kW} = 0{\cdot}05998 \text{ kW}$$

Sag in Overhead Lines

Def:

"The difference in level between points of supports and the lowest point on the conductor is called sag."

Fig. (i) shows a conductor suspended between two equilevel supports A and B. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is O and the sag is S. The following points may be noted :



(i) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(ii) The tension at any point on the conductor acts tangentially. Thus tension T_O at the lowest point O acts horizontally as shown in Fig. (ii).

(iii) The horizontal component of tension is constant throughout the length of the wire.

(iv) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if T is the tension at the support B, then $T = T_O$.

Conductor sag and tension.

This is an important consideration in the mechanical design of overhead lines. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level.

It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports.

However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise in made between the two.

Calculation of Sag

In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits.

The tension is governed by conductor weight, effects of wind, ice loading and temperature variations.

It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be 2.

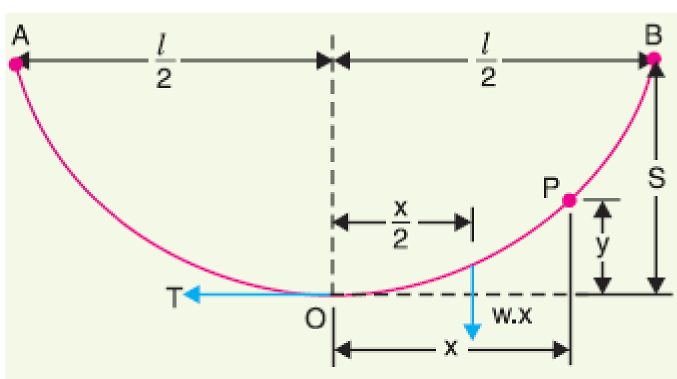
We shall now calculate sag and tension of a conductor when

(i) Supports are at equal levels and

(ii) Supports are at unequal levels.

(i) When supports are at equal levels.

Consider a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.



It can be proved that lowest point will be at the mid-span.

Let

l = Length of span

w = Weight per unit length of con- ductor

T = Tension in the conductor.

Consider a point P on the conductor. Taking the lowest point O as the origin, let the co-ordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (i.e., OP = x), the two forces acting on the portion OP of the conductor are :

(a) The weight wx of conductor acting at a distance x/2 from O.

(b) The tension T acting at O.

Equating the moments of above two forces about point O, we get,

$$Ty = wx \times \frac{x}{2}$$

or $$y = \frac{wx^2}{2T}$$

The maximum dip (sag) is represented by the value of y at either of the supports A and B.

At support A, $x = l/2$ and $y = S$

$$\therefore \quad \text{Sag,} \quad S = \frac{w(l/2)^2}{2T} = \frac{wl^2}{8T}$$

(ii) When supports are at unequal levels.

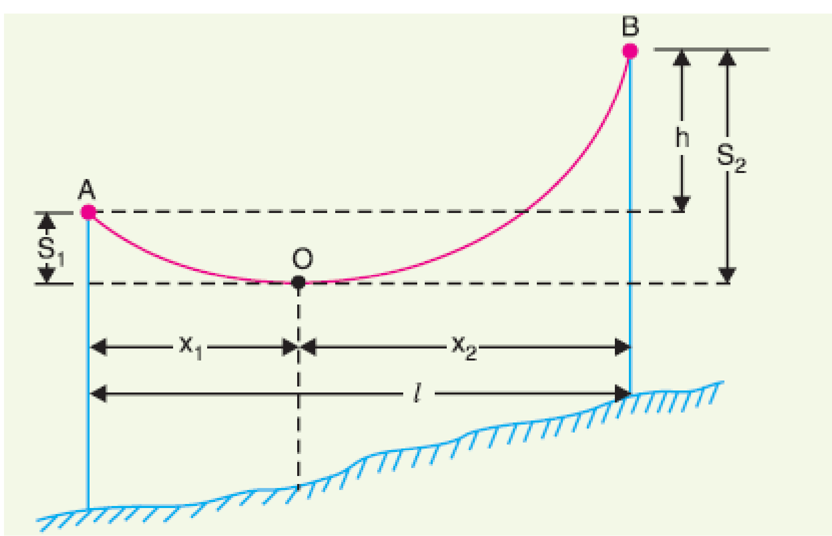
In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig. 8.25 shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O.

Let

l = Span length

h = Difference in levels between two supports

x1 = Distance of support at lower level (i.e., A) from O x2 = Distance of support at higher level (i.e. B) from O T = Tension in the conductor



If w is the weight per unit length of the conductor, then,

$$\text{Sag } S_1 = \frac{w\,x_1^{2*}}{2T}$$

and

$$\text{Sag } S_2 = \frac{w\,x_2^{2}}{2T}$$

Also $$x_1 + x_2 = l \qquad \ldots(i)$$

Now $$S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$\therefore$ $$S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

But $$S_2 - S_1 = h$$

$\therefore$ $$h = \frac{w\,l}{2T}(x_2 - x_1)$$

or $$x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad \ldots(ii)$$

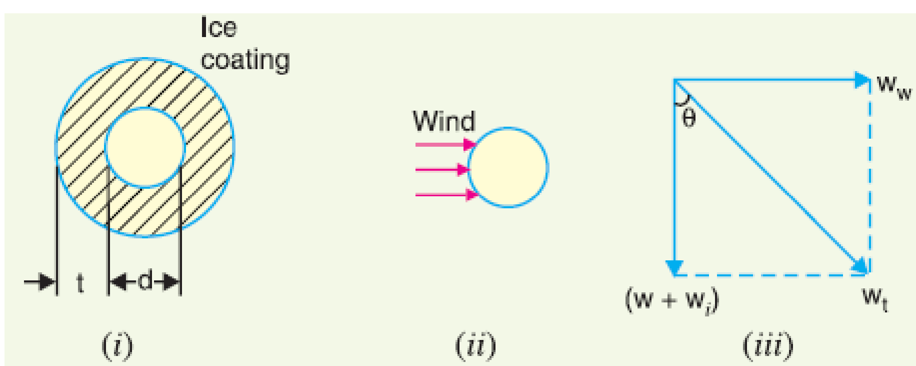
Solving exps. (*i*) and (*ii*), we get,

$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l}$$

$$x_2 = \frac{l}{2} + \frac{T\,h}{w\,l}$$

Having found x_1 and x_2, values of S_1 and S_2 can be easily calculated.

Effect of wind and ice loading. The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards *i.e.*, in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally *i.e.*, at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in



Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

where w = weight of conductor per unit length

= conductor material density × volume per unit length

$$w_i = \text{weight of ice per unit length}$$
$$= \text{density of ice} \times \text{volume of ice per unit length}$$
$$= \text{density of ice} \times \frac{\pi}{4}\,[(d + 2t)^2 - d^2] \times 1$$
$$= \text{density of ice} \times \pi\, t\,(d + t)^*$$
$$w_w = \text{wind force per unit length}$$
$$= \text{wind pressure per unit area} \times \text{projected area per unit length}$$
$$= \text{wind pressure} \times [(d + 2t) \times 1]$$

When the conductor has wind and ice loading also, the following points may be noted :

(*i*) The conductor sets itself in a plane at an angle θ to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

(*ii*) The sag in the conductor is given by :

$$S = \frac{w_t\, l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle θ to the vertical. *If no specific mention is made in the problem, then slant slag is calculated by using the above formula.*

(*iii*) The vertical sag $= S\cos\theta$

Problems

1. A 132 kV transmission line has the following data :

Wt. of conductor = 680 kg/km ; Length of span = 260 m

Ultimate strength = 3100 kg ; Safety factor = 2

Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 metres.

Solution

Wt. of conductor/metre run, $w = 680/1000 = 0{\cdot}68$ kg

Working tension, $T = \dfrac{\text{Ultimate strength}}{\text{Safety factor}} = \dfrac{3100}{2} = 1550$ kg

Span length, $l = 260$ m

$$\therefore \quad \text{Sag} = \frac{w\,l^2}{8T} = \frac{0\cdot 68 \times (260)^2}{8 \times 1550} = 3\cdot 7 \text{ m}$$

∴ Conductor should be supported at a height of 10 + 3·7 = **13·7 m**

2. A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm2. The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9•9 gm/cm3 and wind pressure is 1•5 kg/m length, calculate the sag. What is the vertical sag?

Solution

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1\cdot5$ kg

Wt. of conductor/m length, w = Sp. Gravity × Volume of 1 m conductor

$= 9\cdot9 \times 2 \times 100 = 1980$ gm $= 1\cdot98$ kg

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot98)^2 + (1\cdot5)^2} = 2\cdot48 \text{ kg}$$

$$\therefore \quad \text{Sag,} \quad S = \frac{w_t\, l^2}{8T} = \frac{2\cdot48 \times (150)^2}{8 \times 2000} = 3\cdot48 \text{ m}$$

This is the value of slant sag in a direction making an angle θ with the vertical. Referring to Fig. , the value of θ is given by ;

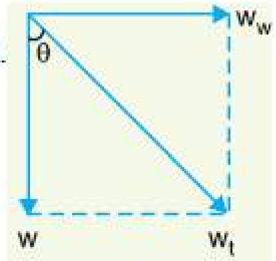


Fig.

$$\tan\theta = w_w/w = 1\cdot5/1\cdot98 = 0\cdot76$$

$$\therefore \quad \theta = \tan^{-1} 0\cdot76 = 37\cdot23°$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta$$

$$= 3\cdot48 \times \cos 37\cdot23° = 2\cdot77 \text{ m}$$

3. A transmission line has a span of 200 metres between level supports. The conductor has a cross-sectional area of 1•29 cm2, weighs 1170 kg/km and has a breaking stress of 4218 kg/cm2. Calculate the sag for a safety factor of 5, allowing a wind pressure of 122 kg per square metre of projected area. What is the vertical sag?

Solution

Span length, $l = 200$ m

Wt. of conductor/m length, $w = 1170/1000 = 1\cdot17$ kg

Working tension, $*T = 4218 \times 1\cdot29/5 = 1088$ kg

Diameter of conductor, $d = \sqrt{\dfrac{4 \times \text{area}}{\pi}} = \sqrt{\dfrac{4 \times 1\cdot29}{\pi}} = 1\cdot28$ cm

Wind force/m length, w_w = Pressure × projected area in m^2

$= (122) \times (1\cdot28 \times 10^{-2} \times 1) = 1\cdot56$ kg

Total weight of conductor per metre length is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot17)^2 + (1\cdot56)^2} = 1\cdot95 \text{ kg}$$

$$\therefore \quad \text{Slant sag,} \quad S = \frac{w_t\, l^2}{8T} = \frac{1\cdot95 \times (200)^2}{8 \times 1088} = 8\cdot96 \text{ m}$$

The slant sag makes an angle θ with the vertical where value of θ is given by :

$$\theta = \tan^{-1}(w_w/w) = \tan^{-1}(1\cdot56/1\cdot17) = 53\cdot13°$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta = 8\cdot96 \times \cos 53\cdot13° = 5\cdot37 \text{ m}$$

4. A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1•96 cm and weighs 0•865 kg/m. Its ultimate strength is 8060 kg. If the conductor has ice coating of radial thickness 1•27 cm and is subjected to a wind pressure of 3•9 gm/ cm2 of projected area, calculate sag for a safety factor of 2. Weight of 1 c.c. of ice is 0•91 gm.

Solution

Span length, $l = 275$ m ; Wt. of conductor/m length, $w = 0{\cdot}865$ kg

Conductor diameter, $d = 1{\cdot}96$ cm ; Ice coating thickness, $t = 1{\cdot}27$ cm

Working tension, $T = 8060/2 = 4030$ kg

Volume of ice per metre (*i.e.*, 100 cm) length of conductor

$$= \pi\, t\,(d + t) \times 100 \text{ cm}^3$$

$$= \pi \times 1{\cdot}27 \times (1{\cdot}96 + 1{\cdot}27) \times 100 = 1288 \text{ cm}^3$$

Weight of ice per metre length of conductor is

$$w_i = 0{\cdot}91 \times 1288 = 1172 \text{ gm} = 1{\cdot}172 \text{ kg}$$

Wind force/m length of conductor is

$$w_w = [\text{Pressure}] \times [(d + 2t) \times 100]$$

$$= [3{\cdot}9] \times (1{\cdot}96 + 2 \times 1{\cdot}27) \times 100 \text{ gm} = 1755 \text{ gm} = 1{\cdot}755 \text{ kg}$$

Total weight of conductor per metre length of conductor is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

$$= \sqrt{(0{\cdot}865 + 1{\cdot}172)^2 + (1{\cdot}755)^2} = 2{\cdot}688 \text{ kg}$$

$$\text{Sag} = \frac{w_t\, l^2}{8T} = \frac{2{\cdot}688 \times (275)^2}{8 \times 4030} = 6{\cdot}3 \text{ m}$$

5. A transmission line has a span of 214 metres between level supports. The conductors have a cross-sectional area of 3•225 cm^2. Calculate the factor of safety under the following conditions :

Vertical sag = 2•35 m ; Wind pressure = 1•5 kg/m run

Breaking stress = 2540 kg/cm2 ; Wt. of conductor = 1•125 kg/m run

Solution

Here, $l = 214$ m ; $w = 1{\cdot}125$ kg ; $w_w = 1{\cdot}5$ kg

Total weight of one metre length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1{\cdot}125)^2 + (1{\cdot}5)^2} = 1{\cdot}875 \text{ kg}$$

If f is the factor of safety, then,

$$\text{Working tension, } T = \frac{\text{Breaking stress} \times \text{conductor area}}{\text{safety factor}} = 2540 \times 3{\cdot}225/f = 8191/f \text{ kg}$$

$$\text{Slant Sag, } S = \frac{\text{Vertical sag}}{{}^*\cos\theta} = \frac{2{\cdot}35 \times 1{\cdot}875}{1{\cdot}125} = 3{\cdot}92 \text{ m}$$

Now $$S = \frac{w_t\, l^2}{8T}$$

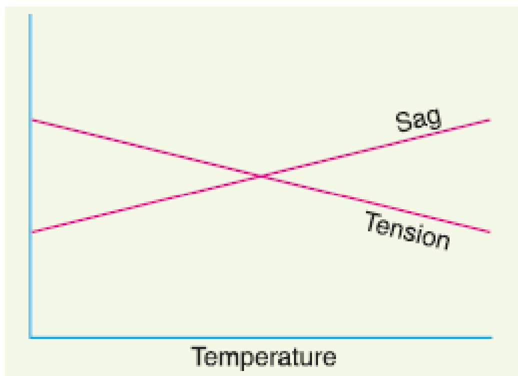
or $$T = \frac{w_t\, l^2}{8\,S}$$

∴ $$\frac{8191}{f} = \frac{1 \cdot 875 \times (214)^2}{8 \times 3 \cdot 92}$$

or Safety factor, $$f = \frac{8191 \times 8 \times 3 \cdot 92}{1 \cdot 875 \times (214)^2} = 3$$

Stringing charts :

For use in the field work of stringing the conductors, temperature-sag and temperature- tension charts are plotted for the given conductor and load- ing conditions. Such curves are called stringing charts (see Fig.) These charts are very helpful while stringing overhead lines.



Underground Cables

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

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

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

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

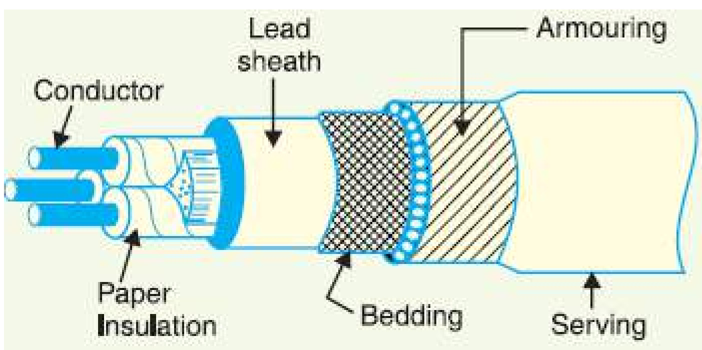
(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

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

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

Construction of Cables

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



Construction of a Cable

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

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

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

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

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

(vi) Serving. In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving.

Insulating Materials for Cables

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. In general, the insulating materials used in cables should have the following properties :

(i) High insulation resistance to avoid leakage current.

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

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

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

(v) Non-inflammable.

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

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

No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at.

The principal insulating materials used in cables are rubber, vulcanised India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

1. Rubber.

Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products.

It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is $10^{17}\Omega$ cm.

Although pure rubber has reasonably high insulating properties, it suffers from some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

2. Vulcanised India Rubber (V.I.R.).

It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber.

Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

3. Impregnated paper.

It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material.

This type of insulation has almost superseded the rubber insulation.

It has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance.

The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed.

4. Varnished cambric.

It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape.

The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent.

As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.

5. Polyvinyl chloride (PVC).

This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder.

For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point.

Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids.

Therefore, this type of insulation is preferred over VIR in extreme environmental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

Classification of Cables

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

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

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

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

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

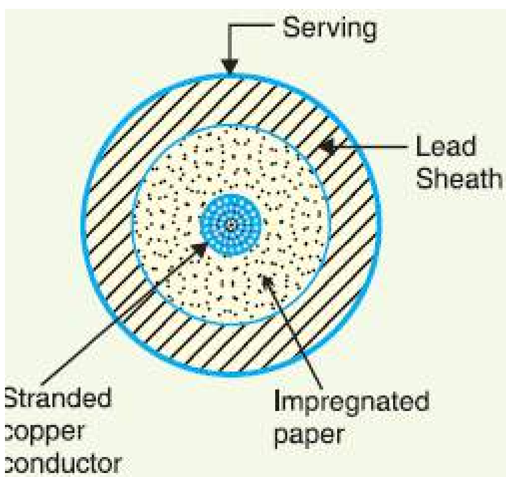
(v) Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended.

It may be (i) single-core (ii) two-core (iii) three-core (iv) four-core etc.

For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

Fig. shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of



Impregnated paper.

The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts.

In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided.

Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

Cables for 3-Phase Service

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used.

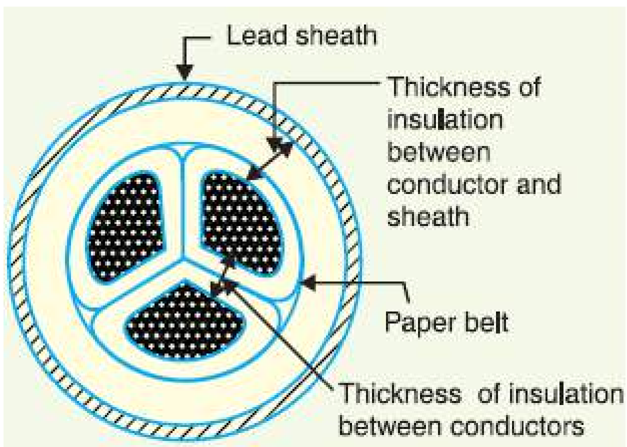
For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single-core cables are used.

