EE6402 – TRANSMISSION AND DISTRIBUTION
UNIT-I

1. Why high voltage is preferred for power transmission? (MJ15, ND15, MJ16)

As voltage increases, current flow through the line decreases and I^2R loss reduces. So transmission efficiency increases. Therefore high voltage is preferred for power transmission.

2. State the disadvantages of HVDC transmission. (ND10)

i) High cost of terminal equipment
ii) Converters require considerable reactive power.
iii) Harmonics are generated which requires filters.
iv) Converters do not have overload capacity.

3. Why the transmission lines 3 phase 3 wire circuits while distribution lines are 3ϕ, 4 wire circuits? (ND10, ND13)

A Balanced 3 phase circuit does not require the neutral conductor, as the instantaneous sum of the 3 line currents are zero. Therefore the transmission lines and feeders are 3 phase 3 wire circuits. The distributors are 3 phase 4 wire circuits because a neutral wire is necessary to supply the 1 phase loads of domestic and commercial consumers.

4. Define the terms feeders and service mains. (ND11, ND15)

Feeders:

It is a conductor which connects the substation to the area where power is to be distributed. Generally, no tappings are taken from the feeder.

Service mains:

A service main is generally a small cable which connects the distributor to the consumer's terminal.

5. List out the advantages of high voltage A.C transmission. (ND11)

i) The power can be generated at high voltages.
ii) The maintenance of ac substation is easy and cheaper.

6. What is ring main distributor? (ND12, MJ17)

In ring main distributor, the distributor is in the form of a closed ring. The distributor ring may be fed from one or more than one point.

7. List the types of HVDC links. (MJ13)

i) Monopolar HVDC link
ii) Bipolar HVDC link
iii) HVDC back to back tie link
iv) Homopolar HVDC link
v) Multi terminal HVDC link

8. What is a distributor? (ND12, MJ17)

A distributor is a conductor from which tappings are taken for supply to the consumers.

9. List out the objectives of FACTS. (MJ16)

i) To increase the power transfer capability of transmission systems.
ii) To keep power flow over designed routes.

10. What are the components of a power system? (MJ14)

i) Generating station
ii) Transmission system
iii) Distribution system

11. State Kelvin's law for size of transmission conductor. (ND14)

The annual expenditure on the variable part of the transmission system should be equal to the annual cost of energy wasted in the conductor used in that system.

12. How does a.c distribution differ from d.c distribution? (ND14)

AC distribution	DC distribution
Transformers are utilized to alter the voltage levels	Expensive rotating machines are employed to alter the voltage levels.
Power factor should be taken into account	Power factor is zero.
Currents are added and subtracted vectorially.	Currents are added and subtracted arithmetically.
Voltages are added and subtracted vectorially.	Voltages are added and subtracted arithmetically.

13. Write the primary distribution voltages in India. (MJ15)

The primary distribution voltages in India are 33KV and 11KV.

14. State the limitation of high transmission voltage. (MJ15, ND15)

i) The increased cost of insulating the conductor.

ii) The increased cost of transformers ,switch gears and other terminal apparatus.

15. Distinguish between a feeder and a distributor. (MJ15)

Feeders:

- Feeders, radiating from the distribution substation supply power to the distributors.
- No consumer is directly connected to the feeder.

Distributor:

- From the distributors, the tappings are taken for the supply to the consumers.
- Hence they are used to transfer power from distribution centre to the consumers.

16. Define feeder and distributor. (ND12, ND16)

Feeders:

It is a conductor which connects the substation to the area where power is to be distributed. Generally, no tappings are taken from the feeder.

Distributor:

A distributor is a conductor from which tappings are taken for supply to the consumers.

17. State the applications of HVDC transmission. (ND16)

i) Long distance bulk power transmission

ii) Underground or sub marine cables.

iii) Asynchronous connection of AC system with different frequencies.

iv) Control and stabilize the power systems with power flow control.

18. What do you understand by distribution system? (ND15)

The distribution of electric power from load centres to the consumer premises as per the requirement.

19. Mention the transmission voltages that are followed in Tamilnadu. (MJ17)

AC: 765KV, 400KV, 230KV, 220KV, 132KV, 110KV and 66KV

DC: 500KV and 400KV

EE6402 – TRANSMISSION AND DISTRIBUTION

UNIT-II

1. Define skin effect. (ND10, ND12, MJ14, MJ15, ND16, MJ17)

The steady current when flowing through the conductor, does not distribute uniformly, rather it has the tendency to concentrate near the surface of the conductor. This phenomenon is called skin effect.

2. On what factors does the skin effect depend? (MJ15)

i) Nature of the material
ii) Diameter of the wire
iii) Frequency and shape of the wire.

3. What are the advantages of using bundled conductors? (ND10, ND14, ND16)

i) Increase in capacitance
ii) Increase in power capability of the line
iii) Reduce the voltage surface gradient
iv) Reduce corona loss
v) Reduce surge impedance
vi) Increases surge impedance loading.

4. What is the need of transposition? (ND11)

The effect of transposition is that each conductor has the same average inductance. After transposition, the voltage drops are equal in all conductors.

5. Define the term critical disruptive voltage. (ND11, ND13, ND14)

The potential difference between conductors, at which electric field intensity at the surface of the conductor exceeds the critical value and generates corona is known as critical disruptive voltage. It is minimum phase to neutral voltage at which corona occurs.

6. Write the expression for a capacitance of a 1ϕ transmission line. (ND12)

Capacitance of a transmission line = $\pi\xi_0 / \ln (d/r)$

Where, $\xi_0 = 8.854 \text{ X } 10^{-12}$ (F/m)

d = distance of separation between two conductors.

r = radius of each conductor.

7. What is proximity effect? (MJ13, MJ14, MJ15, ND15)

The alternating magnetic flux in a conductor caused by the current flowing in a neighbouring conductor gives rise to a circulating current which cause an apparent increase in the resistance of the conductor .This phenomenon is called as proximity effect.

8. Define visual critical voltage. (MJ13)

It is the minimum phase to neutral voltage at which corona glow appears all along the line conductors. In case of parallel line conductors corona glow does not begin at critical disruptive voltage, V_c but at a higher voltage, V_v which is called as visual critical voltage. This is because the dielectric breakdown of air requires a finite volume of over stressed air.

9. What is meant by transposition on overhead line? (MJ15, MJ16)

Transposition means changing the positions of the three phases on the line supports twice over the total length of the line .the line conductors in practice ,are so transposed that each of the three possible arrangements of conductors exit for one-third of the total length of the line .

10. Distinguish between self and mutual GMD. (ND15)

Self GMD:

It is the geometrical mean of the distance between the conductors belonging to same phase. Hence it is otherwise called as geometrical mean radius. It depends only upon the size & shape of the conductor and is independent of spacing between conductors.