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

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV.

1. Belted cables. These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV.

Fig. shows the constructional details of a 3-core belted cable.



The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores.

The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of non- circular shape to make better use of available space.

The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury.

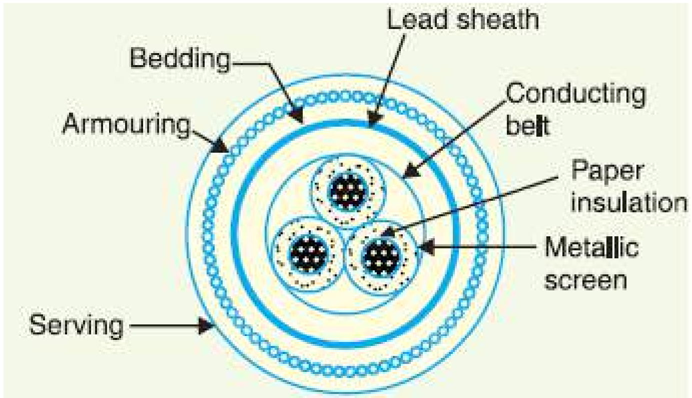
The lead sheath is covered with one or more layers of armouring with an outer serving.

The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial i.e., across the insulation.

2. Screened cables.

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

(i) H-type cables. This type of cable was first designed by H. Hochstadter and hence the name. Fig. shows the constructional details of a typical 3-core, H-type cable.



Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminum foil.

The cores are laid in such a way that metallic screens, make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores.

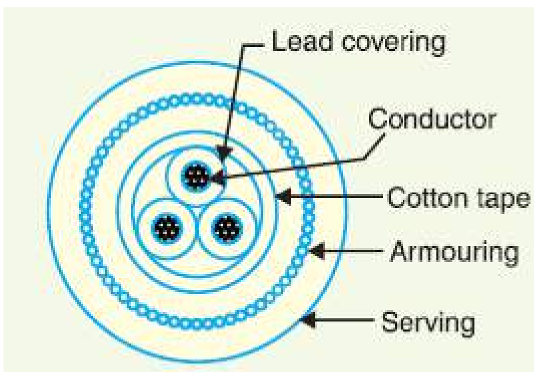
The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual.

It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

Two principal advantages are claimed for H-type cables. Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. Secondly, the metallic screens increase the heat dissipating power of the cable.

(ii) S.L. type cables.

Fig shows the constructional details of a 3-core S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath.



There is no overall lead sheath but only armouring and serving are provided.

The S.L. type cables have two main advantages over H-type cables.

Firstly, the separate sheaths minimize the possibility of core-to-core breakdown.

Secondly, bending of cables becomes easy due to the elimination of overall lead sheath.

However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of H-cable and, therefore, call for greater care in manufacture.

3. Pressure cables

For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids.

When the operating voltages are greater than 66 kV, pressure cables are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables.

Two types of pressure cables viz oil-filled cables and gas pressure cables are commonly used.

(i) Oil-filled cables.

In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable.

Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers.

Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV. Oil-filled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler-space channels.

Fig. shows the constructional details of a single-core conductor channel, oil filled cable.

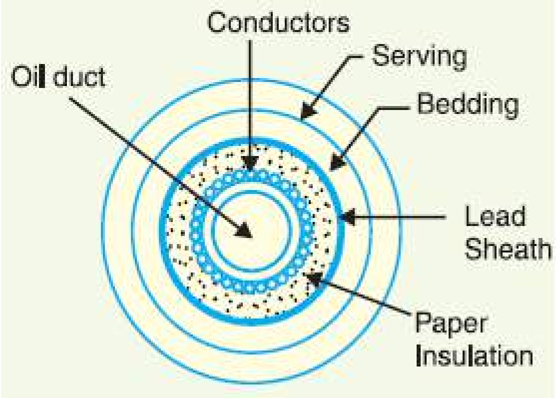


Fig. Single-core conductor channel, oil-filled cable

The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation.

The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir.

However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage w.r.t. earth, so that a very complicated system of joints is necessary.

Fig. shows the constructional details of a single- core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown.

In the 3-core oil-filler cable shown in Fig, the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential.

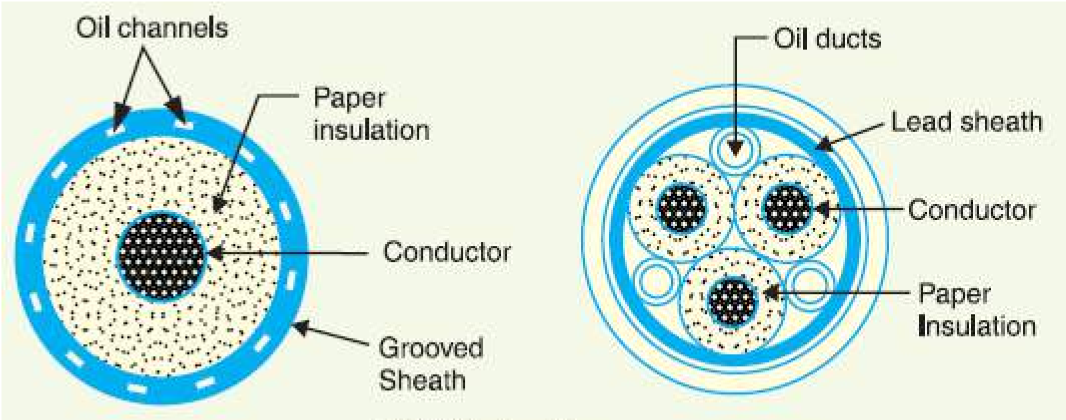


Fig. *Oil-filled cables* Fig.

The oil-filled cables have three principal advantages.

Firstly, formation of voids and ionisation are avoided.

Secondly, allowable temperature range and dielectric strength are increased.

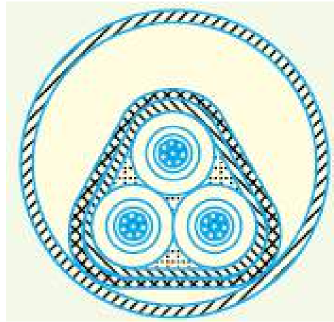
Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased

(ii) Gas pressure cables.

The voltage required to set up ionization inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated.

At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

Fig. shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden.



The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable.

The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe.

The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation.

Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high.

Insulation Resistance of a Single-Core Cable

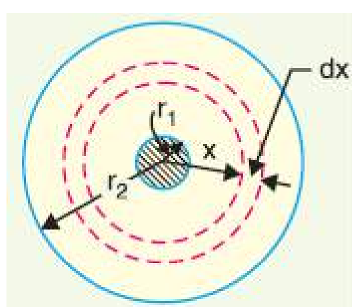
The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The path for leakage current is radial through the insulation.

The opposition offered by insulation to leakage current is known as insulation resistance of the cable.

For satisfactory operation, the insulation resistance of the cable should be very high.

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

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



$\therefore$ Insulation resistance of considered layer

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

Insulation resistance of the whole cable is

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

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

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

1. A single-core cable has a conductor diameter of 1cm and insulation thickness of 0•4 cm. If the specific resistance of insulation is 5 × 1014 -cm, calculate the insulation resistance for a 2 km length of the cable.

Solution

Conductor radius, $r_1 = 1/2 = 0{\cdot}5$ cm

Length of cable, $l = 2$ km $= 2000$ m

Resistivity of insulation, $\rho = 5 \times 10^{14}\ \Omega\text{-cm} = 5 \times 10^{12}\ \Omega\text{-m}$

Internal sheath radius, $r_2 = 0{\cdot}5 + 0{\cdot}4 = 0{\cdot}9$ cm

$\therefore$ Insulation resistance of cable is

$$R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1} = \frac{5 \times 10^{12}}{2\pi \times 2000} \log_e \frac{0\cdot 9}{0\cdot 5}$$

$$= 0{\cdot}234 \times 10^9\ \Omega = 234\ \text{M}\Omega$$

2. The insulation resistance of a single-core cable is 495 M per km. If the core diameter is 2•5 cm and resistivity of insulation is 4•5 × 1014 Ω-cm, find the insulation thickness.

Solution

Length of cable, $l = 1$ km $= 1000$ m

Cable insulation resistance, $R = 495\ \text{M}\Omega = 495 \times 10^6\ \Omega$

Conductor radius, $r_1 = 2{\cdot}5/2 = 1{\cdot}25$ cm

Resistivity of insulation, $\rho = 4{\cdot}5 \times 10^{14}\ \Omega\text{-cm} = 4{\cdot}5 \times 10^{12}\ \Omega\text{m}$

Let r_2 cm be the internal sheath radius.

Now, $$R = \frac{\rho}{2\pi\, l} \log_e \frac{r_2}{r_1}$$

or $$\log_e \frac{r_2}{r_1} = \frac{2\pi\, l\, R}{\rho} = \frac{2\pi \times 1000 \times 495 \times 10^6}{4\cdot 5 \times 10^{12}} = 0{\cdot}69$$

or $$2{\cdot}3 \log_{10} r_2/r_1 = 0{\cdot}69$$

or $$r_2/r_1 = \text{Antilog}\ 0{\cdot}69/2{\cdot}3 = 2$$

or $$r_2 = 2\, r_1 = 2 \times 1{\cdot}25 = 2{\cdot}5\ \text{cm}$$

$\therefore$ Insulation thickness $= r_2 - r_1 = 2{\cdot}5 - 1{\cdot}25 = 1{\cdot}25$ cm

Capacitance Grading

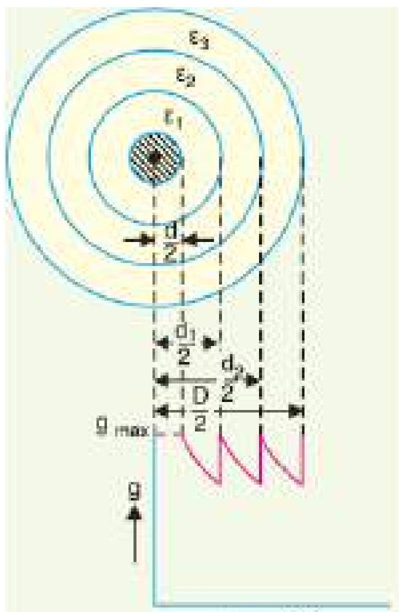
The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity €r of any layer is inversely proportional to its distance from the centre.

Under such conditions, the value of potential gradient at any point in the dielectric is constant and is independent of its distance from the centre.

In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. How ever, ideal grading requires the use of an infinite number of dielectrics which is an impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity ; the dielectric of highest permittivity being used near the core.

The capacitance grading can be explained beautifully by referring to Fig. 1.



There are three dielectrics of outer diameter

d_1, d_2 and D and of relative permittivity ε_1, ε_2 and ε_3 respectively. If the permittivities are such that $\varepsilon_1 > \varepsilon_2 > \varepsilon_3$ and the three dielectrics are worked at the same maximum stress, then,

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

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

Potential difference across the inner layer is

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

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

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

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

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

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

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

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

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

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

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

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

1. A single-core lead sheathed cable is graded by using three dielectrics of relative permittivity 5, 4 and 3 respectively. The conductor diameter is 2 cm and overall diameter is 8 cm. If the three dielectrics are worked at the same maximum stress of 40 kV/cm, find the safe working voltage of the cable.

What will be the value of safe working voltage for an ungraded cable, assuming the same conductor and overall diameter and the maximum dielectric stress ?

Solution

Here, $d = 2$ cm ; $d_1 = ?$; $d_2 = ?$; $D = 8$ cm

$\varepsilon_1 = 5$; $\varepsilon_2 = 4$; $\varepsilon_3 = 3$; $g_{max} = 40$ kV/cm

Graded cable. As the maximum stress in the three dielectrics is the same,

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

or $5 \times 2 = 4 \times d_1 = 3 \times d_2$

$\therefore$ $d_1 = 2{\cdot}5$ cm and $d_2 = 3{\cdot}34$ cm

Permissible peak voltage for the cable

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

$$= \frac{40}{2}\left[2\log_e \frac{2\cdot 5}{2} + 2\cdot 5 \log_e \frac{3\cdot 34}{2\cdot 5} + 3\cdot 34 \log_e \frac{8}{3\cdot 34}\right]$$

$$= 20\,[0{\cdot}4462 + 0{\cdot}7242 + 2{\cdot}92]\text{ kV}$$

$$= 20 \times 4{\cdot}0904 = 81{\cdot}808\text{ kV}$$

$\therefore$ Safe working voltage (r.m.s.) for cable

$$= \frac{81\cdot 808}{\sqrt{2}} = \mathbf{57{\cdot}84\ kV}$$

Ungraded cable. Permissible peak voltage for the cable

$$= \frac{g_{max}}{2}\, d \log_e \frac{D}{d} = \frac{40}{2} \times 2 \log_e \frac{8}{2}\text{kV} = 55{\cdot}44\text{ kV}$$

$\therefore$ Safe working voltage (r.m.s.) for the cable

$$= \frac{55\cdot 44}{\sqrt{2}} = \mathbf{39{\cdot}2\ kV}$$

This example shows the utility of grading the cable. Thus for the same conductor diameter (d) and the same overall dimension (D), the graded cable can be operated at a voltage (57·84 – 39·20) = 18·64 kV (r.m.s.) higher than the homogeneous cable — an increase of about 47%.

Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath.

The intersheaths are held at suit- able potentials which are in between the core potential and earth potential. This arrangement im proves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

Consider a cable of core diameter d and outer lead sheath of diameter D. Suppose that two intersheaths of diameters d1 and d2 are inserted into the homogeneous di electric and maintained at some fixed potentials.

Let V1, V2 and V3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath.

As there is a definite potential difference between the inner and outer layers of each intersheath, therefore, each sheath can be treated like a homogeneous single core cable.

Maximum stress between core and intersheath 1 is

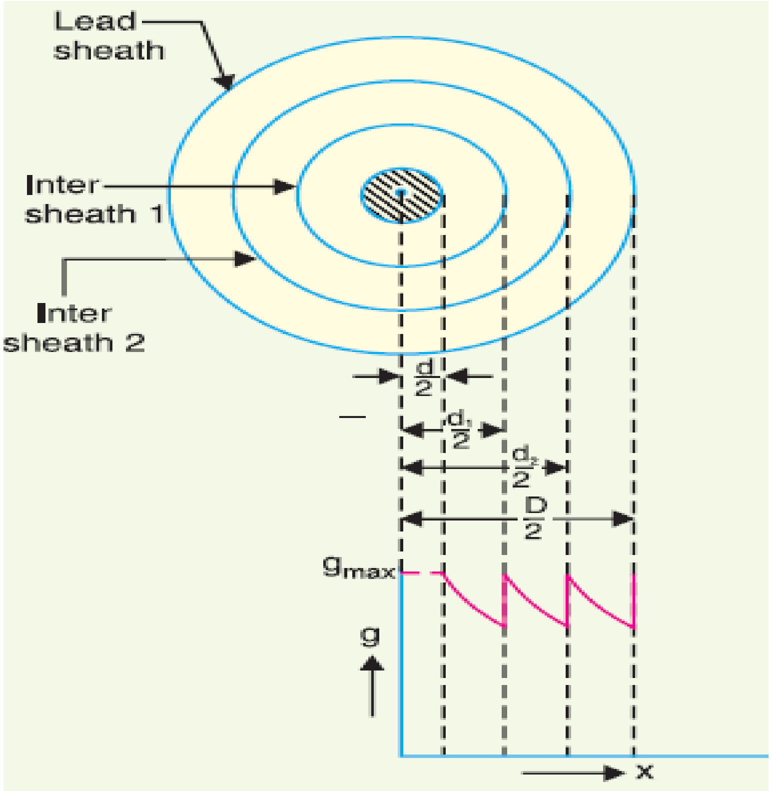
$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

Similarly,

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

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same *i.e.*,



$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.* Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

Intersheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the intersheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the intersheaths due to charging currents. For these reasons, intersheath grading is rarely used.

Problem

A single core cable of conductor diameter 2 cm and lead sheath of diameter 5.3 cm is to be used on a 66 kV, 3-phase system. Two intersheaths of diameter 3•1 cm and 4•2 cm are introduced between the core and lead sheath. If the maximum stress in the layers is the same, find the voltages on the intersheaths.

Solution

Here, $d = 2$ cm ; $d_1 = 3{\cdot}1$ cm ; $d_2 = 4{\cdot}2$ cm

$$D = 5.3 \text{ cm} ; V = \frac{66 \times \sqrt{2}}{\sqrt{3}} = 53{\cdot}9 \text{ kV}$$

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_1}{1 \times \log_e \frac{3\cdot1}{2}} = 2\cdot28\ V_1$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_2}{1\cdot55\ \log_e \frac{4.2}{3.1}} = 2\cdot12\ V_2$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}} = \frac{V_3}{2\cdot1\log_e \frac{5\cdot3}{4\cdot2}} = 2\cdot04\ V_3$$

As the maximum stress in the layers is the same,

$\therefore$ $g_{1max} = g_{2max} = g_{3max}$

or $2\cdot28\ V_1 = 2\cdot12\ V_2 = 2\cdot04\ V_3$

$\therefore$ $V_2 = (2\cdot28/2\cdot12)\ V_1 = 1\cdot075\ V_1$

and $V_3 = (2\cdot28/2\cdot04)\ V_1 = 1\cdot117\ V_1$

Now $V_1 + V_2 + V_3 = V$

or $V_1 + 1\cdot075\ V_1 + 1\cdot117\ V_1 = 53\cdot9$

or $V_1 = 53\cdot9/3\cdot192 = 16\cdot88$ kV

and $V_2 = 1\cdot075\ V_1 = 1\cdot075 \times 16\cdot88 = 18\cdot14$ kV

$\therefore$ Voltage on first intersheath (*i.e.*, near to the core)

$= V - V_1 = 53\cdot9 - 16\cdot88 =$ **37·02 kV**

Voltage on second intersheath $= V - V_1 - V_2 = 53\cdot9 - 16\cdot88 - 18\cdot14 =$ **18·88 kV**

UNIT–5

UNIT V GENERAL ASPECTS OF DISTRIBUTION SYSTEMS

Classification of Distribution Systems - Comparison of DC & AC and Under-Ground & Over - Head Distribution Systems. Voltage Drop and power loss in D.C Distributors for the following cases: Radial D.C Distributors fed at one end and at ends (equal/unequal Voltages), Uniform loading and Ring Main Distributor, LVDC Distribution Network. Design Considerations of Distribution Feeders: Radial and loop types of primary feeders, feeder loading; basic design of secondary distribution. Voltage Drop and power loss in A.C. Distributors.