Mutual GMD:

It is the geometrical mean of the distance between the phases. It depends only upon the spacing and is independent of the exact size, shape and orientation of the conductor.

11. What is corona? (MJ16)

The phenomenon of violet glow, hissing noise and production o ozone gas in an overhead line is called corona.

12. How will you reduce corona loss? (ND15)

By increasing the conductor size and conductor spacing.

13. State the different types of overhead line conductors. (MJ17)

i) Stranded conductors
ii) ACSR conductors
iii) Bundled conductors
iv) Composite conductors.

EE6402 – TRANSMISSION AND DISTRIBUTION
UNIT-III

1. **What is Ferranti effect? (ND10, ND11, MJ13, ND13, MJ15, ND15, MJ16, MJ17)**

   When a transmission line is lightly loaded or open circuited, the voltage at the receiving end becomes greater than the sending end voltage, due to substantial quantity of charging current. This is called Ferranti effect.

2. **What is shunt compensation? (ND10)**

   Shunt compensation is the use of shunt capacitors and shunt reactors is the line to avoid voltage instability.

3. **Define voltage regulation in connection with transmission line. (ND12, ND13, MJ14)**

   Voltage regulation is defined as the change in voltage at the receiving (or load) end when the full-load is thrown off, the sending-end (or supply) voltage and supply frequency remaining unchanged.

4. **What is the range of surge impedance in case of underground cables? (ND12)**

   Surge impedance loading of underground cables is 40 Ω

5. **What is the range of surge impedance in case of overhead transmission lines? (MJ13)**

   Surge impedance loading of overhead transmission lines is 400Ω

6. **What is meant by natural loading of transmission line? (ND14)**

   It is the power transmitted when a lossless line is terminated with a resistance equal to surge impedance of the line. This indicates the maximum power that can be delivered and it is useful in transmission line design.

7. **Define transmission efficiency. (ND15)**

   It is defined as the ratio of receiving end power to the sending end power of the transmission line.

8. **Distinguish between attenuation and phase constant.(ND11)**

Attenuation constant	Phase constant
It is the rate of reduction in amplitude of a wave	It is the rate of variation in phase of a wave
It is a real part of propagation constant	It is a imaginary part of propagation constant
It is measured in nepers per unit length	It is measured in radians per unit length
It is denoted by the symbol α	It is denoted by the symbol β

9. **What is the difference between nominal T method and nominal π method? (MJ14)**

   Nominal T method:

   In this method, the line capacitance is lumped or concentrated at the middle of the line resistance and reactance is lumped on its either side of the capacitance.

   Nominal π method:

   In this method, the line capacitance is lumped or concentrated and divided into two halves. One half is lumped at the sending end and the other half at the receiving end. This method is also called as localised capacitance method.

10. Why the control of reactive power is essential for maintaining a desired voltage profile? (ND14)

The reactive power transferred over a transmission line is proportional to the line voltage drop and is independent of power angle. Transfer of reactive power over the line is the main cause for voltage drop across the line. Thus it is needed to control the reactive power for maintaining the desired voltage profile.

11. What is meant by surge impedance and surge impedance loading of transmission line? (MJ15)

Surge impedance:

The characteristic impedance of a lossless line is known as surge impedance.

Surge impedance loading:

It is the power transmitted when a lossless line is terminated with a resistance equal to surge impedance of the line. This indicates the maximum power that can be delivered and it is useful in transmission line design.

12. What is the importance of voltage control? (MJ15)

i) Lightning loads are very sensitive to change in voltage
ii) Voltage variations will cause erratic operation in inductive motors.
iii) Large variations of voltage cause excessive heating of distribution transformers.

13. Mention the various methods of voltage control in transmission line. (ND16)

i) By excitation control
ii) By using tap changing transformers
iii) Auto transformer tap changing
iv) Booster transformer
v) Induction regulators
vi) By synchronous condenser

14. States the condition for maximum power delivered and draw the power angle diagram. (ND16)

Maximum power can be delivered when

i) δ or power angle is 90·
ii) By increasing sending end or and receiving end voltage magnitude
iii) By reducing the reactance X of the line

15. Define voltage stability. (ND15)

The ability of the system to maintain the voltage level within its acceptable limits is called as voltage stability.

16. Mention the significance of surge impedance loading. (MJ16, MJ17)

- The voltage and current are equal and are in phase at all points along the line.
- No reactive power is generated or absorbed at the line ends.

EE6402 – TRANSMISSION AND DISTRIBUTION

UNIT-IV

1. Name any four insulating materials used for cable. (MJ13, ND16)

i) Rubber (or) Vulcanized Indian Rubber
ii) Impregnated paper
iii) Varnished cambric
iv) polyvinyl Chloride
v) Cross linked poly Ethylene

2. Name the methods for improving string efficiency. (MJ13, ND16)

i) By using longer cross arms
ii) By grading the insulator units
iii) By using a guard ring

3. Define string efficiency.(ND10, ND15)

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.

4. What is the necessity of grading of an underground cable? (ND10)

Distribution of dielectric material is such that the difference between E_{max} and E_{min} is reduced is known as grading of cables. Thereby a cable same size can be operated for high voltage or for the same operation voltage, the size of the cable can be reduced.

5. Enumerate the methods of grading of cables. (ND11, MJ17)

i) Capacitance grading
ii) Intersheath grading

6. Define grading of cable. (ND12, ND15)

The process of achieving uniform electrostatic stress in the dielectric of cables is known as grading of cables.

7. What is meant by birdage? (ND12)

Short – circuiting of the line conductor to earth through the large birds or similar objects is known as birdage.

8. How does grading ring improve string efficiency? (ND13)

Guard ring introduces capacitance between metal fittings and line conductors. These capacitances are greater for lower units and thus the voltage across that bottom unit is reduced. Hence the string efficiency is improved.

9. What are the advantages of string insulators? (ND11)

i) For higher voltages these are cheaper than pin insulators.
ii) This type of insulators provide greater flexibility to the line
iii) The string is suspended and is free to swing in any direction. So it takes the position so that mechanical stresses on the line are minimum.

10. What is shackle insulator?(MJ14)

It is used in low voltage distribution line (11KV). This can be used either in a vertical position or horizontal position. In this type of construction, the conductor is placed between the clamp and the insulator and is fixed along the groove of the insulator using soft binding wires of same material as the conductor.

11. What is meant by dielectric stress in a cable? (MJ14)

Dielectric stress occurs, when the insulation of a cable is subjected to electrostatic forces under normal operating conditions. Dielectric stress at any point in a cable is the electric field intensity at that point.