SUBSTATIONS:
Location of Substations: Rating of distribution substations, service area within primary feeders. Benefits derived through optimal location of substations.
Classification of substations: Air insulated substations - Indoor & Outdoor substations: Substation layout showing the location of all the substation equipment – Gas Insulated Substation (GIS).

Classification of Distribution Systems

A distribution system may be classified according to ;
(*i*) *Nature of current.* According to nature of current, distribution system may be classified as
(*a*) A.C. distribution system (*b*) D.C. distribution system.
Now-a-days, A.C. system is universally adopted for distributionof electric power as it is simpler and more economicalthan direct current method.
(*ii*) *Type of construction.* According to type of construction, distribution system may be classified as
(*a*) Overhead system (*b*) Underground system.
The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by the local laws.
(*iii*) *Scheme of connection.* According to scheme of connection, the distribution system may be classified as
(*a*) Radial system
(*b*) Ring main system
(*c*) Inter-connected system.
Each scheme has its own advantages and disadvantages

(*i*) According to Nature of current

1. A.C. Distribution System

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

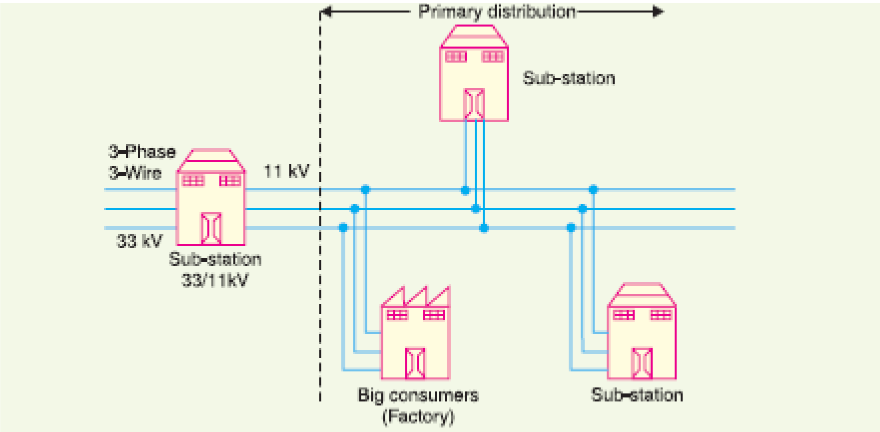
(a) Primary distribution system.

It is that part of A.C. distribution system which operates at voltages somewhat higher than general utilisation

The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed.

The most commonly used primary distribution voltages are 11 kV, 6·6kV and 3·3 kV.

Due to economic considerations, primary distribution is carried out by 3-phase, 3-wire system.



From the above fig, At this substation, voltage is stepped down to 11 kV with the help of step-down transformer. Power is supplied to various substations for distribution or to big consumers at this voltage. This forms the high voltage distribution or primary distribution.

(b) Secondary Distribution System

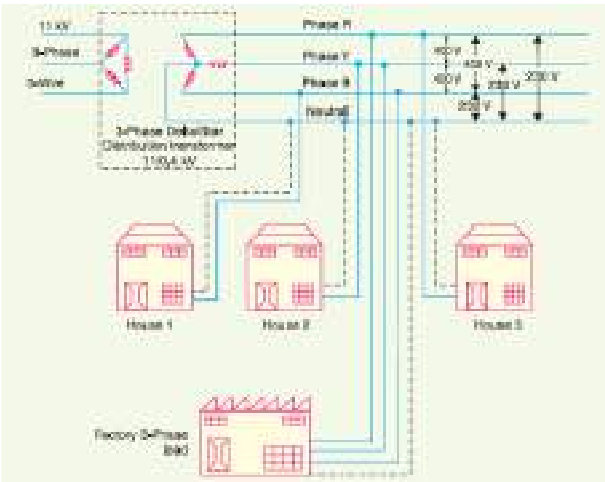
It is that part of A.C. distribution system which includes the range of voltages at which the ultimate consumer utilises the electrical energy delivered to him. The secondary distribution employs 400/230 V, 3-phase, 4-wire system.

Fig. shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution substations.

At each distribution substation, the voltage is stepped down to 400V and power is delivered by3-phase,4-wire a.c. system.

The voltage between any two phases is 400 V and between any phase and neutral is 230V.

The single phase domestic loads are connected between any one phase and the neutral, whereas 3-phase 400 V motor loads are connected across 3-phase lines directly.



2. D.C. Distribution

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

For this purpose,a.c. power is converted into d.c. power at the substation by using converting machinery *e.g.*,mercury arc rectifiers, rotary converters and motor-generator sets.

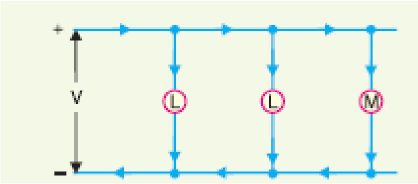
The d.c. supply from the substation may be obtained in the form of
(*i*) 2-wire
(*ii*) 3-wire for distribution.

(*i*) 2-wire d.c distribution:

-As the name implies, this system of distribution consists of two wires.

-One is the outgoing or positive wire and the other is the return or negative wire.
-The loads such as lamps, motors etc. are connected in parallel between the two wires as shown in Fig.

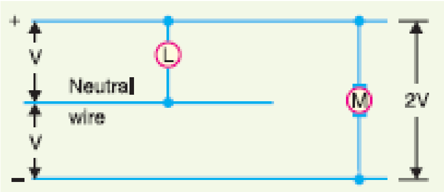
-This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.



(*ii*) *3-wire d.c. system.*

-It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer and neutral wire as shown in Fig.
- The principal advantage of this system is that it makes available two voltages at the consumer terminals *viz.*, *V* between any outer and the neutral and 2V between the outers.

Loads requiring high voltage (*e.g.*, motors) are connected across the outers, whereas lampsand heating circuits requiring less voltage are connected between either outer and the neutral.



(*ii*) According to *Type of construction:*

According to type of construction, distribution system may be classified as
(*a*) Overhead system
(*b*) Underground system.

The distribution system can be Overhead vs Underground System. Overhead lines are generally mounted on wooden, concrete or steel poles which are arranged to carry distribution transformers in addition to the conductors.

The underground system uses conduits, cables and manholes under the surface of streets and sidewalks.

The choice between Overhead vs Underground System system depends upon a number of widely differing factors. Therefore, it is desirable to make a comparison between the two.

- **Public safety:** The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.
- **Initial cost:** The underground system is more expensive due to the high cost of trenching, conduits, cables, manholes and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.
- **Flexibility:** The overhead system is much more flexible than the underground system. In the latter case, manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers etc., can be easily shifted to meet the changes in load conditions.
- **Faults:** The chances of faults in underground system are very rare as the cables are laid underground and are generally provided with better insulation.
- **Appearance:** The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.
- **Fault location and repairs:** In general, there are little chances of faults in an underground system. However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made.
- **Current carrying capacity and voltage drop:** An overhead distribution conductor has a considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. On the other hand, underground cable conductor has much lower inductive reactance than that of an overhead conductor because of closer spacing of conductors.
- **Useful life:** The useful life of underground system is much longer than that of an overhead An overhead system may have a useful life of 25 years, whereas an underground system may have a useful life of more than 50 years.
- **Maintenance cost:** The maintenance cost of underground system is very low as compared with that of overhead system because of less chances of faults and service interruptions from wind, ice, lightning as well as from traffic hazards.
- **Interference with communication circuits:** An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable able level. However, there is no such interference with the underground system.

It is clear from the above comparison that each system has its own advantages and disadvantages. However, comparative economics (i.e., annual cost of operation) is the most powerful factor influencing the choice between Overhead vs Underground System.

The greater capital cost of underground system prohibits its use for distribution.

But sometimes non-economic factors (e.g., general appearance, public safety etc.) exert considerable influence on choosing underground system.

In general, overhead system is adopted for distribution and the use of underground system is made only where overhead construction is impracticable or prohibited by local laws.

(*iii*) According to *Scheme of connection.*

According to scheme of connection,the distribution system may be classified as

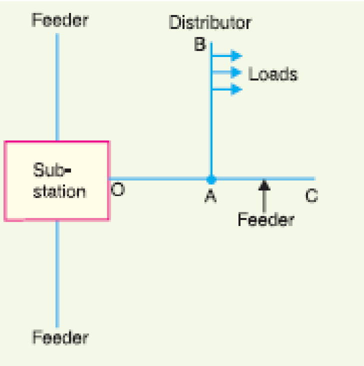
(*a*) Radialsystem

(*b*) Ring main system or Loop Type

(*c*) Inter-connected system.

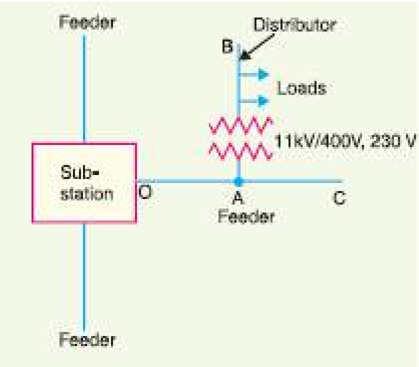
(*a*) Radial system

In this system, separate feeders radiate from a single substation and feedthe distributors at one end only. Fig.(*i*) shows a single line diagram of a radial systemfor d.c. distribution where a feeder *OC* supplies a distributor *AB* at point *A*. Obviously, thedistributor is fed at one end only *i.e*., point *A* is this case.



(*i*)

Fig.(*ii*) shows a single linediagram of radial system for a.c. distribution. The radial system is employed only whenpower is generated at low voltage and the substation is located at the centre of the load.



(*ii*)

Advantage

1. This is the simplest distribution circuit and has the lowest initial cost.
2. The Initial cost required is minimum
3. They are very easy to operate
4. Switching apparatus required is less
5. Size of the conductor required is less.

Disadvantages

1. Less Reliability
2. Continuity of service cannot be maintained
3. The end of the distributor nearest to the feeding point will be heavily loaded
4. The consumers are dependent on a single feeder and single distributor. Therefore, any fault Son the feeder or distributor cuts off supply to the consumers who are on the side of the fault away fromthe substation

5. The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes

Due to these limitations, this system is used for short distances only.

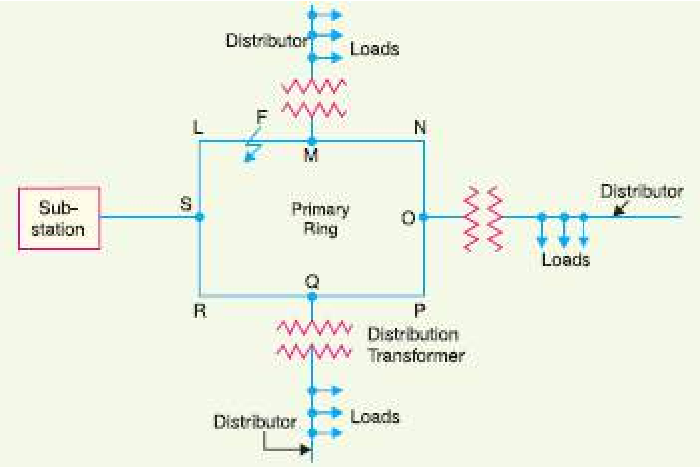
(*b*) Ring main system or Loop Type

In this system, the primaries of distribution transformers form a loop.

The loop circuit starts from the substation bus-bars, makes a loop through the area to be served, and returns to the substation.

Fig.shows the single line diagram of ring mainsystem for a.c. distribution where substation supplies to the closed feeder LMNOPQRS.

The distributors are tapped from different points *M*, *O* and *Q* of the feeder through distribution transformers.



Advantages

1. There are less voltage fluctuations at consumer's terminals.
2. The system is very reliable as each distributor is fed *via* *two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained.
   For example, suppose that fault occurs at any point *F* of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers *via* the feeder *SRQPONM*.
3. Size of the conductor required is less
4. Continuity of service can be maintained

Disadvantages

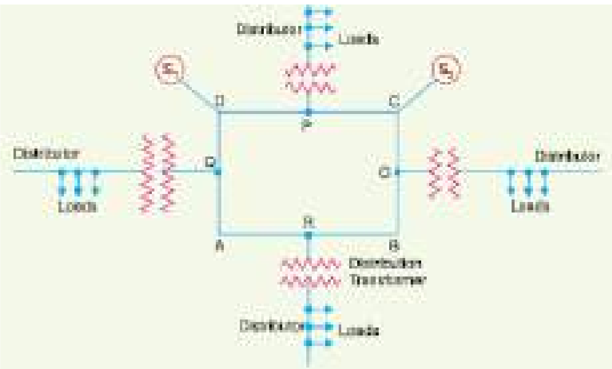
1. When Compared with the radial feeder, the design of ring main system is more complicated
2. Cost of installation is high
3. High Switching equipment is required
4. Difficult to operate.

(*iii*) Interconnected system.

When the feeder ring is energised by two or more than two generating stations or substations, it is called inter-connected system.

Fig. shows the single line diagram of interconnected system where the closed feeder ring *ABCD* is supplied by two substations *S*1 and *S*2 at points *D* and *C* respectively.

Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers.



Advantages

1. It increases the service reliability.
2. Any area fed from one substation during peak load hours can be fed from the other substation. This reduces reserve power capacity and increases efficiency of the system
3. Excellent voltage profile
4. Improved Quality of Service
5. Losses occurring are lower
6. High Efficiency.

Disadvantages

1. High Initial cost
2. Complicated in construction
3. Difficult to operate
4. Switching apparatus required are more
5. Size of the conductor required is very large.

S.No	Radial System	Ring main or Loop type	Interconnected System
1	Most Simple in Construction	Little bit complicated in construction	Highly complicated in construction
2	Low cost	Moderate cost	High cost
3	Very less Reliability	High Reliability	Very High Reliability
4	No continuity of supply	High continuity of supply	Very high continuity of supply
5	The switching equipment required is less	The switching equipment required is high as compared to radial system	The switching equipment required is high as compared to radial system and loop type
6	Very easy in operation	A bit complex in operation as compared to radial system	Highly complex in operation as compared to radial system and loop type

7	Losses occurring are high	Losses occurring are low	Losses occurring are very low
8	Low voltage profile	High voltage profile	Very High voltage profile
9	The size of the conductor required is less	The size of the conductor required is high	The size of the conductor required is very high

COMPARISON OF D.C. AND A.C. DISTRIBUTION:

The electric power can be distributed either by means of d.c. or a.c. Each system has its own merits and demerits.

D.C DISTRIBUTION:

ADVANTAGES:

(i) It requires only two conductors as compared to three for a.c. distribution.

(ii) There is no inductance, capacitance, phase displacement and surge problems in d.c. distribution.

(iii) Due to the absence of inductance, the voltage drop in a d.c. distribution line is less than the a.c. line for the same load and sending end voltage. For this reason, a d.c.distribution line has better voltage regulation.

(iv) There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilized. Skin effect is a tendency for alternating current (AC) to flow mostly near the outer surface of an electrical conductor, such as metal wire.

(v) For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation.

(vi) A d.c. line has less corona loss and reduced interference with communication circuits.

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

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

(vii) The high voltage d.c.distrubution is free from the dielectric losses, particularly in the case of cables.

(viii) In d.c.distrubution, there are no stability problems and synchronising difficulties.

DISADVANTAGES:

(i) Electric power cannot be generated at high d.c. voltage due to commutation problems.

(ii) The d.c. voltage cannot be stepped up for distribution of power at high voltages.

(iii) The d.c. switches and circuit breakers have their own limitations.

A.C. DISTRIBUTION:

ADVANTAGES:

(i) The power can be generated at high voltages.

(ii) The maintenance of a.c. sub-stations is easy and cheaper.

(iii) The a.c. voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

DISADVANTAGES:

(i) An a.c. line requires more copper than a d.c. line.

(ii) The construction of a.c. distrubution line is more complicated than a d.c.distrubution line.
(iii) Due to skin effect in the a.c. system, the effective resistance of the line is increased.
(iv) An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open.

COMPARISON OF D.C. AND A.C. DISTRIBUTION:

S.No	A.C distribution	D.C. distribution
1	3 phase A.C distribution system requires 4 wires	D.C distribution system requires only one wire with the ground as a return path
2	The voltage at the far end is a less i.e. voltage drop in the distributor is more due to the presence of inductance.	The voltage at the far end is more i.e. voltage drop in the distributor is less due to the absence of inductance
3	The efficiency of AC Distribution system is less	The efficiency of DC Distribution system is more
4	due to the presence of inductance voltage regulation is poor	due to the absence of inductance voltage regulation is good
5	cost of erection is more than the D.C system	cost of erection is less than the A.C system
6	3-phase 3 wire and 3-phase 4-wires are the types of AC Distribution system	2-wire and 3-wire are the types of DC Distribution system
7	The a.c. voltage can be stepped up or stepped down by transformers	The d.c. voltage can not be stepped up or stepped down by transformers
8	The maintenance of a.c. sub-stations is easy and cheaper	The maintenance of d.c. sub-stations is not easy and cheaper
9	An a.c. line requires more conductor than a d.c. line	An d.c. line requires less conductor than a.c. line
10	The construction of a.c. distrubution line is more complicated than a d.c.distrubution line	The construction of d.c.distrubution line is less complicated than a a.c. distrubution line
11	Due to skin effect in a a.c. system. the entire cross-section of the line conductor is not utilized	There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilized
12	Due to skin effect in the a.c. system, the effective resistance of the line is increased	Due to no skin effect in the d.c. system, the effective resistance of the line is not increased
13	An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open	An d.c. line has no capacitance. Therefore, there is a no loss of power due to charging current
14	For the same working voltage, the potential stress on the insulation is more in case of a.c. system than that in d.c. system. Therefore, a a.c. line requires more insulation	For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation
15	A a.c. line has increased interference with communication circuits	A d.c. line has reduced interference with communication circuits
16	The high voltage a.c. distrubution is not free from the dielectric losses, particularly in the case of cables.	The high voltage d.c.distrubution is free from the dielectric losses, particularly in the case of cables.
17	In a.c. distrubution, there are some stability problems and synchronising difficulties	In d.c.distrubution, there are no stability problems and synchronising difficulties
18	Electric power can be generated at high d.c.	Electric power cannot be generated at high

	voltage	d.c. voltage due to commutation problems
19	There is inductance, capacitance, phase displacement and surge problems in a.c. distribution	There is no inductance, capacitance, phase displacement and surge problems in d.c. distribution

Requirements of a Distribution System

A considerable amount of effort is necessary to maintain an electric power supply within the requirementsof various types of consumers. Some of the requirements of a good distribution system are:proper voltage, availability of power on demand and reliability.

(*i*) Proper voltage.

One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system.

Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumer's terminals are within Permissible limits.

The statutory limit of voltage variations is ± 6% of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

(*ii*) Availability of Power on demand.

Power must be available to the consumers in any amount that they may require from time to time.

For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company.

As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers.

(*iii*) Reliability.

Modern industry is almost dependent on electric power for its operation.

Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This call for reliable service.

Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable.

However, the reliability can be improved to a considerable extent by

(*a*) Interconnected system (*b*) reliable automatic control system (*c*) providing additional reserve facilities.

Voltage drop and power loss calculations in DC Distributor

Uniformly loaded distributor fed at one end

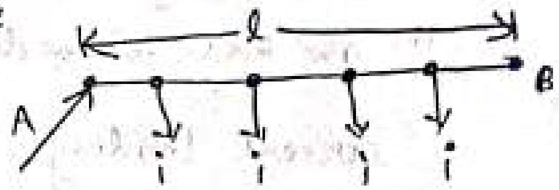
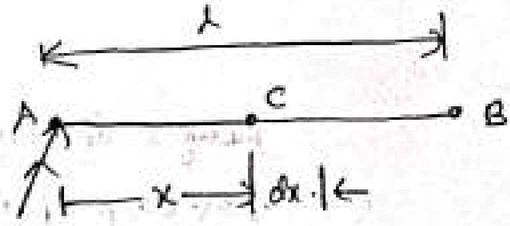


Fig shows single line diagram of a 2-wire dc distributor AB fed at one end A and loaded uniformly with i amps per metre length. i.e at every 1m length of the distributor, the load tapped is i amps.



Let 'l' meters be the length of the distributor and r ohm be the resistance per metre run.

consider at point 'c' on the distributor at a distance 'x' meters from the feeding point 'A' as shown in fig.

The current at point 'c' is $= il - ix$ amps

$= i(l-x)$ amps.

Now, consider small length dx near point 'c'. its resistance is $r\,dx$ and the voltage drop over length 'dx' is

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

total voltage drop in the distributor upto point 'c' is

$$v = \int_0^x ir(l-x)dx = ir\left(lx - \frac{x^2}{2}\right)$$

The total voltage drop upto point 'B' by putting $x = l$ in the above equation

$$v = ir\left(l \times l - \frac{l^2}{2}\right)$$

$$= ir\frac{l^2}{2}$$

$$= \frac{1}{2}(il)(rl)$$

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

, $il \rightarrow$ total current entering at point 'A'

$rl \rightarrow$ total resistance of the conductor.

∴ total load is concentrated at mid point.

Problems

(1) A 2-wire dc distributor 200 m long is uniformly loaded with 2 A/metre. Resistance of single wire is 0.3 Ω/km. If the distributor is fed at one end, calculate,

(a) the voltage drop upto a distance of 150 m from the feeding point.

(b) the max. voltage drop.

Sol)

current loading $i = 2\,A/m$

Resistance of distributor per metre run

$$r = 2 \times \frac{0.3}{1000} = 0.0006\,\Omega \quad (2\text{-wire})$$

Length of distributor $l = 200\,m$.

(a) vol. drop upto distance of 'x' metres from feeding point

$$= ir\left(lx - \frac{x^2}{2}\right)$$

here $x = 150\,m$

$$\text{Desired vol. drop} = 2 \times 0.0006\left[200 \times 150 - \frac{(150)^2}{2}\right]$$

$$= 22.5\,V.$$

(2) total current entering the distributor

$$I = i \times l = 2 \times 200 = 400\,A.$$

Total resistance of the distributor

$$R = r \times l = 0.0006 \times 200 = 0.12\,\Omega$$

Total vol. drop over the distributor

$$= \frac{1}{2} IR = \frac{1}{2} \times 400 \times 0.12 = 24\,V.$$

(2) A 250 m, 2 wire dc distributor fed from one end is loaded uniformly at the rate of 1.6 A/m. The resistance of each conductor is 0.0002 Ω/m. Find the voltage necessary at feed point to maintain 250 V (i) at the far end (ii) at the mid point of the distributor.

Sol)

current loading $i = 1.6\,A/m$

current entering the distributor $I = i \times l = 1.6 \times 250$
$= 400\,A$

Resistance of distributor per metre run $= r = 2 \times 0.0002$
$= 0.0004\,\Omega$

Total resistance $R = r \times l = 0.0004 \times 250 = 0.1\Omega$

(1) voltage drop at the far end.

Voltage drop at far end means voltage drop over the entire distributor

$$= \frac{1}{2} IR = \frac{1}{2} \times 400 \times 0.1 = 20V$$

(2) voltage drop upto distance of x m from the feeding point

$$= ir\left(lx - \frac{x^2}{2}\right)$$

$$x = \text{mid point} = \frac{l}{2} = \frac{250}{2} = 125m$$

$$\text{vol. drop} = 1.6 \times 0.0004 \left(250 \times 125 - \frac{(125)^2}{2}\right)$$

$$= 15V.$$

voltage at the feeding point $= 250V + 15V = 265V$.

Uniformly distributed load fed at both Ends

In this method, There are two cases

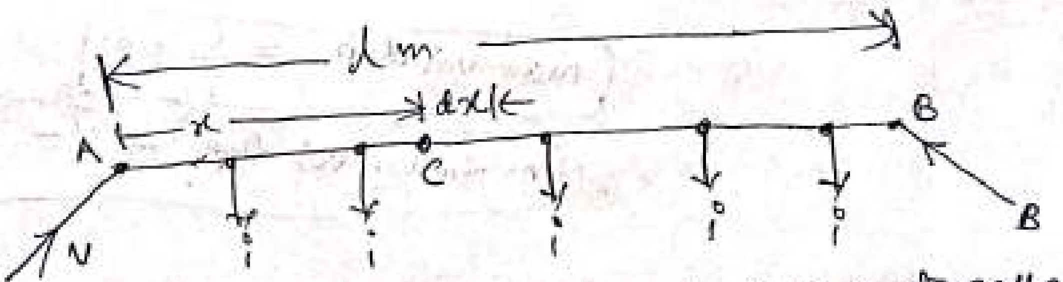
(1) Distributor fed at both ends with equal voltages

(2) Distribution fed at both ends with unequal voltages.

(3) Distribution fed at both ends with equal voltages

(1) Distributor fed at both ends with equal voltages

Consider a distributor AB of length l m, having resistance r Ω per metre run and with uniform loading of i amps per metre run as shown in fig.



Let the distributor be fed at both ends A & B at equal voltages say 'V' volts

Total current supplied to the distributor is il.

As the voltages are equal, current supplied from each feeding point is $\frac{il}{2}$ i.e $= \frac{il}{2}$

consider at point 'c' at a distance 'x' m from the feeding point 'A'

Then current at point 'c' is

$$= \frac{il}{2} - ix = i\left(\frac{l}{2} - x\right)$$

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

$$dv = i\left(\frac{l}{2} - x\right) r\,dx = ir\left(\frac{l}{2} - x\right) dx$$

$\therefore$ voltage drop upto point 'c' $= \int_0^x ir\left(\frac{l}{2} - x\right) dx$

$$= ir\left(\frac{lx}{2} - \frac{x^2}{2}\right)$$

$$= \frac{ir}{2}\left[lx - x^2\right]$$

• At mid point, potential will be minimum. Therefore max. voltage drop will occurs at mid point i.e $x = \frac{l}{2}$

$$\text{max. vol. drop} = \frac{ir}{2}\left(lx - x^2\right)$$

put $x = \frac{l}{2}$

$$\text{max. vol. drop} = \frac{ir}{2}\left(l \cdot \frac{l}{2} - \frac{l^2}{4}\right)$$

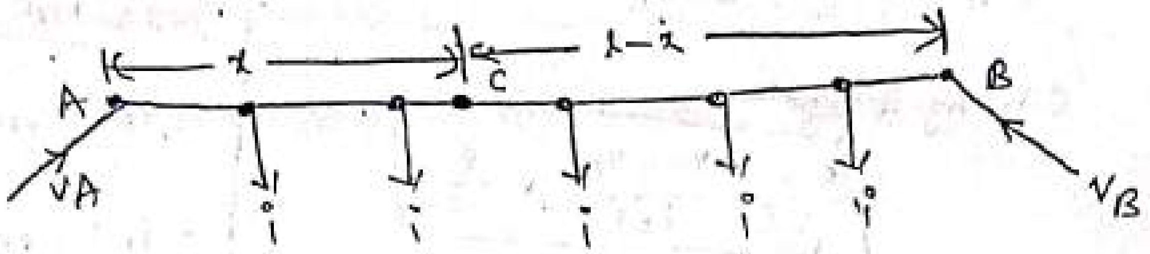
$$= \frac{1}{8}\, irl^2$$

$$= \frac{1}{8}(il)(rl)$$

$$\boxed{\text{max. vol. drop} = \frac{1}{8} IR}$$

$$\boxed{\text{minimum vol. drop} \Rightarrow V - \frac{IR}{8}}$$

Distributor fed at both ends with unequal voltages



Consider a distributor AB of length l m having resistance r Ω/metre run and with a uniform loading of i amps per metre run as shown in fig.

Let the distributor be fed from feeding points A & B of voltages V_A & V_B respectively.

Suppose that the point of minimum potential 'C' is situated at a distance 'x' m from the feeding point 'A'. Then current supplied by the feeding points 'A' will be ix

Voltage drop in section AC = $\int_0^x ix \cdot r$

$$= ir \cdot \frac{x^2}{2} \text{ volts}$$

Distance of 'C' from B is $= (l-x)$

voltage drop in section BC $= \int_0^{(l-x)} i(l-x) \cdot r$

$$= ir \cdot \frac{(l-x)^2}{2} \text{ volts.}$$

Voltage at C, $V_C = V_A -$ drop over AC

$$= V_A - ir\frac{x^2}{2} \quad \text{---(1)}$$

Also, voltage at point 'C' $= V_B -$ drop over BC

$$= V_B - ir\frac{(l-x)^2}{2} \quad \text{---(2)}$$

From eq (1) & (2)

$$V_A - \frac{ir \cdot x^2}{2} = V_B - \frac{ir(l-x)^2}{2}$$

$$V_A - V_B = \frac{irx^2}{2} - \frac{ir}{2}(l^2 + x^2 - 2lx)$$

$$= \frac{irx^2}{2} - \frac{irl^2}{2} - \frac{irx^2}{2} + \frac{2irlx}{2}$$

$$= -\frac{irl^2}{2} + irlx$$

$$= irl\left[-\frac{l}{2} + x\right]$$

$$\frac{V_A - V_B}{irl} = -\frac{l}{2} + x$$

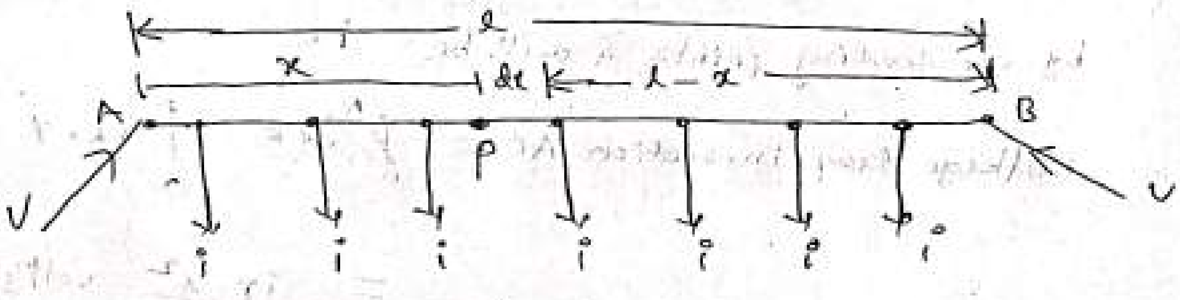
$$x = \frac{V_A - V_B}{irl} + \frac{l}{2}$$

Solving we get

$$\boxed{x = \frac{V_A - V_B}{irl} + \frac{l}{2}}$$

Point on the distributor where min potential occurs.

Expression for the power loss in a uniformly loaded distributor fed at both ends with equal voltages



Consider a distributor AB of length l m, having resistance r Ω/metre run with uniform loading of i amps per metre run as shown in fig.

Let the distributor be fed at the feeding points A & B at equal voltages say 'V' volts.

The total current supplied by the distributor $= il$

As the two end voltages are equal, therefore, current supplied from each feeding point $= \frac{il}{2}$

Consider a small length 'dx' of the distributor at point 'p' which is at a distance 'x' from the feeding end A.

Resistance of length $dx = r.dx$

current in length $dx = \frac{il}{2} - ix$

$$= i\left(\frac{l}{2} - x\right)$$

Power loss in length $dx = (\text{current in } dx)^2 \times$ resistance of dx

$$= \left[i\left(\frac{l}{2} - x\right)\right]^2 \times r.dx$$

Total power loss in the distributor is

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

$$= \int_0^l i^2\left(\frac{l^2}{4} + x^2 - \frac{2lx}{2}\right) r.dx$$

$$= i^2 r\left[\frac{l^2 x}{4} - \frac{lx^2}{2} + \frac{x^3}{3}\right]_0^l$$

$$= i^2 r\left[\frac{l^3}{4} - \frac{l^3}{2} + \frac{l^3}{3}\right]$$

$$= i^2 r\left[\frac{3l^3 - 6l^3 + 4l^3}{12}\right]$$

$$\boxed{P = \frac{i^2 r\, l^3}{12}}$$

Problems

① A two wire dc distributor cable 1000 metres long is loaded with 0.5 A/metre. Resistance of each conductor is 0.05 Ω/km. Calculate the max. voltage drop if the distributor is fed from both ends with equal voltages of 220V. What is the minimum voltage and where it occurs?

Sol: current loading $= i = 0.5\ A/m$

Resistance of distributor/m $r = 2 \times \frac{0.05}{1000} = 0.1 \times 10^{-3}\ \Omega$

Length of distributor $l = 1000\ m$.

Total current supplied by distributor

$$I = il = 0.5 \times 1000 = 500\ A.$$

Total resistance of the distributor, $R = rl$

$$= 0.1 \times 10^{-3} \times 1000$$

$$= 0.1\ \Omega$$

$$\text{max. voltage drop} = \frac{IR}{8} = \frac{500 \times 0.1}{8} = 6.25\ V$$

minimum voltage will occur at the mid point of the distributor and its value is

$$= 220 - 6.25\ V$$

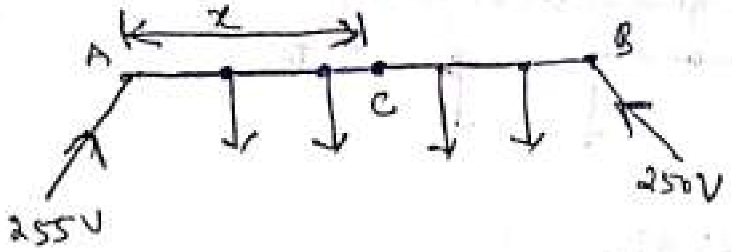
$$= 213.75\ V.$$

② A 2-wire dc distributor AB 500 m long ~~has~~ is fed from both ends and is loaded uniformly at the rate of 1.0 A/m. At feeding point A, the voltage is maintained at 255 V and at B at 250 V. If the resistance of each conductor is 0.1 Ω per km. Determine

(a) the minimum voltage and the point where it occurs

(b) the currents supplied from feeding points A & B.

Sol



Voltage at feeding point A = V_A = 255 V

Voltage at feeding point B V_B = 250 V

Length of the distributor l = 500 m.

current loading i = 1 A/m

r of distributor $r = 2 \times 0.1 \times \frac{1}{1000} = 0.0002\ \Omega$

(1) Let the min potential occur at a point 'C' distant 'x' metres from the feeding point 'A'

$$x = \frac{V_A - V_B}{irl} + \frac{l}{2}$$

$$= \frac{255 - 250}{1 \times 0.0002 \times 500} + \frac{500}{2}$$

$$= 50 + 250 = 300\ m$$

Minimum voltage $V_C = V_A - \frac{irx^2}{2}$

$$= 255 - \frac{1 \times 0.0002 \times (300)^2}{2}$$

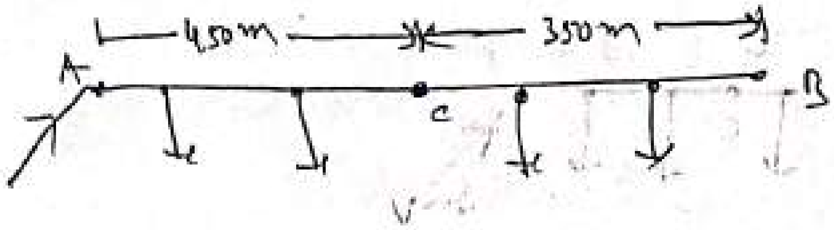
$$= 255 - 9 = 246\ V.$$

(2) current supplied from A = ix = 1×300 = 300 A

current supplied from B = $i(l-x)$ = $1(500-300)$ = 200 A.

(3) A 800 m 2 wire dc distributor AB fed from both ends is uniformly loaded at the rate of 1.25 A/m run. Calculate the voltage at the feeding points A & B if the minimum potential of 220 V occurs at point 'C' at a distance of 450 m from the end A. Resistance of each conductor is 0.05 Ω/km.

sol)



current loading $i = 1.25\,A/m$

r of distributor 1m is $r = \frac{2 \times 0.05}{1000} = 0.0001\,\Omega$

Voltage at C, $V_C = 220\,V$

$l = 800\,m$

Distance of point 'C' from A, $x = 450\,m$

vol. drop in section AC $= \frac{irx^2}{2} = \frac{1.25 \times 0.0001 \times (450)^2}{2}$

$= 12.65\,V$

Voltage at feeding point A, $V_A = 220 + 12.65$

$= 232.65\,V$

vol. drop in section BC $= \frac{ir(l-x)^2}{2} = \frac{1.25 \times 0.0001 \times (800-450)^2}{2}$

$= 7.65\,V$

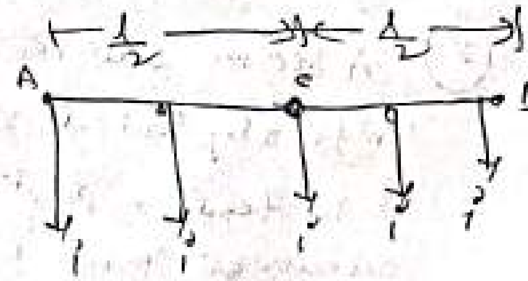
voltage at feeding point B,

$V_B = 220 + 7.65$

$\boxed{V_B = 227.65\,V}$

(4) (i) A uniformly loaded distributor is fed at the centre. Show that maximum vol. drop $= \frac{IR}{8}$.