12. Why are insulators used with overhead lines? (ND14)

i) To provide necessary insulation between line conductors and supports

ii) To prevent any leakage current from conductors to earth

iii) To provide necessary mechanical support for the conductor

13. What are the factors to be considered while selecting a cable for a particular service? (ND14)

i) Operating voltage

ii) Current carrying capacity

iii) Voltage drop

iv) Site requirement

v) Economic evauation

14. Define safety factor of insulator. Why it is desired to have this value be high?(MJ15)

It is defined as the ratio of puncture strength to the flashover voltage.
It is desirable to have high safety factor so that flashover takes place before the insulator gets punctured. For pin type insulators, the value of safety factor is above 10.

15. State the limitation of solid type cables. How are these overcome in pressure cables? (MJ15)

For voltages beyond 66KV, solid type cables are unreliable, because there is no danger of breakdown of insulation due to the presence of voids.

But in pressure cables, voids are eliminated by increasing the pressure of the compound by using oil, gas etc.

16. What is the main purpose of armouring? (MJ15)

The purpose of armour is to protect the cable from mechanical injury while laying it and during the course of handling.

It consists of one or more layers of galvanized steel wire or steel tape.

17. Specify the different types of insulators. (MJ17)

i) Pin type insulators

ii) Suspension type insulators

iii) Strain insulators

iv) Shackle insulators

v) Stay insulators

18. What are the tests performed on the insulators? (MJ16)

i) Mechanical test

ii) Electrical insulation test

iii) Environmental test

iv) Temporary cycle test

v) Corona and radio interference test

19. Classify the cables used for three phase service. (MJ16)

i) Belted cables (up to 11KV)

ii) Screened cables (up to 33KV)

iii) Pressure cables (beyond 66KV)

EE6402 – TRANSMISSION AND DISTRIBUTION

UNIT-V

1. List the various substation equipments. (ND10)

i) Transformer
ii) Circuit breakers
iii) Isolating switches
iv) Protective relays
v) Bus bars
vi) Current and potential transformers
vii) Surge arresters
viii) Control room equipments

2. What are the various methods of earthing in substations? (ND11)

i) Solid (or) effective grounding
ii) Resistance grounding
iii) Reactance grounding
iv) Resonant grounding

3. Give any two factors that affect sag in an overhead line. (ND10, ND12, ND16, MJ17)

i) Weight of the conductor
ii) Span length
iii) Working tension
iv) Atmospheric condition
v) Temperature

4. List the types of substations. (ND12)

According to constructional features

i) Indoor substation
ii) Outdoor substation
iii) Underground substation
iv) Pole mounted substation

5. What is deviation tower? (MJ13)

Deviation tower are used at points where the transmission lines changes direction. These towers have to withstand the resultant forces due to change in direction. They have broader base, stronger members and are costlier as compared to other towers.

6. Mention any 4 bus schemes in the substation. (MJ13)

i) Single bus scheme
ii) Single bus bar with bus sectionalizer
iii) Double bus with double breaker
iv) Double bus with single breaker
v) Main and transfer bus
vi) Ring bus
vii) Breaker and half with two main buses
viii) Double bus bar with bypass isolators.

7. What is meant by sag? (ND13, ND15, MJ16)

The difference in voltage level between the points of support and the lowest point of the conductor is called sag.

8. What is a sag template? (MJ14, ND15)

It is the plot of curves prepared on celluloid or tracing both which are used in locating the towers in the field.

9. What is the need of an earthing system? (ND13, ND16)

i) To prevent accidents and damage to the equipment of the power system
ii) To ensure the safety of the persons handling the equipment
iii) To maintain the continuity of supply at the same time.

10. What is meant by tower spotting?(ND15)

Tower spotting is the art of locating structures in the right way and selecting height and the type of towers to be used.

11. What is meant by stringing chart? What is its use? (ND11, MJ16)

The curves of sag and tension with temperature variations are called as stringing chart. These charts are very helpful while stringing querhead lines. By using stringing charts, the tension and sag can be found at any temperature and loading conditions.

12. What are the materials mainly used in bus bars?(MJ15)

Materials used for bus bars:

i) Aluminium
ii) Copper

Materials used for coating:

i) Tin
ii) Silver

13. What is the purpose of terminal and through substations in the power system?(ND14)

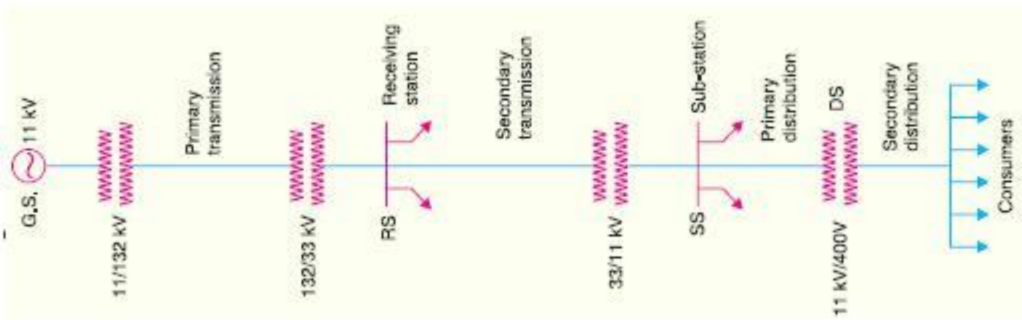
Terminal – To end or terminate the line supplying the substation
Through – To pass the incoming line through at the same voltage.

UNIT - I

1. Explain with neat sketch, the structure of power system. (MJ13, ND13,MJ14,ND15,MJ16)

Introduction

- An electric power supply system consists of three principal components, the power station, transmission lines and distribution system.
- Electric power is generated at power stations, which are located at favorable places, generally quite away from the consumer.
- It is then transmitted over large distances to load centres with the help of conductors known as transmission lines. Finally, it is distributed to a large number of small and big consumers through a distribution network.
- The electric supply system can be broadly classified into (*i*) d.c. or a.c. system (*ii*) overhead or underground system. Now-a- days, 3-phase, 3-wire a.c. system is universally adopted for generation and transmission of electric power as an economical proposition. However, distribution of electric power is done by 3-phase, 4-wire a.c. system.
- The underground system is more expensive than the overhead system. Therefore, in our country, overhead system is mostly adopted for transmission and distribution of electric power.
- The large network of conductor between the power station and the consumers can be broadly divided into two parts; viz; Transmission and distribution system.
- Each part can further be sub divided into two, primary transmission and secondary transmission and primary distribution and secondary distribution.



1. Generating station:

i) Generating station represents the generating station, where electric power is produced by 3 phase alternator operating in parallel.

ii) The usual generation voltage is 11kV. The power generated at this voltage is stepped upto 132 kV, 220kV, 400 kV.

iii) As the transmission of electric power at high voltages have so many advantages, viz; saving of conducting material, high transmission efficiency and less sine loss.

2. Primary Transmission:

i) The electric power at high voltage (say 132 kV) is transmitted by 3 phase, 3 wire overhead system to the outskirts of the city. This form the primary transmission.