(ii). A 2 wire dc distributor 1000 m long is fed at the centre and is loaded uniformly at the rate of 1.25 A/m. If the resistance of each conductor is 0.05 Ω/km, Find the maximum vol. drop in the distributor.



sol From the fig; the distributor AB fed at centre 'C' & uniformly loaded with $i\,A/m$.

length $= l$, resistance $= r/m$

max. vol. drop = vol. drop in half distributor

$$= \frac{1}{2}\left(\frac{il}{2}\right)\left(\frac{rl}{2}\right)$$

$$= \frac{1}{8}\,(il)(rl)$$

(il) → Total current of distributor

(rl) → Total resistance of distributor

$$= \frac{1}{8}\,(IR)$$

(2) Total current fed to the distributor is

$$I = il = 1.25 \times 1000 = 1250\,A$$

Total Resistance of distributor

$$R = rl = 2 \times 0.05 \times 1000$$

$$= 100\,\Omega$$

$$\text{max. vol. drop} = \frac{1}{8} IR = \frac{1}{8} \times 1250 \times 100$$

$$= 156.2\,V$$

Expression for the power loss in a uniformly loaded distributor fed at one end

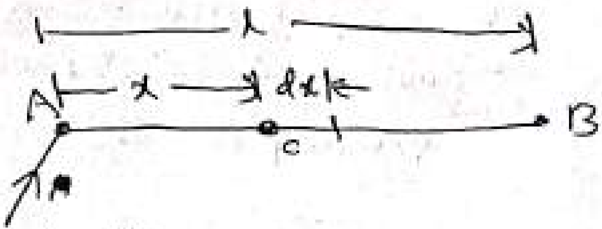


Fig shows single line diagram of a 2-wire dc distributor AB fed at one end 'A' and loaded uniformly with 'i' amps per metre length.

Let ⇒ l = length of the distributor in metres

r = resistance of distributor (both conductors)

consider a small length 'dx' of the distributor at point 'c' at a distant 'x' from the feeding point 'A'

The small length 'dx' will carry current in the length CB.

$$\text{current in } dx = il - ix$$

$$= i(l-x)$$

Power loss in length dx $= [i(l-x)]^2 \times r\,dx$

Total power loss of distributer

$$P_L = \int_0^l (i(l-x))^2 \cdot r\,dx$$

$$= \int_0^l i^2(l^2+x^2-2lx)\, r \cdot dx$$

$$= i^2 r\left[l^2 x + \frac{x^3}{3} - 2l\frac{x^2}{2}\right]_0^l$$

$$= i^2 r\left[l^3 + \frac{l^3}{3} - l^3\right]$$

$$\boxed{P_L = \frac{i^2 r l^3}{3}}$$

⇒ calculate the voltage at a distance of 200 m of a 300 m long distributer uniformly loaded at the rate of 0.75 A per metre. The distributer is fed at one end at 250 V. The resistance of the distributer (go & return) per metre is 0.00018 Ω. Also find power loss in the distributer?

Sol: vol. drop at a distance 'x' from supply end

$$= ir\left(lx - \frac{x^2}{2}\right)$$

$$= 0.75 \times 0.00018\left[300 \times 200 - \frac{(200)^2}{2}\right]$$

$$= 5.4\,V$$

∴ voltage at a distance of 200 m from supply end

$$\Rightarrow 250 - 5.4 = 244.6\,V$$

Power loss in the distributer is

$$P = \frac{i^2 r l^3}{3} = \frac{(0.75)^2 \times 0.00018 \times (300)^3}{3}$$

$$= 911.25\,W$$

Design Considerations of Distribution System

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers.

For this purpose, design of feeders and distributors requires careful consideration.

(*i*) *Feeders.* A feeder is designed from the point of view of its **current carrying capacity** while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.
(*ii*) *Distributors.* A distributor is designed from the point of view of the **voltage drop** in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals (± 6% of rated value).

Primary feeder loading

The process of loading a feeder during a peak load condition as measured at a substation is known as Primary feeder loading.

Factors affecting Primary feeder loading in terms of **Design**

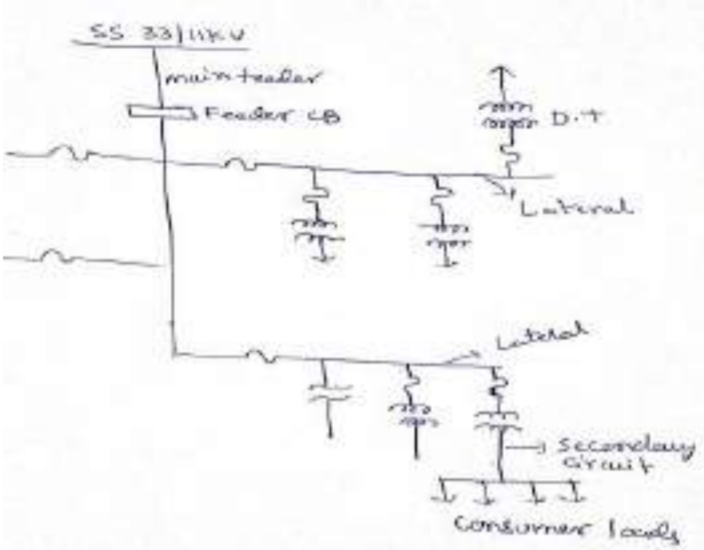
1. The density of the feeder
2. The nature of load on feeder
3. The growth rate of feeder
4. The reserve capacity requirement in case of emergency
5. The continuity requirement of service
6. The service reliability of requirement
7. The quality of service
8. The primary feeder voltage level
9. The cost and type of construction
10. The capacity of distribution substation
11. The location of substation
12. The voltage regulation requirements
13. Size of the conductor
14. Selected no.of feeders
15. Feeder rating

Factors affecting Primary feeder loading in terms of **Decisions for feeder routing**

The various factors affecting the loading when decisions for feeder routing considered are

1. The voltage drops in feeder
2. The way of development patterns
3. The economy of the feeder
4. The type of physical barriers usage
5. Increasing growth rate of load
6. The type of the feeders used.

Basic Design Practice of the Secondary Distribution System



The part of electrical distribution system which is between the primary system and the consumer's property is called Secondary distribution system.

The Secondary distribution system includes step down transformers, secondary circuits and consumer services and meters to measure consumer's energy consumption.

Design Practices of Secondary distribution system

The Secondary distribution systems are designed in 1-phase for residential customers and 3-phase for industrial or commercial customers with high load density and also include

1. The separate service system for each consumer with separate distribution transformer and secondary system
2. The radial system with common secondary main which is supplied by one distribution system and feeding a group of consumers
3. The secondary bank system, with the common secondary main that is supplied by several distribution transformers which are all fed by the same primary feeder
4. The secondary network system having a common grid type main that is supplied by a large number of distribution transformers that may connected to various feeders.

Voltage Drop Calculations (Numerical Problems) in A.C.Distributors

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

(*i*) In case of d.c. system, the voltage drop is due to resistance alone. However, in a.c. system, the voltage drops are due to the combined effects of resistance, inductance and capacitance.
(*ii*) In a d.c. system, additions and subtractions of currents or voltages are done arithmetically but in case of a.c. system, these operations are done vectorially.
(*iii*) In an a.c. system, power factor (p.f.) has to be taken into account. Loads tapped off form the distributor are generally at different power factors. There are two ways of referring power factor *viz*
(*a*) It may be referred to supply or receiving end voltage which is regarded as the reference vector.
(*b*) It may be referred to the voltage at the load point itself.

There are several ways of solving a.c. distribution problems. However, symbolic notation method has been found to be most convenient for this purpose. In this method, voltages, currents and impedances are expressed in complex notation and the calculations are made exactly as in d.c. distribution.

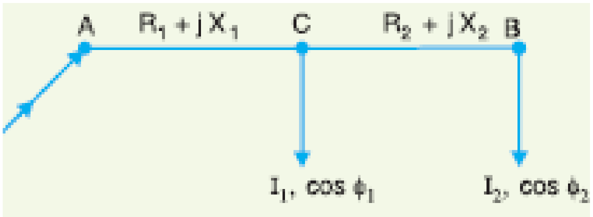
Voltage Drop Calculations (Numerical Problems) In A.C.Distributors are of two types

In a.c. distribution calculations, power factors of various load currents have to be considered sincecurrents in different sections of the distributor will be the vector sum of load currents and not thearithmetic sum. The power factors of load currents may be given

1. With Respect to Receiving End Voltage
2. With Respect to Respective Load Voltages

1. Power Factors with respected to Receiving End Voltage:

Consider an a.c. distributor *AB* with concentrated loads of *I*1 and *I*2 tapped off at points *C* and *B* as shown in Fig. Taking the receiving end voltage V_B as the reference vector, let lagging power factors at *C* and *B* be cos φ1 and cos φ2 *w.r.t.* V_B. Let *R*1, *X*1 and *R*2, *X*2 be the resistance and reactance of sections *AC* and *CB* of the distributor.



$$\text{Impedance of section } AC, \quad \overrightarrow{Z_{AC}} = R_1 + j X_1$$

$$\text{Impedance of section } CB, \quad \overrightarrow{Z_{CB}} = R_2 + j X_2$$

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

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

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

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

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

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

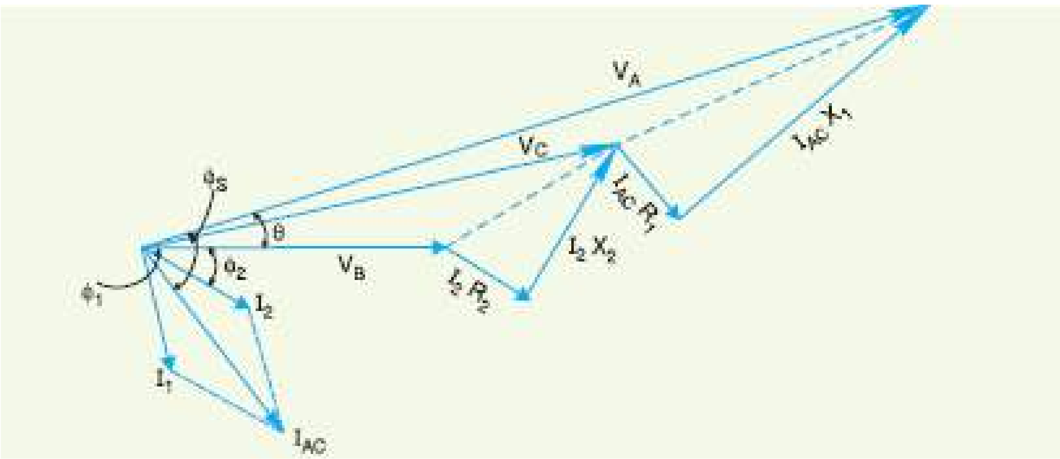
$$\text{Voltage drop in section } AC, \quad \overrightarrow{V_{AC}} = \overline{I_{AC}}\,\overline{Z_{AC}} = \left(\overline{I_1} + \overline{I_2}\right) Z_{AC}$$

$$= [I_1(\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)]\,[R_1 + jX_1]$$

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

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

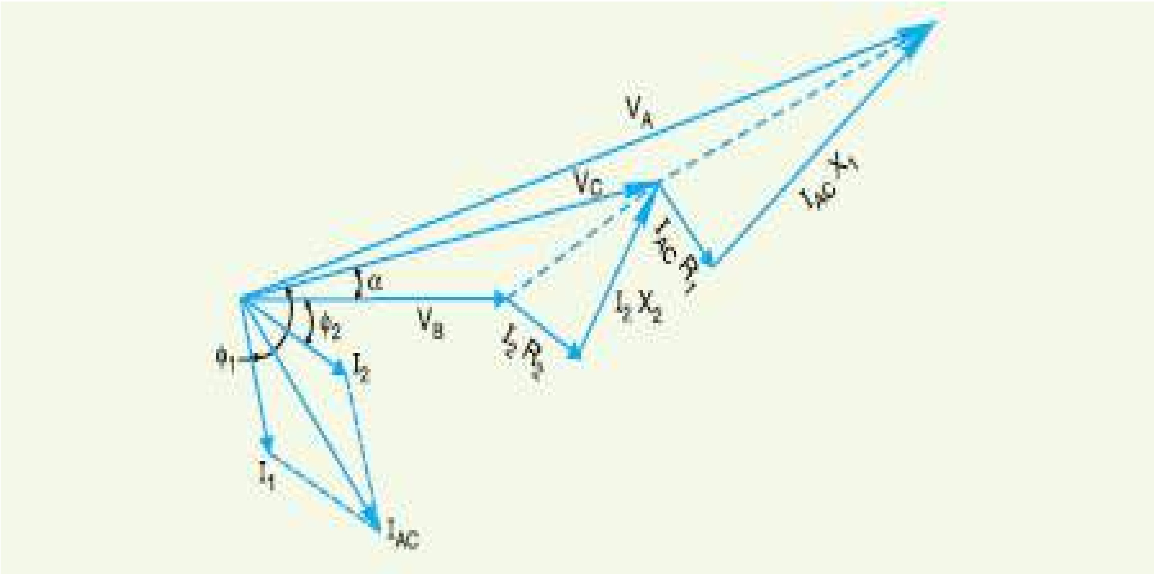
Phasor diagram shown below

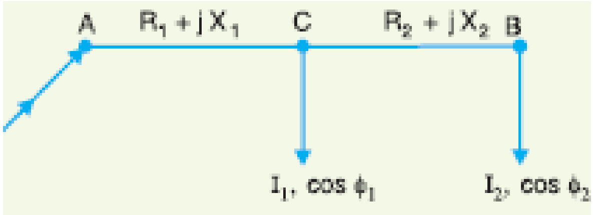


The vector diagram of the a.c. distributor under these conditions is shown in above Fig. Here, thereceiving end voltage $V_B$is taken as the reference vector. As power factors of loads are given *w.r.t.*V_B, therefore, $I1$ and $I2$ lag behind $V_B$by φ1 and φ2 respectively.

Power factors referred to respective load voltages

Suppose the power factors of loads in the previous Fig. are referred to their respective load voltages. Then φ1 is the phase angle between *VC* and *I*1 and φ2 is the phase angle between *VB* and *I*2. The vector diagram under these conditions is shown in Fig.





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

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

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

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

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

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

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

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

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

Problems

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

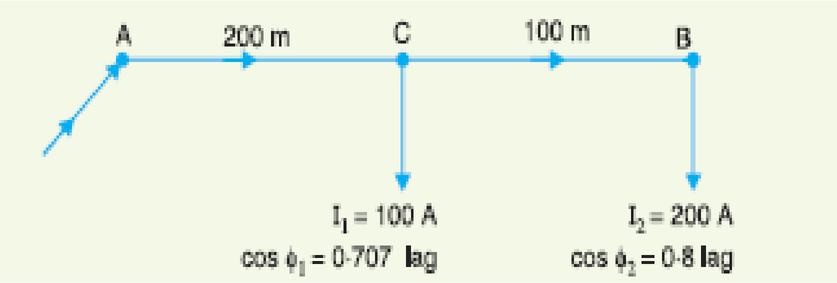
(*i*) *100 A at 0·707 p.f. lagging 200 m from point A*

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

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

Solution:

Fig shows the single line diagram of the distributor.



Impedance of distributor/km = $(0{\cdot}2 + j\,0{\cdot}1)$

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

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

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

Load current at point B, $\vec{I}_2 = I_2(\cos\phi_2 - j\sin\phi_2) = 200\,(0{\cdot}8 - j\,0{\cdot}6)$
$= (160 - j\,120)$ A

Load current at point C, $\vec{I}_1 = I_1(\cos\phi_1 - j\sin\phi_1) = 100\,(0{\cdot}707 - j\,0{\cdot}707)$
$= (70{\cdot}7 - j\,70{\cdot}7)$ A

Current in section CB, $\vec{I}_{CB} = \vec{I}_2 = (160 - j\,120)$ A

Current in section AC, $\vec{I}_{AC} = \vec{I}_1 + \vec{I}_2 = (70{\cdot}7 - j\,70{\cdot}7) + (160 - j\,120)$
$= (230{\cdot}7 - j\,190{\cdot}7)$ A

Voltage drop in section CB, $\vec{V}_{CB} = \vec{I}_{CB}\,\vec{Z}_{CB} = (160 - j\,120)\,(0{\cdot}02 + j\,0{\cdot}01)$
$= (4{\cdot}4 - j\,0{\cdot}8)$ volts

Voltage drop in section AC, $\vec{V}_{AC} = \vec{I}_{AC}\,\vec{Z}_{AC} = (230{\cdot}7 - j\,190{\cdot}7)\,(0{\cdot}04 + j\,0{\cdot}02)$
$= (13{\cdot}04 - j\,3{\cdot}01)$ volts

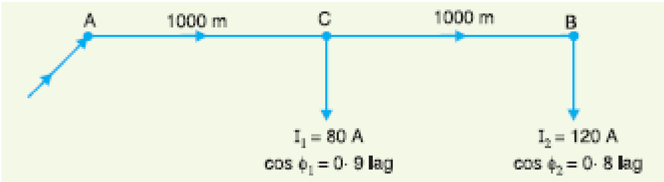
Voltage drop in the distributor $= \vec{V}_{AC} + \vec{V}_{CB} = (13{\cdot}04 - j\,3{\cdot}01) + (4{\cdot}4 - j\,0{\cdot}8)$
$= (17{\cdot}44 - j\,3{\cdot}81)$ volts

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

2) A single phase distributor 2 kilometres long supplies a load of 120 A at 0·8 p.f.lagging at its far end and a load of 80 A at 0·9 p.f. lagging at its mid-point. Both power factors are referred to the voltage at the far end. The resistance and reactance per km (go and return) are0·05 Ω and 0·1 Ω respectively. If the voltage at the far end is maintained at 230 V, calculate:
(i) voltage at the sending end
(ii) phase angle between voltages at the two ends.

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

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



Impedance of section *AC*, Z_{AC}= (0·05 + *j* 0·1) × 1000/1000 = (0·05 + *j* 0·1) Ω

Impedance of section *CB*, Z_{CB}= (0·05 + *j* 0·1) × 1000/1000 = (0·05 + *j* 0·1) Ω

Let the voltage VB at point B be taken as the reference vector.
Then, VB = 230 + j 0

(i) Load current at point B (I_2)= 120 (0·8 − j 0·6) = 96 − j 72

Load current at point C, (I_1)= 80 (0·9 − j 0·436) = 72 − j 34·88

Current in section CB, I_{CB}= I2 = 96 − j 72

Current in section AC (I_{AC}) = I_I+ 1_2 = (72 − j 34·88) + (96 − j 72)= 168 − j 106·88

Drop in section CB, VCB = ICB ZCB = (96 − j 72) (0·05 + j 0·1)= 12 + j 6

Drop in section AC, VAC = IAC ZAC = (168 − j 106·88) (0·05 + j 0·1)= 19·08 + j 11·45

∴ Sending end voltage, VA = VB + VCB + VAC= (230 + j 0) + (12 + j 6) + (19.08 + j 11.45)

= 261.08 + j 17.45

Its magnitude is = $\sqrt{(261\cdot08)^2 + (17\cdot45)^2}$ =261.67 V

(ii) The phase difference θ between *VA* and *VB* is given by :

$$\tan\theta = \frac{17.45}{261.08} = 0\cdot0668$$

∴ θ= tan−1 0·(0668) = **3·82º**

3) A single phase distributor one km long has resistance and reactance per conductorof 0·1 Ω and 0·15 Ω respectively. At the far end, the voltage VB = 200 V and the current is 100A at a p.f. of 0·8 lagging. At the mid-point M of the distributor, a current of 100 A is tapped at a p.f.of 0·6 lagging with reference to the voltage VM at the mid-point. Calculate :

(i) voltage at mid-point

(ii) sending end voltage VA

(iii) phase angle between VA and VB

Solution:

Fig. shows the single line diagram of the distributor *AB* with *M* as the mid-point.

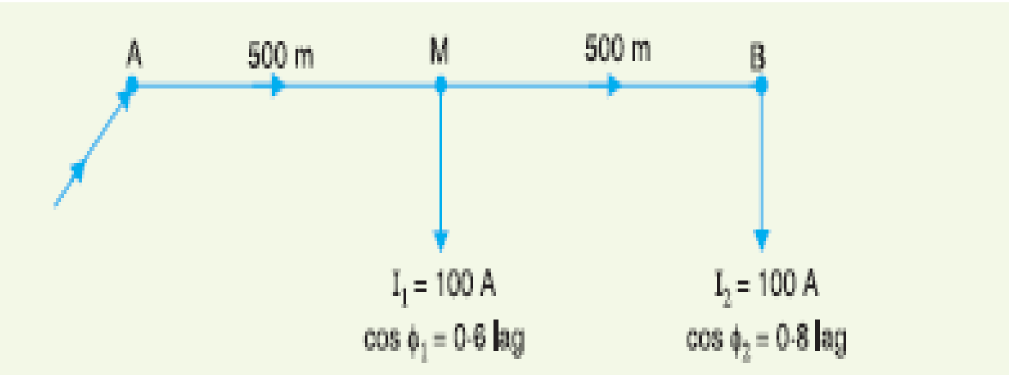
Total impedance of distributor = 2(0·1 + j 0·15) = (0·2 + j 0·3) Ω

Impedance of section *AM*, Z_{AM} = (0·1 + j 0·15) Ω

Impedance of section *MB*, Z_{MB} = (0·1 + j 0·15) Ω

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

Then, $V_B = 200 + j\,0$



(*i*) Load current at point *B*, $\vec{I_2} = 100\,(0{\cdot}8 - j\,0{\cdot}6) = 80 - j\,60$

Current in section *MB*, $\overrightarrow{I_{MB}} = \vec{I_2} = 80 - j\,60$

Drop in section *MB*, $\overrightarrow{V_{MB}} = \overrightarrow{I_{MB}}\;\overrightarrow{Z_{MB}}$

$= (80 - j\,60)\,(0{\cdot}1 + j\,0{\cdot}15) = 17 + j\,6$

∴ Voltage at point *M*, $\overrightarrow{V_M} = \vec{V_B} + \overrightarrow{V_{MB}} = (200 + j\,0) + (17 + j\,6)$

$= 217 + j\,6$

Its magnitude is $= \sqrt{(217)^2 + (6)^2} = $ **217·1 V**

Phase angle between V_M and V_B, $\alpha = \tan^{-1} 6/217 = \tan^{-1} 0{\cdot}0276 = 1{\cdot}58°$

(ii) The load current I_1 has a lagging p.f. of 0·6 w.r.t. V_M. It lags behind V_M by an angle $\phi_1 = \cos^{-1} 0{\cdot}6 = 53{\cdot}13°$

$\therefore$ Phase angle between I_1 and V_B, $\phi'_1 = \phi_1 - \alpha = 53{\cdot}13° - 1{\cdot}58 = 51{\cdot}55°$

Load current at M, $\vec{I_1} = I_1 (\cos \phi_1' - j \sin \phi_1') = 100 (\cos 51{\cdot}55° - j \sin 51{\cdot}55°)$
$= 62{\cdot}2 - j\, 78{\cdot}3$

Current in section AM, $\vec{I_{AM}} = \vec{I_1} + \vec{I_2} = (62{\cdot}2 - j\, 78{\cdot}3) + (80 - j\, 60)$
$= 142{\cdot}2 - j\, 138{\cdot}3$

Drop in section AM, $\vec{V_{AM}} = \overline{I_{AM}}\, \overline{Z_{AM}} = (142{\cdot}2 - j\, 138{\cdot}3)(0{\cdot}1 + j\, 0{\cdot}15)$
$= 34{\cdot}96 + j\, 7{\cdot}5$

Sending end voltage, $\vec{V_A} = \vec{V_M} + \vec{V_{AM}} = (217 + j\, 6) + (34{\cdot}96 + j\, 7{\cdot}5)$

$= 251{\cdot}96 + j\, 13{\cdot}5$

Its magnitude is $= \sqrt{(251{\cdot}96)^2 + (13{\cdot}5)^2} = 252{\cdot}32$ V

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

$\tan \theta = 13{\cdot}5/251{\cdot}96 = 0{\cdot}05358$

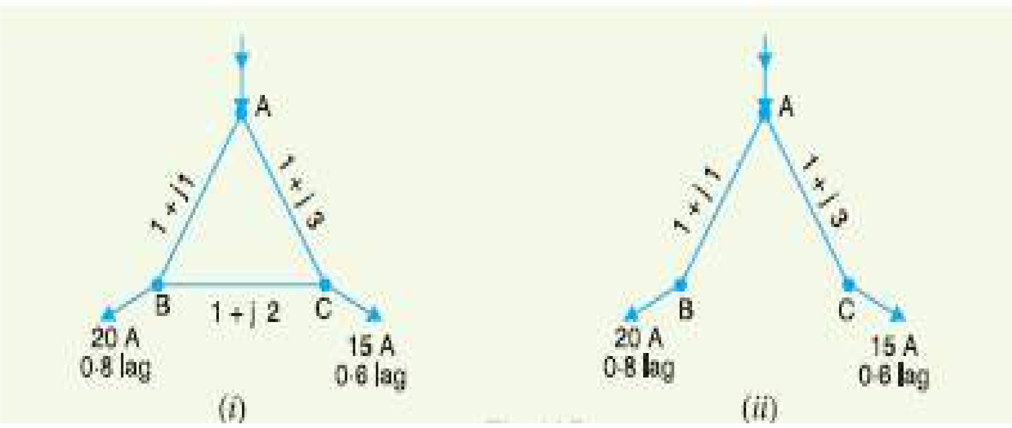
$\therefore$ $\theta = \tan^{-1} 0{\cdot}05358 = 3{\cdot}07°$

Hence supply voltage is 252·32 V and leads V_B by 3·07°.

4) A single phase ring distributor ABC is fed at A. The loads at B and C are 20 Aat 0.8 p.f. lagging and 15 A at 0.6 p.f. lagging respectively ; both expressed with reference to thevoltage at A. The total impedance of the three sections AB, BC and CA are (1 + j 1), (1+ j2) and(1 + j3) ohms respectively. Find the total current fed at A and the current in each section. UseThevenin's theorem to obtain the results

Solution:

Fig (*i*) shows the ring distributor *ABC*. Thevenin's theorem will be used to solvethis problem. First, let us find the current in *BC*. For this purpose, imagine that section *BC* is removed as shown in Fig. (*ii*).



Referring to Fig. (ii), we have,

Current in section AB = 20 (0·8 + j 0.6) = 16 + j 12

Current in section AC = 15 (0·6 + j 0·8) = 9 + j 12

Voltage drop in section AB = (16 + j 12) (1 + j1) = 28 + j 4

Voltage drop in section AC = (9 + j 12) (1 + j 3) = 45 + j 15

Obviously, point B is at higher potential than point C. The p.d. between B and C is Thevenin's equivalent circuit e.m.f. E_0 i.e.

Thevenin's equivalent circuit e.m.f., E_0 = p.d. between B and C

= (45 + j 15) + (28 + j 4) = 17 + j 11

Thevenin's equivalent impedance Z_0 can be found by looking into the network from points B and C. Obviously, Z_0 = (1 + j1) + (1 + j 3) = 2 + j4 Ω

$$\text{Current in } BC = \frac{E_0}{Z_0 + \text{Impedance of } BC}$$

$$= \frac{17 + j11}{(2 + j4) + (1 + j2)} = \frac{17 + j11}{3 + j6}$$

$$= 2{\cdot}6 - j\,1{\cdot}53 = 3\angle -30{\cdot}48^\circ \text{ A}$$

$$\text{Current in } AB = (16 - j\,12) + (2{\cdot}6 - j\,1{\cdot}53)$$

$$= 18{\cdot}6 - j\,13{\cdot}53 = 23\angle -36{\cdot}03^\circ \text{ A}$$

$$\text{Current in } AC = (9 - j\,12) - (2{\cdot}6 - j\,1{\cdot}53)$$

$$= 6{\cdot}4 - j\,10{\cdot}47 = 12{\cdot}27\angle -58{\cdot}56^\circ \text{ A}$$

$$\text{Current fed at } A = (16 - j\,12) + (9 - j\,12)$$

$$= 25 - j\,24 = 34{\cdot}65\angle -43{\cdot}83^\circ \text{ A}$$

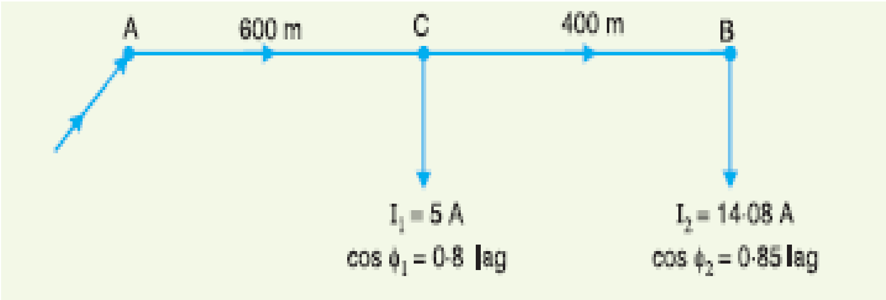
5) A 3-phase, 400V distributor AB is loaded as shown in Fig.14.8. The 3-phaseload at point C takes 5A per phase at a p.f. of 0·8 lagging. At point B, a 3-phase, 400 V inductionmotor is connected which has an output of 10 H.P. with an efficiency of 90% and p.f. 0·85 lagging.If voltage at point B is to be maintained at 400 V, what should be the voltage at point A ? Theresistance and reactance of the line are 1Ω and 0·5Ω per phase per kilometre respectively.

Solution:

It is convenient to consider one phase only. Fig.shows the single line diagram ofthe distributor. Impedance of the distributor per phase per kilometre = (1 + j 0·5) Ω.

Impedance of section AC, Z_{AC} = (1 + j 0·5) · 600/1000 = (0·6 + j 0·3) Ω

Impedance of section CB, Z_{CB} = (1 + j 0·5) · 400/1000 = (0·4 + j 0·2) Ω



Phase voltage at point B, $V_B = 400/\sqrt{3} = 231$ V

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

Then, $\vec{V_B} = 231 + j\,0$

Line current at B $= \dfrac{\text{H.P.} \times 746}{\sqrt{3} \times \text{line voltage} \times \text{p.f.} \times \text{efficiency}}$

$= \dfrac{10 \times 746}{\sqrt{3} \times 400 \times 0.85 \times 0.9} = 14.08$ A

$\therefore$ *Current/phase at B, $I_2 = 14.08$ A

Load current at B, $\vec{I_2} = 14.08\,(0.85 - j\,0.527) = 12 - j\,7.4$

Load current at C, $\vec{I_1} = 5\,(0.8 - j\,0.6) = 4 - j\,3$

Current in section AC, $\vec{I_{AC}} = \vec{I_1} + \vec{I_2} = (4 - j\,3) + (12 - j\,7.4)$

$= 16 - j\,10.4$

Current in section CB, $\vec{I_{CB}} = \vec{I_2} = 12 - j\,7.4$

Voltage drop in CB, $\vec{V_{CB}} = \vec{I_{CB}}\vec{Z_{CB}} = (12 - j\,7.4)\,(0.4 + j\,0.2)$

$= 6.28 - j\,0.56$

Voltage drop in AC, $\vec{V_{AC}} = \vec{I_{AC}}\vec{Z_{AC}} = (16 - j\,10.4)\,(0.6 + j\,0.3)$

$= 12.72 - j\,1.44$

Voltage at A per phase, $\vec{V_A} = \vec{V_B} + \vec{V_{CB}} + \vec{V_{AC}}$

$= (231 + j\,0) + (6.28 - j\,0.56) + (12.72 - j\,1.44)$

$= 250 - j\,2$

Magnitude of V_A/phase $= \sqrt{(250)^2 + (2)^2} = 250$ V

$\therefore$ Line voltage at A $= \sqrt{3} \times 250 = 433$ V

SUBSTATIONS

Location of Substations: Rating of Distribution Substation, Service Area within PrimaryFeeders. Benefits Derived Through Optimal Location of Substations.

Classification of Substations: Air Insulated Substations - Indoor & Outdoor Substations: Substation Layout showing the Location of all the Substation Equipment.

Sub-Station

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

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

(i) It should be located at a proper site. As far as possible, it should be located nearer to load centre to reduce transmission losses and cost of distribution system.
(ii) It should provide safe and reliable arrangement. For safety, consideration must be given to the maintenance of regulation clearances, facilities for carrying out repairs and maintenance, abnormal occurrences such as possibility of explosion or fire etc. For reliability, consideration must be given for good design and construction, the provision of suitable protective gear etc.

(iii) It should be easily operated and maintained.

(iv) Itshould involve minimum capital cost.

(v) Control cables should be separated from power cables.

(vi) For oil handling purpose, adequate arrangement should be made.

Location of Substations

Factors affecting substation

Generally the continuity of supply is based on effective operation of the substation, therefore selection and location of site for substation requires more careful consideration. The following factors are to be considered, while locating site for substation.

1. **Substation type**: Depending upon the type of substation, proper site is selected.
   - Different substations are located at different sites based on the requirements such as step up substation is located closed to the generating station to reduce the transmission line losses

   - Whereas step down substation is to be located close to the load centre to minimize the transmission line losses to achieve better reliability of supply.

2. **Availability of land:** The availability of enough land for substation is veryimportant**.** The land opted for a substation must fulfil following requirements.
   a. The land must be level and open from all sides
   b. The land must be free from water logged specially in rainy seasons.
   c. The land or site must not be selected at the places which are closer to shooting practice grounds, aerodrome etc,.

  d. Without any obstruction the transmission lines must be able to approach and take off to the site selected for substation.

3. **Communication and Transportation facility:**The land selected should besuch that during and after installation or construction of building of substation, there should be no communication problems. So if site is selected on road side then the transportation will be very much easier and expenditure incurred is also be very less.
4. **Atmospheric Pollution:**The site selected should be free from Atmospheric Pollution. The places near factories, sea coasts should not be selected as the air around factories produces harmful gases which are not suitable for proper functioning of the power system.
5. **Availability of basic facilities:** The basic facilities like school, hospital, housing, water should be available for the staff.
6. **Drainage facility:** The site selected for substation should have proper drainage facility so that it does not lead to pollution and growth of unwanted micro-organisms which are harmful to the health of staff and equipment.
7. **Expenditure & cost:** The site selected for substation should be of low cost and it should involve minimum expenditure for its construction.

Rating of Substation:

The rating of the substation is decided based on the following factors

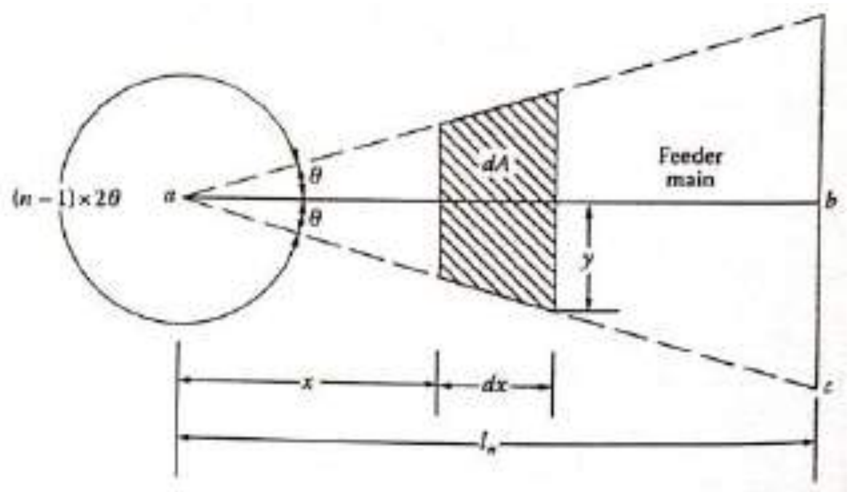
a. The nature of the load connected
b. The load density of the area fed through the substation
c. The rate of growth in load
d. The type of design adopted for the substation
e. The type of equipment employed in the substation
f. The quality of service to be provided
g. The number of feeders leaving the substation
h. The different primary feeder voltages.

Calculation of Rating of Substation with "n" feeders

Or

Expression for distribution substation service area with in primary feeders and also total kVA load served by one of the "n" feeders

The service area of the substation with "n" number of feeders shown in the fig.