3. Secondary Transmission:

i) The primary transmission line terminates at the receiving station, which usually lies at the outsides of the city at the receiving station, the voltage is reduced is reduced to 33 kV by 3 phase, 3 wire over head system to various sub stations located at the strategic points in the city. This forms secondary transmission.

4. Primary Distribution :

i) The secondary transmission line terminates at the sub station where voltage is reduced from 33 kV to 11 kV 3 phase 3 wire.

ii) The 11 kV line runs along the important roadsides of the city. This forms the primary Distribution.

5. Secondary Distribution:

i) The electric power from primary distribution line is delivered to distribution sub stations.

ii) These sub stations are located near the consumer localities and step down the voltage to 400 V and between any phase and neutral is 230V.

iii) The 3 phase residential lighting load is connected between any one phase and neutral whereas 3 phase 400V motor loads are connected across 3 phase lines directly.

(v) has less corona loss and reduced interference with communication circuits.

(vii) The high voltage d.c. transmission is free from the dielectric losses, particularly in the case of cables.

(viii) In d.c. transmission, 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 transmission of power at high voltages.

(iii) The d.c. switches and circuit breakers have their own limitations.

2. Explain the advantages and disadvantages of EHVAC transmission system. (ND14)

Advantages of High Transmission Voltage

(i) Reduces volume of conductor material

(ii) Increases transmission efficiency

(iii) Decreases percentage line drop.

(i) Reduces volume of conductor material.

V = line voltage in volts

cosφ = power factor of the load

l = length of the line in metres

R = resistance per conductor in ohms

ρ = resistivity of conductor material

a = area of X-section of conductor

$$\text{Load current, } I = \frac{P}{\sqrt{3}\, V \cos\phi}$$

$$\text{Resistance/conductor, } R = \rho l/a$$

$$\text{Total power loss, } W = 3I^2 R = 3\left(\frac{P}{\sqrt{3}\, V\cos\phi}\right)^2 \times \frac{\rho l}{a}$$

$$= \frac{P^2 \rho l}{V^2 \cos^2\phi\, a}$$

$$\therefore \quad \text{Area of X-section, } a = \frac{P^2 \rho l}{W V^2 \cos^2\phi}$$

Total volume of conductor material required

$$= 3\,a\,l = 3\left(\frac{P^2 \rho\, l}{W V^2 \cos^2\phi}\right) l$$

$$= \frac{3P^2 \rho l^2}{W V^2 \cos^2\phi} \qquad \ldots(i)$$

It is clear from exp. (*i*) that for given values of *P*, *l*, ρ and *W*, the volume of conductor material required is inversely proportional to the square of transmission voltage and power factor. In other words, the greater the transmission voltage, the lesser is the conductor material required.

(ii)Increases transmission efficiency

$$\text{Input power} = P + \text{Total losses}$$

$$= P + \frac{P^2 \rho l}{V^2 \cos^2\phi\, a}$$

Assuming J to be the current density of the conductor, then,

$$a = I/J$$

$$\therefore \quad \text{Input power} = P + \frac{P^2 \rho\, l\, J}{V^2 \cos^2\phi\, I} = P + \frac{P^2 \rho\, l\, J}{V^2 \cos^2\phi} \times \frac{1}{I}$$

$$= P + \frac{P^2\, \rho\, l\, J}{V^2 \cos^2\phi} \times \frac{{}^{*}\sqrt{3}\, V\cos\phi}{P}$$

$$= P + \frac{\sqrt{3}\; P\, J\, \rho\, l}{V\cos\phi} = P\left[1 + \frac{\sqrt{3}\;\; J\,\rho\, l}{V\cos\phi}\right]$$

$$\text{Transmission efficiency} = \frac{\text{Output power}}{\text{Input power}} = \frac{P}{P\left[1 + \frac{\sqrt{3}\;\; J\rho\, l}{V\cos\phi}\right]} = \frac{1}{\left[1 + \frac{\sqrt{3}\;\; J\rho\, l}{V\cos\phi}\right]}$$

$$= {}^{**}\left[1 - \frac{\sqrt{3}\;\; J\rho\, l}{V\cos\phi}\right] \text{ approx.} \qquad \ldots(ii)$$

As *J*, ρ and *l* are constants, therefore, transmission efficiency increases when the line voltage is increased.

(iii) Decreases percentage line drop

$$\text{Line drop} = I R = I \times \frac{\rho l}{a}$$
$$= I \times \rho l \times J/I = \rho l J \qquad [\because a = I/J]$$
$$\text{\%age line drop} = \frac{J \rho l}{V} \times 100 \qquad ...(iii)$$

As J, ρ and l are constants, therefore, percentage line drop decreases when the transmission voltage increases.

Limitations of high transmission voltage. From the above discussion, it might appear advis- able to use the highest possible voltage for transmission of power in a bid to save conductor material.

However, it must be realised that high transmission voltage results in

(i) the increased cost of insulating the conductors

(ii) the increased cost of transformers, switchgear and other terminal apparatus.

Therefore, there is a limit to the higher transmission voltage which can be economically employed in a particular case. This limit is reached when the saving in cost of conductor material due to higher voltage is offset by the increased cost of insulation, transformer, switchgear etc.

3. Derive the expression for Volume of copper conductor material required for DC and AC Distributors.(MJ13, ND14)

Comparison of Conductor Material in Overhead system:

In comparing the relative amounts of conductor material necessary for different systems of transmission, similar conditions will be assumed in each case *viz.*,

(i) Same power (*P watts*) transmitted by each system.

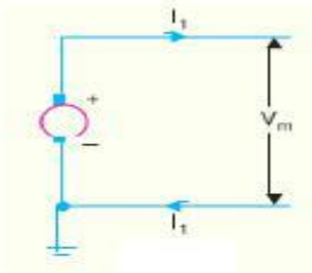
(ii) the distance (*l metres*) over which power is transmitted remains the same.

(iii) the line losses (*W watts*) are the same in each case.

(iv) the maximum voltage between any conductor and earth (V_m) is the same in each case.

1. Two-wire d.c. system with one conductor earthed

In the 2-wire d.c. system, one is the outgoing or positive wire and the other is the return or negative wire as shown in Fig.1.2. The load is connected between the two wires.