From the fig, the following relationship exits

Tanθ = $\frac{y}{x+dx}$ (1)

y= (x+dx)Tanθ

≡ xXtanθ (2)

The total service area of the feeder can be calculated as

$A_n = \int_{x=0}^{l_n} dA$

$= l^2{}_n$*tanθ (3)

The total kilovolt ampere load served by one of n feeders can be calculated as

$S_n = \int_{x=0}^{l_n} dS$

= D* $l^2{}_n$* tanθ (4)

This total load is located, as a lump sum load, at a point on the main feeder at a distance of (2/3)*l_n

From the feed point a. Hence, the summation of the percent voltage contributions of all such area is

$\%VD_n = \frac{2}{3} * l_n * K * S_n$ (5)

Substitute eq(4) in eq(5) gives

$\%VD_n = \frac{2}{3} * l^3_n * K * \tan\theta * D$ (6)

From the fig

$N(2\theta) = 360^0$ (7)

Substitute eq (7) in eq (6)

the percent voltage drop in the **"n"** feeders is

$\%VD_n = \frac{2}{3} * l^3_n * K * D * \tan\frac{360^0}{2n}$ (8)

Eq (7) and (8) only applicable $n \geq 3$.

For n=1, the percent voltage drop in the feeder main is

$\%VD_n = \frac{2}{3} * l^3_n * K * D$ (9)

For n=2

$\%VD_n = \frac{2}{3} * l^3_n * K * D$ (10)

Comparison between Four and six feeder patterns of substation service area if they are thermally loaded and VDL

For a square shaped distribution substation area served by four primary feeders, i.e n=4, the area served by one of the four feeders is

$A_4 = l_4^2 \text{ mi}^2$ (1)

The total area served by all four feeders is

$$TA_4 = 4A_4 = 4l_4^2 \text{ mi}^2 \quad (2)$$

The kilovolt-ampere load served by one of the feeders is

$$S_4 = D \times l_4^2 \text{ kVA} \quad (3)$$

Thus, the total kilovolt-ampere load served by all four feeders is

$$TS_4 = 4D \times l_4^2 \text{ kVA} \quad (4)$$

The percent voltage drop in the main feeder is

$$\%\mathrm{VD}_{4,\mathrm{main}} = \frac{2}{3} \times K \times D \times l_4^3 \qquad (5)$$

The load current in the main feeder at the feed point *a* is

$$I_4 = \frac{S_4}{\sqrt{3} \times V_{L-L}} \qquad (6)$$

or

$$I_4 = \frac{D \times l_4^2}{\sqrt{3} \times V_{L-L}} \qquad (7)$$

The ampacity, that is, the current-carrying capacity, of a conductor selected for the main feeder should be larger than the current values that can be obtained from Equations 6 & 7

On the other hand, for a hexagonally shaped distribution substation area served by six primary feeders, that is, $n = 6$, the area served by one of the six feeders is

$$A_6 = \frac{1}{\sqrt{3}} \times l_6^2 \text{ mi}^2 \qquad (8)$$

The total area served by all six feeders is

$$TA_6 = \frac{6}{\sqrt{3}} \times l_6^2 \text{ mi}^2 \qquad (9)$$

The kilovolt-ampere load served by one of the feeders is

$$S_6 = \frac{1}{\sqrt{3}} D \times l_6^2 \text{ kVA} \qquad (10)$$

Therefore, the total kilovolt-ampere load served by all six feeders is

$$TS_6 = \frac{6}{\sqrt{3}} \times D \times l_6^2 \text{ kVA} \qquad (11)$$

The percent voltage drop in the main feeder is

$$\%\mathrm{VD}_{6,\mathrm{main}} = \frac{2}{3\sqrt{3}} \times K \times D \times l_6^3 \qquad (12)$$

The load current in the main feeder at the feed point *a* is

$$I_6 = \frac{S_6}{\sqrt{3} \times V_{L-L}} \qquad (13)$$

or

$$I_6 = \frac{D \times l_6^2}{3 \times V_{L-L}} \qquad (14)$$

The relationship between the service areas of the four- and six-feeder patterns can be found under two assumptions: (1) feeder circuits are thermally limited (TL) and (2) feeder circuits are voltage-drop-limited (VDL).

1. *For TL feeder circuits*: For a given conductor size and neglecting voltage drop,

$$I_4 = I_6 \qquad (15)$$

Substitute eq (7) & (14) into eq (15)

$$\frac{D \times l_4^2}{\sqrt{3} \times V_{L-L}} = \frac{D \times l_6^2}{3 \times V_{L-L}} \qquad (16)$$

Simplifying eq (16)

$$\left(\frac{l_6}{l_4}\right)^2 = \sqrt{3} \qquad (17)$$

Also, dividing eq (9) by eq (2)

$$\frac{TA_6}{TA_4} = \frac{6/\sqrt{3}l_6^2}{4l_4^2}$$

$$= \frac{\sqrt{3}}{2}\left(\frac{l_6}{l_4}\right)^2 \qquad (18)$$

Substitute eq (17) into eq(18)

$$\frac{TA_6}{TA_4} = \frac{3}{2} \qquad (19)$$

or

$$TA_6 = 1.50 TA_4$$

Therefore, the six feeders can carry 1.50 times as much load as the four feeders if they are thermally loaded.

2. For VDL feeder circuits: For a given conductor size and assuming equal percent voltage drops

$$\%VD_4 = \%VD_6 \qquad (20)$$

Substitute eq (5) & (12) in eq (20)

$$l_4 = 0.833 \times l_6 \qquad (21)$$

From eq (9), the total area served by all six feeders is

$$TA_6 = \frac{6}{\sqrt{3}} \times l_6^2 \qquad (22)$$

Substitute eq (21) into (2), the total area served by all four feeders is

$$TA_4 = 2.78 \times l_6^2 \qquad (23)$$

Dividing eq (22) by eq (23)

$$\frac{TA_6}{TA_4} = \frac{5}{4} \qquad (24)$$

or

$$TA_6 = 1.25 TA_4 \qquad (25)$$

Therefore, the six feeders can carry only 1.25 times as much load as the four feeders if they are VDL.

Benefits derived through the optimal location of substations

Optimal location of substation is necessary to reduce the cost and service interruptions. The following benefits are obtained from the optimal location of the substation.

1. Design of substation becomes cheap, simple and feasible.
2. The substation is very close to the load center of its service area.
3. Capital cost is low.
4. The product of kVA and the distance is minimum.
5. Voltage regulation is improved.
6. When future loads are added the access for the incoming and outgoing feeders is good.
7. Voltage regulation requirement at the farthest load point are satisfied.
8. The number of customers effected by the service outage is less due to the possibility of alternate supply arrangements.
9. Enough space for the future substation expansion is alloted i.e., extension of substation is possible.
10. The cost of feeders and the power losses are reduced.
11. There is no objection or opposition by legal administration laws for the right way for the feeders and approach roads to the substation.
12. Time required for the erection of substation is reduced.

Classification of Substations

Classification of Sub-Stations

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

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

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

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

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

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

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

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

2. According to constructional (Design) features. A sub-station has many components (*e.g.* circuitbreakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous andreliable service. According to constructional features, the sub-stations are classified as :

(*i*) Indoor sub-station **(*ii*)** Outdoor sub-station
(*iii*) Underground sub-station **(*iv*)** Pole-mounted sub-station

(*i*) Indoor sub-stations. For voltages upto 11 kV, the equipment of the sub-station is installedindoor because of economic considerations. However, when the atmosphere is contaminated withimpurities, these sub-stations can be erected for voltages upto 66 kV.

(*ii*) Outdoor sub-stations. For voltages beyond 66 kV, equipment is invariably installed outdoor.It is because for such voltages, the clearances between conductors and the space required forswitches, circuit breakers and other equipment becomes so great that it is not economical to install theequipment indoor.

(*iii*) Underground sub-stations. In thickly populated areas, the space available for equipmentand building is limited and the cost of land is high. Under such situations, the sub-station is createdunderground.

(*iv*) Pole-mounted sub-stations. This is an outdoor sub-station with equipment installed overheadon *H*-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such substations.

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

3. Depending upon Nature of duties:

Depending upon Nature of duties, the substations are further divided into three types

(i) Step up substation

(ii) Primary grid substation

(iii) Step down substation

(i) Step up substation

The voltage generated in electrical power station is of low value and needs to be stepped up in order to transmit it to far off places near the consumers economically. Hence step up substations are used to step up the generated voltage. The step up substations arenormally associated with generating stations.

(ii) Primary grid substation

The stepped up voltage transmitted from the generating station needs to be stepped down before it is distributed to the consumers.Hence, primary grid substation performs this operation and issituated in the intermediate points between the step up substation and step down substation.

The transmission lines from the primary grid substation are then connected to the step down substation near load centers. It is used for compensation purposes.

(iii) Step down substation

The voltage transmitted from primary grid substation needs to be stepped down to low voltage level which is used to supply to the consumers and hence it ensures safe operation at consumer's premises. Step down sub stations are located near load Centre.

4. On the basis of Importance

On the basis of importance, the substations are classified into two types

(i) Town substations

(ii) Grid substation

(i) Town substations

This type of substations is considered to be important because a failure in the single substation may cause power failure to the whole town. This type of substations are used for stepping down the voltage at 33/11 kv for further distribution in the towns.

(ii) Grid substations

This type of substations is considered to be important because any sort of disturbance in these substations ay lead to failure of the grid. These types of substations are used to transmit huge amount of power from one point to the other point in the grid.

5. Depending on the Operating Voltage:

On the basis of Operating Voltage, the substations are classified into three types.

(i) High voltage substations

(ii) Extra High voltage substations

(iii) Ultra High voltage substations

(i) High voltage substations

These types of substations are also called as HV substations. In this substations, operating voltage ranges between 11kV to 66kV.

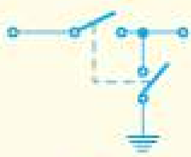
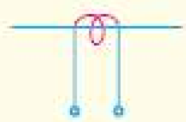
(ii) Extra High voltage substations

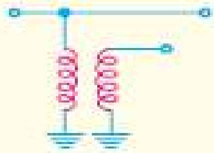
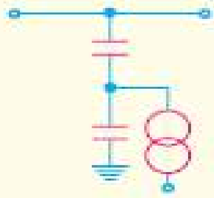
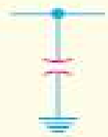
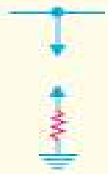
These types of substations are also called as EHV substations. In this substations, operating voltage ranges between 132kV to 400kV.

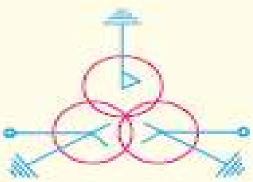
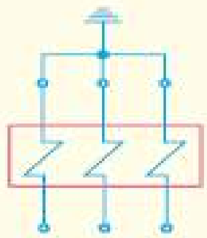
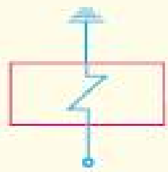
(iii) Ultra High voltage substations

These types of substations are also called as UHV substations. In this substations, operating voltage > 400kV.

Symbols for Equipment in Sub-Stations

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

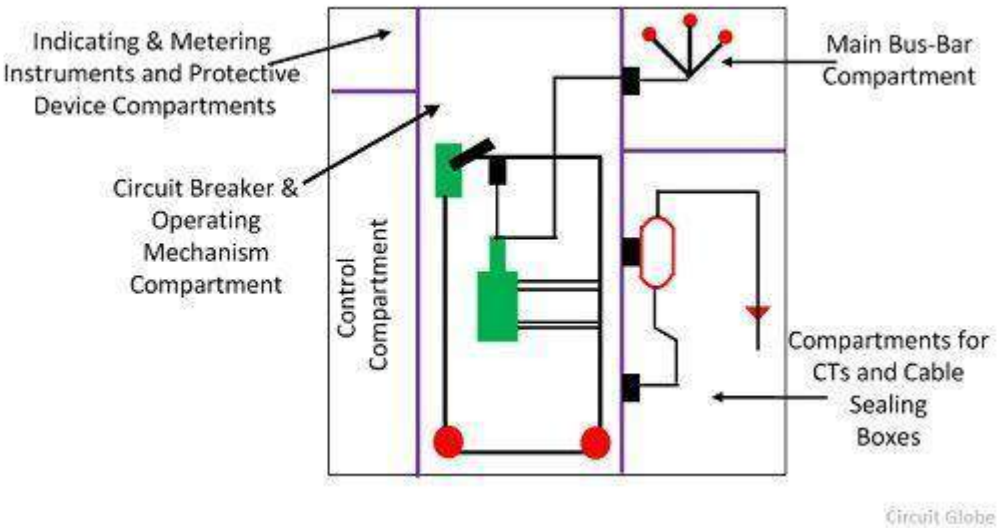
7	Potential transformer	
8	Capacitive voltage transformer	
9	Oil circuit breaker	
10	Air circuit breaker with overcurrent tripping device	
11	Air blast circuit breaker	
12	Lightning arrester (active gap)	
13	Lightning arrester (valve type)	

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

INDOOR SUB STATIONS

A substation in which the apparatus is equipped inside the substation building is called indoor substation. Such type of substation is mainly used for the voltage up to 11000 v, but when the surrounding air is contaminated by impurities such as metal corroding gases and fumes, conductive dust, etc., their voltage can be raised up to 33000 V to 66000 v.

The indoor substation is subdivided into several compartments like control compartment, indicating and metering instruments and protective device compartment main bus-bar compartment, current transformer and cable sealing box compartment as shown in the figure below.



The switch gear on the supply or primary side will consist of oil circuit breaker only. The high voltage supply is given to the primary of the transformer through a circuit breaker. From the bus bar, various feeders emerge out. The panel on each feeder consists of an isolator switch and a circuit breaker. In addition to isolator and circuit breaker, the panel also provided the measuring instrument.

For the protection of feeders usually, reverse power relay is used. For the protection of oil filled transformer Buchholz relay is used. The accessories of the indoors type substations are a storage battery, fire fighting equipment such as water, buckets, and fire extinguisher, etc., The battery is used for the operation of protective gear and switching operating solenoids and emergency lighting in substations in the case of failure of supply.

Indoor substations and transformer substation, as well as, high voltage switchboards consist of a series of open and enclosed chamber or compartments. The main equipment for this installation is arranged in these compartments. The chamber space within which the equipment of the main bus-bar is connected is called a compartment or a cubical cell.

Advantages

The indoor type switchgear is generally used for voltage below 11kv. However, recent applications are seeing switchgear above 11kv installed. In higher voltages, gas insulated components are usually used. In addition to the wide application, several indoor switchgear advantages make it ideal in many situations. Here are some of them.

1. Increased Safety

Indoor electric switchgear is normally housed in metal enclosures. This makes it much safer than outdoor switchgear. The enclosure shields users from live electrical components by providing an extra layer of protection against shock or electrocution.
The higher level of safety makes indoor switchgear suitable for use in residential, industrial and institutional settings. This is critical when it comes to ensuring the safety of electrical equipment and workers or other persons who may come near the installation.

2. More Protection

One of the key advantages of indoor substation or switchgear is that it offers superior protection against dust, moisture and other forms of contaminants that may be present in the surrounding environment.

The increased protection is especially important for applications in industrial settings, where there may be high levels of particulate matter or conductive dust from nearby machining operations.

3. Increased Reliability

Another key advantage that indoor type switchgear has over outdoor switchgear is increased reliability. Because it's installed indoors, there are fewer risks of being exposed to extreme weather events that could damage the switchgear.

In other words, it means the switchgear is less likely to suffer from power surges and fluctuations in electrical current. This can help improve system reliability over the long term, resulting in fewer outages over time, among other benefits.

4. Cheaper to Maintain

Indoor switchgear is also cheaper to maintain compared to outdoor switchgear. Inside building or switchgear room, the equipment is less likely to get damaged by harsh environment. This lowers maintenance costs.

5. Requires Less Space

Indoor switchgear requires less installation space than outdoor switchgear. Since it is installed indoors, there is no need to provide an external shelter for protection from the elements. This eliminates additional site preparation costs.

The smaller footprint of indoor electric switchgear makes indoor makes it ideal for small-sized facilities or in crowded urban environments. Also, for places where the cost of land is too high and outdoor switchgear would increase cost unnecessarily.

Disadvantages

Higher Upfront Costs

Indoor type switchgear is initially more expensive than outdoor types of switchgear. However, the costs to maintain the switchgear are generally lower, seeing that it's less prone to environmental causes of damage such as rain and dust.

Not Easy to Expand

Indoor switchgear may be difficult to expand or modify after installation since the equipment is generally contained within a building. This may necessitate an additional investment in replacement parts or reconfiguration of the entire system, which can become costly over time.

OUTDOOR SUBSTATIONS

A substation which is used for all voltage levels between 55 KV to 765 KV is called outdoor substation. Such type of substation requires less time for construction but uses more space. The outdoor substations are mainly classified into two types, namely pole-mounted substation and foundation-mounted substations.

Pole Mounted Substation

Such substations are used for supporting distribution transformers having the capacity up to 250 KVA. Such types of transformers are the cheapest, simplest, and smallest of distributions. All the equipment is the outdoor type and mounted on the supporting structures of high tension distribution line. Triple pole mechanically operated switch used for switching on and off the high tension transmission line.

HT fuse is used for protection of the high tension transmission line. For controlling the low tension lines, low tension switches along with fuses is equipped. Lightning arresters are equipped over the high tension line for the protection of the transformers from the surges. Pole-Mounted substations are earthed at two or more places.

The transformers having a capacity up to 125 KVA are mounted on the double pole structure and for the transformer having a capacity between 125 to 250 KVA 4-pole structure with the suitable platform is used. Such types of the substation are placed in very thickly populated location.

Their maintenance cost is low, and by using a large number of the substation in a town, it is desirable to lay the distributors at a lower cost. But when the number of transformers is increasing, total KVA is increased, no load losses in increases and the cost per KVA increases.

Foundation Mounted Substation

In foundation mounted substation all the equipment area assembled and the substations are embedded by the fence for safety purpose. The equipment required for such type of substations are heavy, and hence the site selected for such type of substation must have a good path for heavy transport. Foundation mounted outdoor substation is shown in the figure below

Advantages of Outdoor Substation

The outdoor substations have the following main advantages. These are

All the equipment in the outdoor substations is within view, and therefore fault location is easier.
The expansion of the installation is easier in the outdoor substations.
The time requires in the construction of such substations is lesser.
The smaller amount of building material like steel, concrete is required.
The construction work required is comparatively less, and the cost of the switchgear installation is also very low.
Repairing work is easy, and proper space is provided between the apparatus so that the fault occur at one point will not be carried over to another point.

Disadvantages of Outdoor Substation

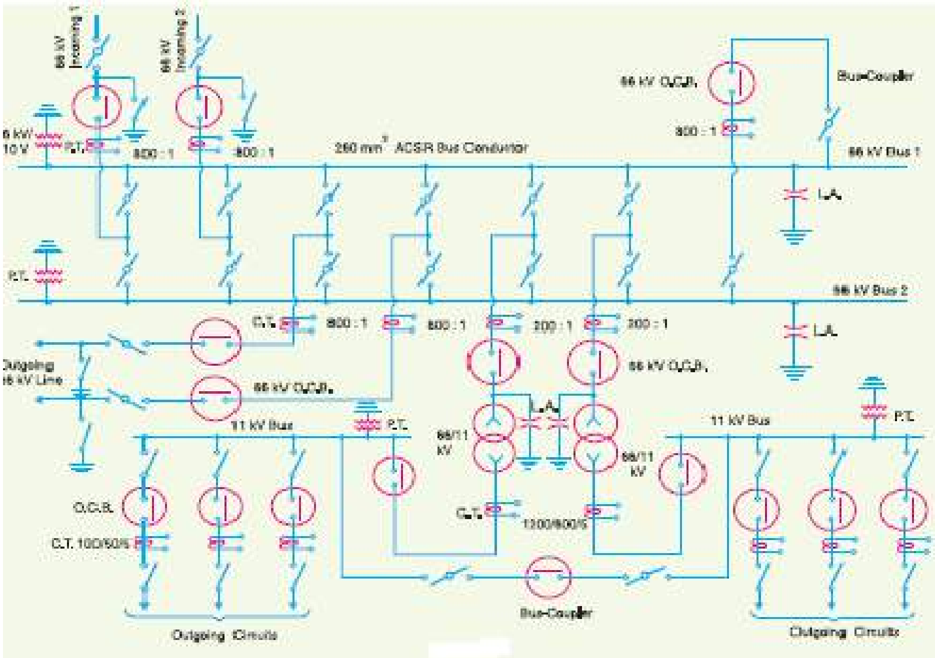
More space is required for the outdoor substations.
Protection devices are required to be installed for the protection against lightning surges.
The length of the control cables increases which increase the cost of the substation.
Equipment designed for outdoor substation are more costly because outdoor door substation equipment required additional protection from the dirt and dust.

Comparison between Outdoor and Indoor Sub-Stations

S.No	Particular	Outdoor Substation	Indoor Substation
1	Space required	More	Less
2	Time required for erection	Less	More
3	Future extension	Easy	Difficult
4	Fault location	Easier because the equipment is in full view	Difficultbeacuse the equipment is enclosed
5	Capital cost	Low	High
6	Operation	Difficult	Easier
7	Possibility of fault escalation	Less because greater clearances can be provided	More
8	Severity of fire effects	Less	More
9	Maintanance	easy	difficult
10	If any fault occurs,	the repaire work is easy	It is difficult to repair
11	The effect of lightning stokes	More	Less
12	Public safety	It is not suitable	It is more suitable
13	The effect of environmental conditions	More favourable	Less favourable
14	Annual cost for operation	less	More

Key Diagram of 66/11 kV Outdoor Sub-Station

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



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

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

(iii) There is an arrangement in the sub-station by which the same 66 kV double circuit supply isgoing out *i.e.* 66 kV double circuit supply is passing through the sub-station. The outgoing66 kV double circuit line can be made to act as incoming line.

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

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

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

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

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

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

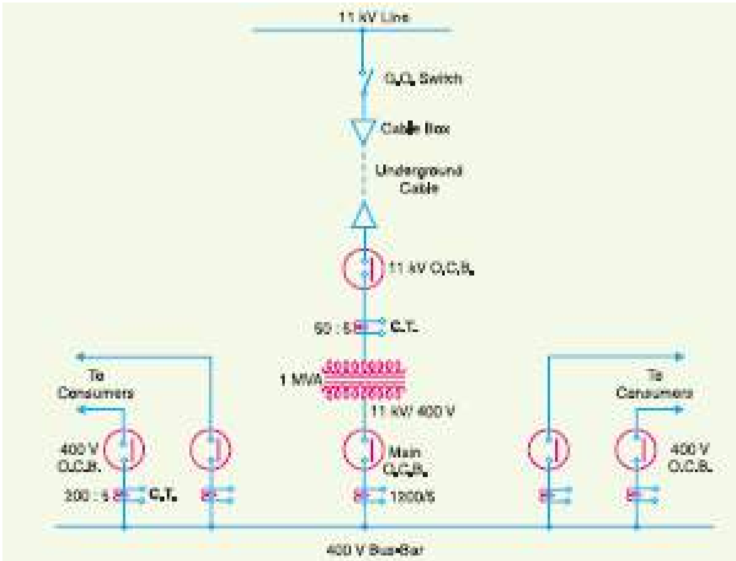
Fig. shows the key diagram of a typical 11 kV/400 V indoor sub-station. The key diagram ofthis sub-station can be explained as under :

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

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

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

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



Substation Layout showing the Location of all the Substation Equipment

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

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

(*i*) Single bus-bar arrangement

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

(*iii*) Double bus-bar arrangement

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

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

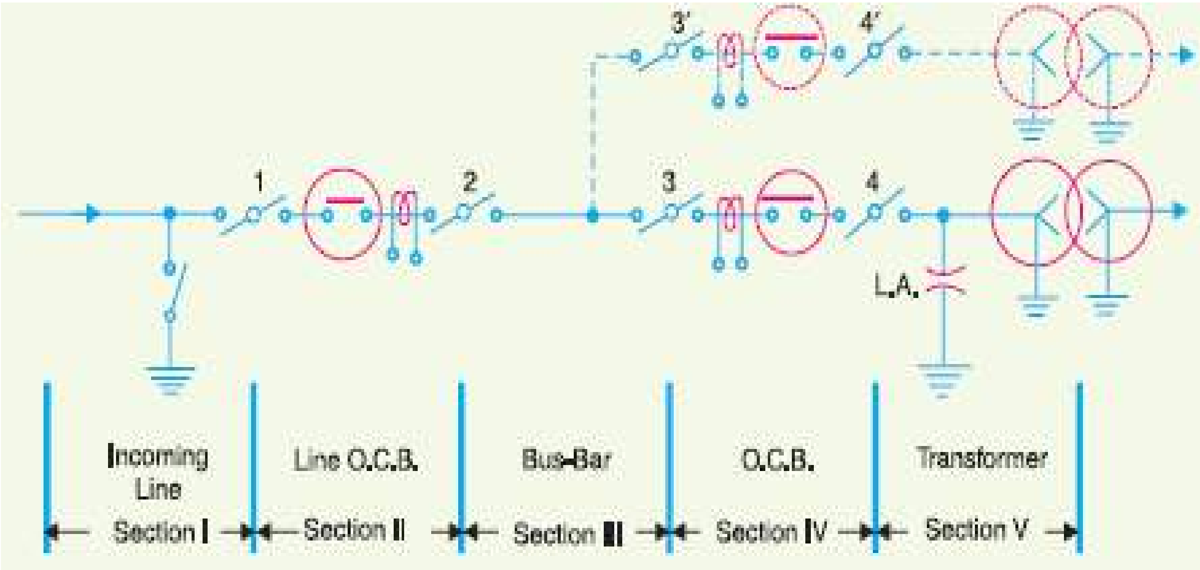


Fig. shows the use of isolators in a typical sub-station. The entire sub-station has beendivided into V sections. Each section can be disconnected with the help of isolators for repair andmaintenance. For instance, if it is desired to repair section No. II, the procedure of disconnecting thissection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

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

5. Power Transformers. A power transformer is used in a sub-station to step-up or step-downthe voltage. Except at the power station, all the subsequent sub-stations use step-down transformersto gradually reduce the voltage of electric supply and finally deliver it at utilisation voltage. Themodern practice is to use 3-phase transformers in sub-stations ; although 3 single phase bank oftransformers can also be used. The use of 3-phase transformer (instead of 3 single phase bank oftransformers) permits two advantages. Firstly, only one 3-phase load-tap changing mechanism canbe used. Secondly, its installation is much simpler than the three single phase transformers.

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

6. Instrument transformers. The lines in sub-stations operate at high voltages and carrycurrent of thousands of amperes. The measuring instruments and protective devices are designed forlow voltages (generally 110 V) and currents (about 5 A).

Therefore, they will not work satisfactorilyif mounted directly on the power lines. This difficulty is overcome by installing instrument transformerson the power lines. The function of these instrument transformers is to transfer voltages orcurrents in the power lines to values which are convenient for the operation of measuring instrumentsand relays. There are two types of instrument transformers viz.

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

(i) Current transformer (C.T.). A current transformer in essentially a step-up transformerwhich steps down the current to a known ratio. The primary of this transformer consists of one ormore turns of thick wire connected in series with the line. The secondary consists of a large numberof turns of fine wire and provides for the measuring instruments and relays a current which is aconstant fraction of the current in the line.

Suppose a current transformer rated at 100/5 A is connectedin the line to measure current. If the current in the line is 100 A, then current in the secondarywill be 5A.

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

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

8. Miscellaneous equipment. In addition to above, there may be following equipment in asub-station :
(i) fuses(ii) carrier-current equipment(iii) sub-station auxiliary supplies

9. Indicating & Recording Instruments:

Various types of meters such as voltmeters, ammeters, wattmeters, kWh meters, kVARh meters, power factor meters and etc are used in the control house to control and monitor the currents flowing through the circuits.

10. Control House: Thesubstation control house contains control panels, batteries, meters, battery chargers, supervisory control and relays. It provides all environmental protection and security for the control equipments.

11. Control Panels: Control panel contains meters, control switches and recorders. These are used to control substation equipments, to send power from one circuit to another circuit and open or close the circuit under normal and abnormal conditions.

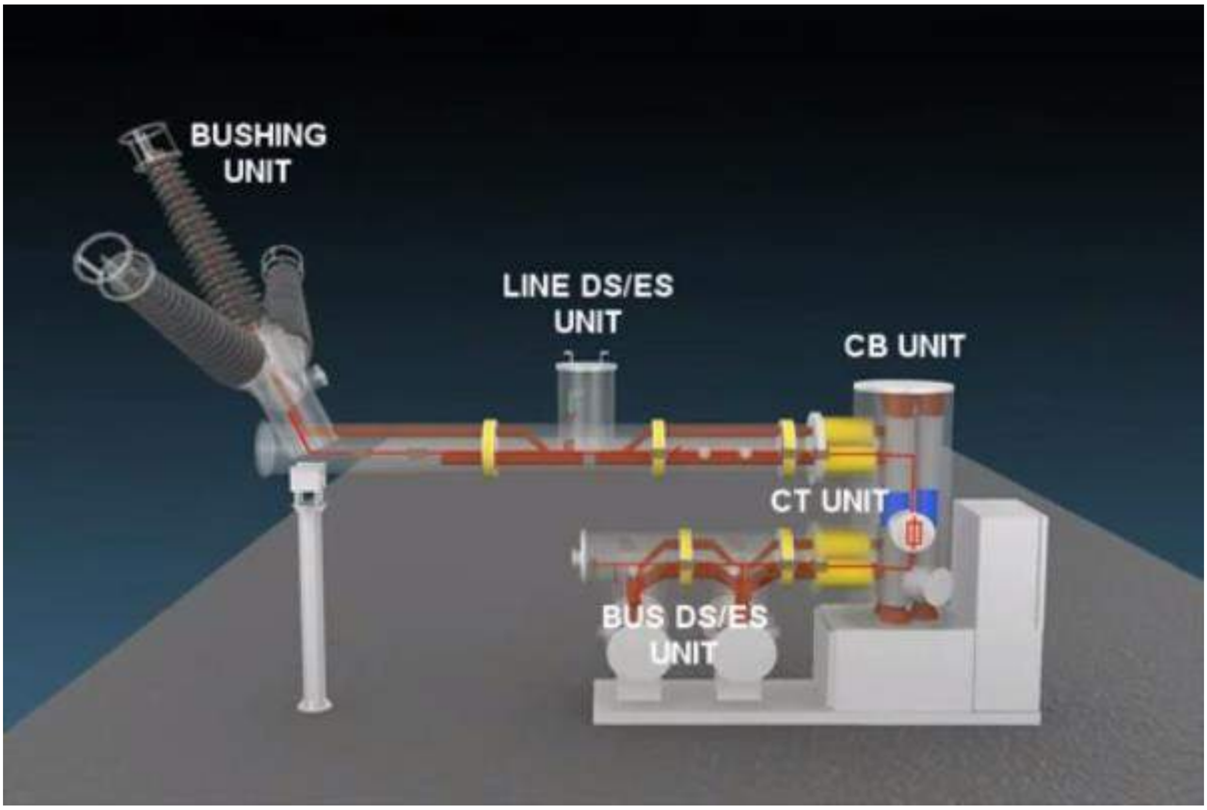
12. Control wires: Control wires are installed for connecting the control house and control panels to all the equipment in the substation. A typical substation control house contains several thousand feet of conduit and miles of control wires. For laying of these cables generally ducts are run from control house.

13. Batteries: These are used in the substation control house as a backup, to power the automatic control circuits, the protective relay systems and emergency lighting circuits in case of power failure.

14. High Voltage fuses: These are used to protect the electrical system in a substation from power transformer faults. They are switched for maintenance and safety purpose.

15.Carrier-Current Equipment: These types of equipments are used for communication, relaying, supervisory control and telemetering purposes. These equipments are placed in a career room and are connected to the high voltage power circuit.

Gas Insulated Substations



Gas-insulated substations (GIS) have been used in power systems over the last three decades because of their high reliability, easy maintenance, small ground space requirement, etc. This article is an introduction to Gas-insulated Substations.

Gas Insulated Substation (GIS) also called SF6 Gas Insulated Metalclad Switchgear is preferred for 12kV, 36kV, 72.5kV, 145 kV, 245 kV, 420 kV, and above voltages.

In a GIS substation, the various equipment like Circuit Breakers, Bus bars, Isolators, Load break switches, Current transformers, Voltage transformers, Earthing switches, etc. are housed in separate metal-enclosed modules filled with SF6 gas. The SF6 gas provides the phase to ground insulation.

As the dielectric strength of SF6 gas is higher than air, the clearances required are smaller. Hence the overall size of each equipment and the complete sub-station is reduced.

SF6 Gas Insulated Substations are compact and can be installed conveniently on any floor of a multi-storeyed building or in an underground substation. As the units are factory assembled, the installation time is substantially reduced.

Such installations are preferred in composition cities, industrial townships, hydro stations where land is very costly.

The higher cost of SF6 insulated switchgear is justified by saving to the reduction in floor-area requirement.

SF6 insulated switchgear is also preferred in heavily polluted areas where dust, chemical fumes and salt layers can cause frequent flashovers in conventional outdoor sub-stations.

The GIS require less number of lightning arresters than a conventional one. This is mainly because of its compactness.

Why SF6 is Used?

SF6 is used in GIS at pressures from 400 to 600 kPa absolute. The pressure is chosen so that the SF6 will not condense into a liquid at the lowest temperatures the equipment experiences.

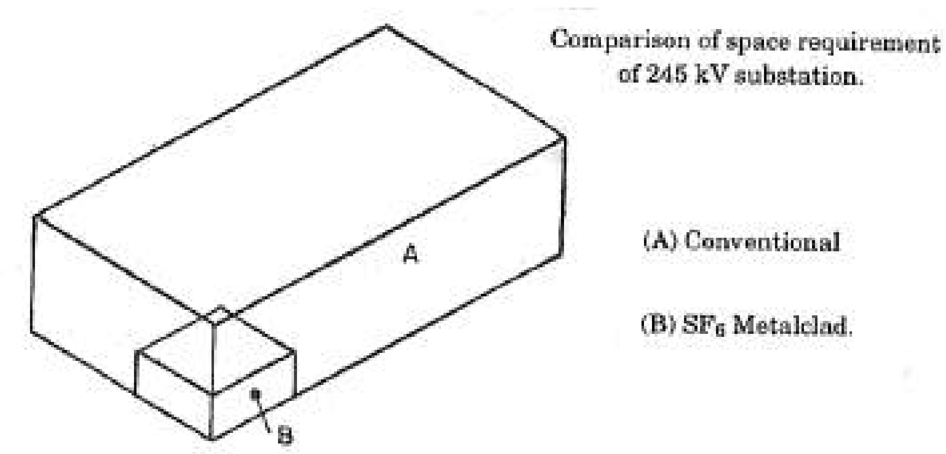
SF6 has two to three times the insulating ability of air at the same pressure. SF6 is about 100 times better than air for interrupting arcs.

Advantages of Gas Insulated Substations

The following are the main advantages of Gas Insulated Substations over Air Insulated Substations and Hybrid Substations.

Compactness of GIS

The space occupied by SF6 installation is only about 10% of that of a conventional outdoor substation. High cost is partly compensated by saving in cost of space.



Protection from pollution

The moisture, pollution, dust etc., have little influence on SF6 insulated sub-stations. However, to facilitate installation and maintenance, such substations are generally housed inside a small building.

The construction of the building need not be very strong like conventional power houses.

Reduced Switching over voltages

The over voltages while closing and opening line, cables motors capacitors etc. are low.

Reduced Installation Time

The principle of building-block construction (modular construction) reduces the installation time to a few weeks. Conventional sub-stations require a few months for installation.

Superior Arc Interruption

SF6 gas is used in the circuit-breaker unit for arc quenching. This type of breaker can interrupt current without overvoltages and with minimum acing time. Contacts have long life and the breaker is maintenance free.

Gas Pressure

The gas pressure (4 kgf/cm2) is relatively low and does not pose serious leakage problems.

Increased Safety

As the enclosures are at earth potential, there is no possibility of accidental contact by service personnel to live parts.

Demerits of GIS

The following are the main disadvantages of Gas Insulated Substations over Air Insulated Substations and Hybrid Substations.

1. High cost compared to conventional outdoor sub-station.
2. Excessive damage in case of internal fault. Long outage periods as repair of damaged part at site may be difficult.
3. Requirements of cleanliness are very stringent. Dust or moisture can cause internal flashovers.

4. Such sub-stations generally indoor. They need a separate building. This is generally not required for conventional outdoor sub-stations. Procurement of gas and supply of gas to site is problematic. Adequate stock of gas must be maintained.