Max. voltage between conductors = V_m Power to be transmitted = P

∴ Load current, $I_1 = P/V_m$

If R_1 is the resistance of each line conductor, then,

$$R_1 = \rho \, l/a_1$$

where a_1 is the area of X-section of the conductor

$$\text{Line losses,} \quad W = 2I_1^2 R_1 = 2\left(\frac{P}{V_m}\right)^2 \rho \frac{l}{a_1}$$

$$\therefore \quad \text{Area of X-section, } a_1 = \frac{2P^2 \rho l}{W V_m^2}$$

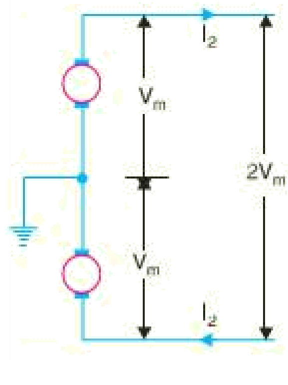
Volume of conductor material required

$$= 2 a_1 l = 2\left(\frac{2P^2 \rho l}{W V_m^2}\right) l = \frac{4P^2 \rho l^2}{W V_m^2}$$

It is a usual practice to make this system as the basis for comparison with other systems. Therefore, volume of conductor material required in this system shall be taken as the basic quantity *i.e.*

$$\frac{4P^2 \rho l^2}{W V_m^2} = K \text{ (say)}$$

2. Two-wire d.c. system with mid-point earthed. Fig.1.3 shows the two-wire d.c. system with mid-point earthed. The maximum voltage between any conductor and earth is V_m so that maximum voltage between conductors is $2V_m$.



Load current, $I_2 = P/2V_m$

Let a_2 be the area of X-section of the conductor.

$$\text{Line losses, } W = 2I_2^2 R_2 = 2\left(\frac{P}{2V_m}\right)^2 \times \frac{\rho l}{a_2} \quad [\because R_2 = \rho\, l/a_2]$$

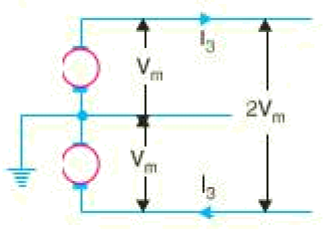
$$\therefore \quad W = \frac{P^2 \rho l}{2a_2 V_m^2}$$

Hence, the volume of conductor material required in this system is *one-fourth* of that required in a two-wire d.c. system with one conductor earthed

3. Three-wire d.c. system. In a 3-wire d.c. system, there are two outers and a middle or neutral wire which is earthed at the genera - tor end as shown in Fig. 1.4. If the load is balanced, the current in the neutral wire is zero. Assuming balanced loads,

Load current, $I_3 = P/2V_m$

Let a_3 be the area of X-section of each outer wire.



$$\text{Line losses, } W = 2I_3^2 R_3 = 2\left(\frac{P}{2V_m}\right)^2 \times \rho\frac{l}{a_3} = \frac{P^2 \rho l}{2V_m^2 a_3}$$

$$\therefore \quad \text{Area of X-section, } a_3 = \frac{P^2 \rho l}{2WV_m^2}$$

Assuming the area of X-section of neutral wire to be half that of the outer wire,

Volume of conductor material required

$$= 2{\cdot}5\, a_3 l = 2{\cdot}5\left(\frac{P^2\rho l}{2WV_m^2}\right) l = \frac{2{\cdot}5}{2}\left(\frac{P^2 \rho l^2}{WV_m^2}\right)$$

$$= \frac{5}{16}K \quad \left[\because K = \frac{4P^2\rho l^2}{WV_m^2}\right]$$

Hence the volume of conductor material required in this system is 5/16th of what is required for a 2-wire d.c. system with one conductor earthed.

4. Single phase 2-wire a.c. system with one conductor earthed. Fig. 1.5. shows a single phase 2-wire a.c. system with one conductor earthed. The maximum voltage between conductors is Vm so that r.m.s. value of voltage between them is √ . Assuming the load power factor to be cos ϕ,

$$\text{Load current, } I_4 = \frac{P}{(V_m/\sqrt{2})\cos\phi} = \frac{\sqrt{2}\,P}{V_m\cos\phi}$$

Let a_4 be the area of X-section of the conductor.

$$\therefore \quad \text{Line losses, } W = 2\,I_4^2\,R_4 = 2\left(\frac{\sqrt{2}\,P}{V_m\cos\phi}\right)^2 \times \frac{\rho\,l}{a_4} = \frac{4\,P^2\rho\,l}{\cos^2\phi\,V_m^2\,a_4}$$

$$\therefore \quad \text{Area of X-section, } a_4 = \frac{4\,P^2\rho\,l}{\cos^2\phi\,W V_m^2}$$

Volume of conductor material required

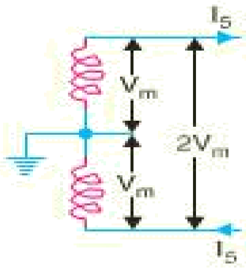
$$= 2\,a_4\,l = 2\left(\frac{4\,P^2\rho\,l}{V_m^2\,W\cos^2\phi}\right)l$$

$$= \frac{2}{\cos^2\phi} \times \frac{4\,P^2\rho\,l^2}{W\,V_m^2}$$

$$= \frac{2K}{\cos^2\phi} \qquad \left[\because K = \frac{4\,P^2\rho\,l^2}{W\,V_m^2}\right]$$

Hence the volume of conductor material required in this system is $2/\cos^2\phi$ times that of 2-wire d.c. system with the one conductor earthed.

5. Single phase 2-wire system with mid-point earthed. Fig. 1.6. shows a single phase a.c. system with mid-point earthed. The two wires possess equal and opposite voltages to earth (*i.e.*, Vm). Therefore, the maximum voltage between the two wires is $2Vm$. The r.m.s. value of voltage between conductors is √ .√ Assuming the power factor of the load to be cosϕ,



$$\text{Load current, } I_5 = \frac{P}{\sqrt{2}\,V_m\cos\phi}$$

Let a_5 be the area of X-section of the conductor.

$$\text{Line losses, } W = 2\,I_5^2\,R_5 = 2\left(\frac{P}{\sqrt{2}\,V_m\cos\phi}\right)^2 R_5$$

$$\therefore \quad W = \frac{P^2\rho\,l}{a_5\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_5 = \frac{P^2\rho\,l}{W\,V_m^2\cos^2\phi}$$

Volume of conductor material required

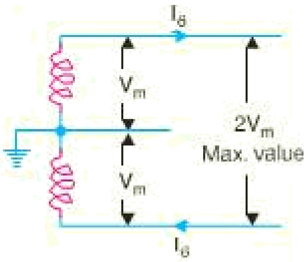
$$= 2\,a_5\,l = 2\left(\frac{P^2\rho\,l}{W\,V_m^2\cos^2\phi}\right)l = \frac{2\,P^2\rho\,l^2}{W\,V_m^2\cos^2\phi}$$

$$= \frac{2}{\cos^2\phi}\times\frac{P^2\rho l^2}{W\,V_m^2}$$

$$= \frac{K}{2\cos^2\phi} \qquad \left[\because K = \frac{4\,P^2\rho\,l^2}{W\,V_m^2}\right]$$

Hence the volume of conductor material required in this system is 1/2 $\cos^2\phi$ times that of 2-wire d.c. system with one conductor earthed.

6. Single phase, 3-wire system. The single phase 3-wire system is identical in principle with 3-wire d.c. system. The system consists of two outers and neutral wire taken from the mid-point of the phase winding as shown in Fig. 1.7. If the load is balanced, the current through the neutral wire is zero. Assuming balanced load,



Max. voltage between conductors = 2 V_m

R.M.S. value of voltage between conductors $= 2V_m/\sqrt{2} = \sqrt{2}V_m$

If the p.f of the load is $\cos\phi$, then,

$$\text{Load current, } I_6 = \frac{P}{\sqrt{2}\,V_m\cos\phi}$$

Let a_6 be the area of X-section of each outer conductor.

$$\text{Line losses, } W = 2\,I_6^2\,R_6 = 2\left(\frac{P}{\sqrt{2}\,V_m\cos\phi}\right)^2\times\frac{\rho\,l}{a_6}$$

$$= \frac{P^2\rho\,l}{a_6\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_6 = \frac{P^2\rho\,l}{W\,V_m^2\cos^2\phi}$$

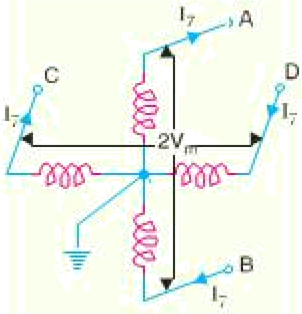
Assuming the area of X-section of neutral wire to be half that of the outer wire, Volume of conductor material required

$$= 2{\cdot}5\,a_6\,l = 2{\cdot}5\left(\frac{P^2\rho\,l}{W\,V_m^2\cos^2\phi}\right)l = \frac{2{\cdot}5\,P^2\rho\,l^2}{W\,V_m^2\cos^2\phi}$$

$$= \frac{2{\cdot}5}{\cos^2\phi}\times\frac{P^2\rho\,l^2}{W\,V_m^2}$$

$$= \frac{5K}{8\cos^2\phi} \qquad \left[\because K = \frac{4P^2\rho\,l^2}{W\,V_m^2}\right]$$

7. **Two phase, 4-wire a.c. system.** As shown in Fig. 1.8. the four wires are taken from the ends of the two-phase windings and the mid-points of the two windings are connected together. This system can be considered as two independent single phase systems, each trans- mitting one half of the total power.



Max. voltage between outers A and B = $2V_m$

R.M.S. value of voltage $= 2V_m/\sqrt{2} = \sqrt{2}\,V_m$

Power supplied per phase (*i.e.*, by outers A and B) $= P/2$

Assuming p.f. of the load to be $\cos\phi$,

$$\text{Load current, } I_7 = \frac{P/2}{\sqrt{2}\,V_m\cos\phi} = \frac{P}{2\sqrt{2}\,V_m\cos\phi}$$

Let a_7 be the area of X-section of one conductor.

$$\text{Line losses, } W = 4\,I_7^2\,R_7 = 4\left(\frac{P}{2\sqrt{2}\,V_m\cos\phi}\right)^2 \times \frac{\rho\,l}{a_7}$$

$$\therefore \quad W = \frac{P^2\,\rho\,l}{2a_7\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_7 = \frac{P^2\,\rho\,l}{2\,W\,V_m^2\cos^2\phi}$$

$\therefore$ Volume of conductor material required

$$= 4\,a_7\,l$$

$$= 4\left(\frac{P^2\,\rho\,l}{2\,W\,V_m^2\cos^2\phi}\right)l = \frac{4P^2\rho\,l^2}{2\,W\,V_m^2\cos^2\phi}$$

$$= \frac{1}{2\cos^2\phi} \times \frac{4P^2\,\rho\,l^2}{W\,V_m^2}$$

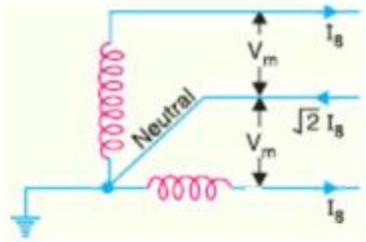
$$= \frac{K}{2\cos^2\phi} \qquad \left[\because K = \frac{4P^2\,\rho\,l^2}{W\,V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $1/2\cos^2\phi$ times that of 2-wire d.c. system with one conductor earthed.

8. Two-phase, 3-wire system. Fig. 1.9. shows two-phase, 3-wire a.c. system. The third or neutral wire is taken from the junction of two-phase windings whose voltages are in quadrature with each other. Obviously, each phase transmits one half of the total power. The R.M.S. voltage between

outgoing conductor and neutral= √ –

$$\therefore \quad \text{Current in each outer, } I_8 = \frac{P/2}{\frac{V_m}{\sqrt{2}}\cos\phi} = \frac{P}{\sqrt{2}\,V_m\cos\phi}$$



$$\text{Current in neutral* wire} = \sqrt{I_8^2 + I_8^2} = \sqrt{2}I_8$$

Assuming the current density to be constant, the area of X-section of the neutral wire will be √ ** times that of either of the outers.

* Current in the neutral wire is the phasor sum of currents in the outer wires. Now, the currents in the outers are in quadrature (*i.e.*, 90^{O} apart) with each other.

** Since the neutral wire carries √ times the current in each of the outers, its X-section must be increased in the same ratio to maintain the same current density.

$$\therefore \quad \text{Resistance of neutral wire} = \frac{R_8}{\sqrt{2}} = \frac{\rho l}{\sqrt{2}\,a_8}$$

$$\text{Line losses, } W = 2I_8^2 R_8 + \left(\sqrt{2}\,I_8\right)^2 \frac{R_8}{\sqrt{2}} = I_8^2 R_8\left(2+\sqrt{2}\right)$$

$$= \left(\frac{P}{\sqrt{2}\,V_m\cos\phi}\right)^2 \times \frac{\rho l}{a_8}\left(2+\sqrt{2}\right)$$

$$\therefore \quad W = \frac{P^2\rho l}{2a_8 V_m^2\cos^2\phi}\left(2+\sqrt{2}\right)$$

$$\therefore \quad \text{Area of X-section, } a_8 = \frac{P^2\rho l}{2W V_m^2\cos^2\phi}\left(2+\sqrt{2}\right)$$

Volume of conductor material required

$$= 2a_8 l + \sqrt{2}\,a_8 l = a_8 l\left(2+\sqrt{2}\right)$$

$$= \frac{P^2\rho l^2}{2W V_m^2\cos^2\phi}\left(2+\sqrt{2}\right)^2$$

$$= \frac{1\cdot457}{\cos^2\phi}K \qquad \left[\because K = \frac{4P^2\rho l^2}{W V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $1\cdot457/\cos^2\phi$ times that of 2-wire d.c. system with one conductor earthed.

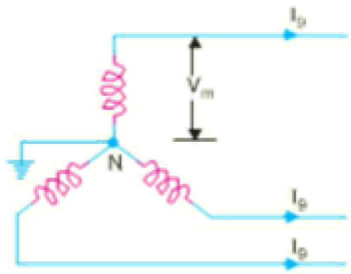
9. 3-Phase, 3-wire system. This system is almost universally adopted for transmission of electric power. The 3-phase, 3- wire system may be star connected or delta connected. Fig. 1.10 shows 3-phase, 3-wire star† connected system. The neutral point N is earthed.

† The same result will be obtained if Δ-connected system is considered.

R.M.S. voltage per phase = $V_m/\sqrt{}$

Power transmitted per phase = $P/3$

$$\text{Load current per phase,} \quad I_9 = \frac{P/3}{\left(V_m/\sqrt{2}\cos\phi\right)} = \frac{\sqrt{2}\,P}{3\,V_m\cos\phi}$$



Let a_9 be the area of X-section of each conductor.

$$\text{Line losses, } W = 3\,I_9^2\,R_9 = 3\left(\frac{\sqrt{2}\,P}{3\,V_m\cos\phi}\right)^2\frac{\rho\,l}{a_9} = \frac{2\,P^2\rho\,l}{3\,a_9\,V_m^2\cos^2\phi}$$

$$\therefore \quad \text{Area of X-section, } a_9 = \frac{2\,P^2\rho\,l}{3\,W\,V_m^2\cos^2\phi}$$

Volume of conductor material required

$$= 3\,a_9\,l = 3\left(\frac{2\,P^2\rho\,l}{3\,W\,V_m^2\cos^2\phi}\right)l = \frac{2\,P^2\rho\,l^2}{W\,V_m^2\cos^2\phi}$$

$$= \frac{0\cdot5\,K}{\cos^2\phi} \qquad \left[\because K = \frac{4P^2\rho\,l^2}{W\,V_m^2}\right]$$

Hence, the volume of conductor material required for this system is $0\cdot5/\cos^2\phi$ times that required for 2-wire d.c. system with one conductor earthed.

10.3-phase, 4-wire system. In this case, 4th or neutral wire is taken from the neutral point as shown in Fig.1.11 The area of X-section of the neutral wire is generally one-half that of the line conductor. If the loads are balanced, then current through the neutral wire is zero. Assuming balanced loads and p.f. of the load as cos ϕ,

Line losses, *W* = Same as in 3 phase, 3-wire

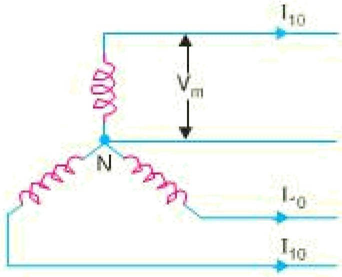


Fig.1.11

∴ Volume of conductor material required

$$= 3{\cdot}5\, a_{10}\, l = 3{\cdot}5\left(\frac{2P^2\rho l}{3WV_m^2\cos^2\phi}\right)\times l$$

$$= \frac{7P^2\rho l^2}{3WV_m^2\cos^2\phi} = \frac{7}{3\cos^2\phi}\times\frac{P^2\rho l^2}{WV_m^2}$$

$$= \frac{7K}{12\cos^2\phi} \qquad \left[\because K = \frac{4P^2\rho l^2}{WV_m^2}\right]$$

4. A 50 km long transmission line supplies a load of 5 MVA at 0·8 p.f. lagging at 33 kV. The efficiency of transmission is 90%. Calculate the volume of aluminium conductor required for the line when (i) single phase, 2-wire system is used (ii) 3-phase, 3-wire system is used. The specific resistance of aluminium is $2{\cdot}85 \times 10^{-8}$ Ω m.

Solution.

Power transmitted = MVA × cos ϕ = 5 × 0·8 = 4 MW = 4×10^6 W

Line loss, W = 10% of power transmitted = (10/100) × 4 × 10^6 = 4×10^5 W

Length of line, l = 50 km = 50×10^3 m

(i) Single phase, 2-wire system

Apparent power = $V I_1$

$$\therefore \quad I_1 = \frac{\text{Apparent power}}{V} = \frac{5 \times 10^6}{33 \times 10^3} = 151{\cdot}5 \text{ A}$$

Suppose a_1 is the area of cross-section of aluminium conductor.

$$\text{Line loss, } W = 2 I_1^2 R_1 = 2 I_1^2 \left(\rho \frac{l}{a_1} \right)$$

$$\therefore \quad \text{Area of X-section, } a_1 = \frac{2 I_1^2 \rho l}{W} = \frac{2 \times (151{\cdot}5)^2 \times (2{\cdot}85 \times 10^{-8})\, 50 \times 10^3}{4 \times 10^5}$$

$$= 1{\cdot}635 \times 10^{-4} \text{ m}^3$$

Volume of conductor required = $2 a_1 l$ = 2 × (1·635 × 10^{-4}) × 50 × 10^3 = **16·35 m^3**

(ii) 3-phase, 3-wire system

$$\text{Line current, } I_2 = \frac{\text{Apparent power}}{\sqrt{3}\, V} = \frac{5 \times 10^6}{\sqrt{3} \times 33 \times 10^3} = 87{\cdot}5 \text{ A}$$

Suppose a_2 is the area of cross-section of the conductor in this case.

$$\text{Line loss, } W = 3 I_2^2 R_2 = 3 I_2^2 \left(\rho \frac{l}{a_2} \right)$$

$$\therefore \quad \text{Area of X-section, } a_2 = \frac{3 I_2^2 \rho l}{W} = \frac{3 \times (87{\cdot}5)^2 \times (2{\cdot}85 \times 10^{-8}) \times 50 \times 10^3}{4 \times 10^5}$$

$$= 0{\cdot}818 \times 10^{-4} \text{ m}^2$$

Volume of conductor required = $3 a_2 l$ = 3 × (0·818 × 10^{-4}) × 50 × 10^3 = **12·27 m^3**

Note that volume of conductor (and hence weight) required is less in case of 3-phase, 3-wire system

5. A uniform 2-wire d.c. distributor 500 metres long is loaded with 0.4 ampere/ metre and is fed at one end. If the maximum permissible voltage drop is not to exceed 10 V, find the cross- sectional area of the distributor conductor. Take ρ = 1·7 × 10^{-6} Ω cm.(ND15)

Solution.

Current entering the distributor, $I = i \times l = 0·4 \times 500 = 200$ A Max.

permissible voltage drop = 10 V

Let r ohm be the resistance per metre length of the distributor (both wires).

Max. voltage drop $= \frac{1}{2} I R$

or $10 = \frac{1}{2} I r l$ $\quad [\because R = r\,l]$

or $\therefore \quad I_A = \frac{239 - 235}{0·12} = 33·34\text{ A} \quad ^{-3}\,\Omega$

∴ Area of cross-section of the distributor conductor is

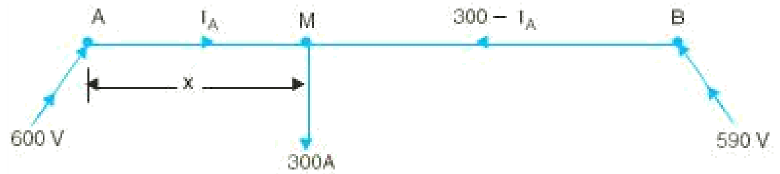
$$a = \frac{\rho\, l}{r/2} = \frac{1·7 \times 10^{-6} \times 100^{*} \times 2}{0·2 \times 10^{-3}} = 1·7\text{ cm}^2$$

6. An electric train runs between two sub-stations 6 km apart maintained at voltages 600 V and 590 V respectively and draws a constant current of 300 A while in motion. The track resistance of go and return path is 0·04 Ω/km. Calculate :

(i) the point along the track where minimum potential occurs

(ii) the current supplied by the two sub-stations when the train is at the point of minimum potential (MJ14)

Solution. The single line diagram is shown in Fig. where substation A is at 600 V and sub-station B at 590 V. Suppose that minimum potential occurs at point M at a distance x km from the substation A . Let I_A amperes be the current supplied by the sub-station A . Then current supplied by sub-station B is 300 -I_A as shown in Fig.



Resistance of track (go and return path) per km

$= 0·04\ \Omega$

Track resistance for section AM, $R_{AM} = 0·04\,x\ \Omega$

Track resistance for section MB, $R_{MB} = 0·04\,(6 - x)\Omega$

Potential at M, $V_M = V_A - I_A R_{AM}$

Also Potential at M, $V_M = V_B - (300 - I_A)\, R_{MB}$

From equations (i) and (ii), we get,

$$V_A - I_A R_{AM} = V_B - (300 - I_A)\, R_{MB}$$

or $\quad 600 - 0·04\,x\,I_A = 590 - (300 - I_A) \times 0·04\,(6 - x)$

or $\quad 600 - 0·04\,x\,I_A = 590 - 0·04\,(1800 - 300\,x - 6\,I_A + I_A \times x)$

or $\quad 600 - 0·04\,x\,I_A = 590 - 72 + 12\,x + 0·24\,I_A - 0·04\,x\,I_A$

or $\quad 0·24\,I_A = 82 - 12\,x$

or $\quad I_A = 341·7 - 50\,x$

Substituting the value of I_A in eq. (i), we get

$$V_M = V_A - (341·7 - 50\,x) \times 0·04\,x$$

$V_{..}$ $\quad 600 - 13·7x + 2x^2$

For VM to be minimum, its differential coefficient *w.r.t.* x must be zero *i.e.*

$$\frac{d}{dx}(600 - 13{\cdot}7\,x + 2x^2) = 0$$

or $$0 - 13{\cdot}7 + 4x = 0$$

$$\therefore \quad x = 13{\cdot}7/4 = \mathbf{3{\cdot}425\ km}$$

i.e. minimum potential occurs at a distance of 3·425 km from the sub-station A .

(i) $\therefore$ Current supplied by sub-station A

$$= 341{\cdot}7 - 50 \times 3{\cdot}425 = 341{\cdot}7 - 171{\cdot}25 = \mathbf{170{\cdot}45\ A}$$

Current supplied by sub-station $B = 300 - I_A = 300 - 170{\cdot}45 =$ **129·55 A**

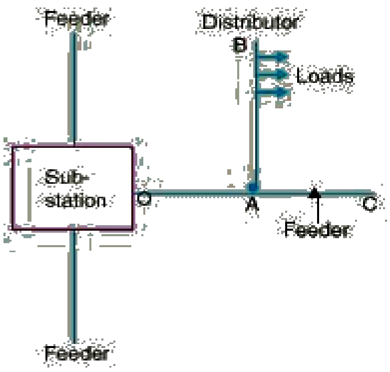
7. Explain i) Radial System ii) Ring main system iii) Interconnected system(ND10,ND13)

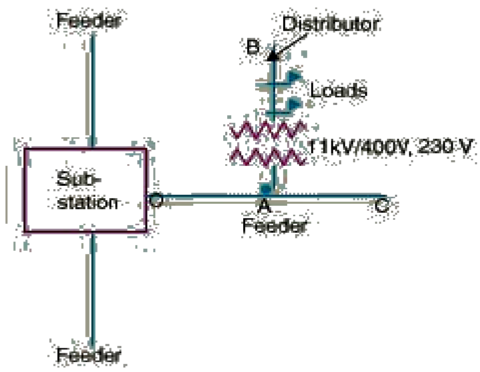
(i) Radial System.

In this system, separate feeders radiate from a single substation and feed the distributors at one end only.

Fig. 1.43 (*i*) shows a single line diagram of a radial system for d.c. distribution where a feeder *OC* supplies a distributor *AB* at point *A* . Obviously, the distributor is fed at one end only *i.e.*, point *A* is this case.

Fig. 1.43 (*ii*) shows a single line diagram of radial system for a.c. distribution. The radial system is employed only when power is generated at low voltage and the substation is located at the centre of the load.





This is the simplest distribution circuit and has the lowest initial cost. However, it suffers from the following drawbacks :

(a) The end of the distributor nearest to the feeding point will be heavily loaded.

(b) The consumers are dependent on a single feeder and single distributor. Therefore, any fault on the feeder or distributor cuts off supply to the consumers who are on the side of the fault away from the substation.

(c) 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.

(ii)Ring main system.

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.

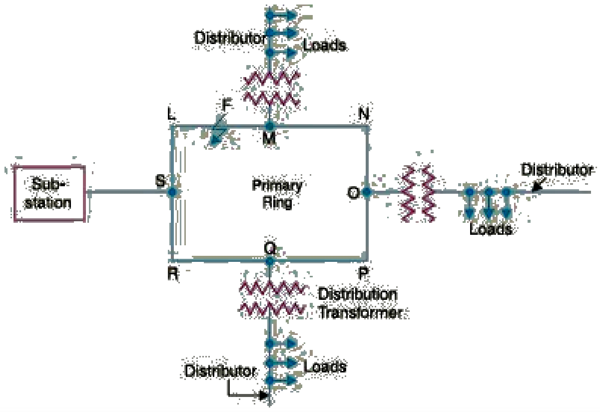
Fig.1.44.shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS. The distributors are tapped from different points *M*, *O* and *Q* of the feeder through distribu- tion transformers.

The ring main system has the following advantages :

(a) There are less voltage fluctuations at consumer's terminals.

The system is very reliable as each distributor is fed *via* the distributor from point *M* is supplied by the feeders SLM and SRQPONM.

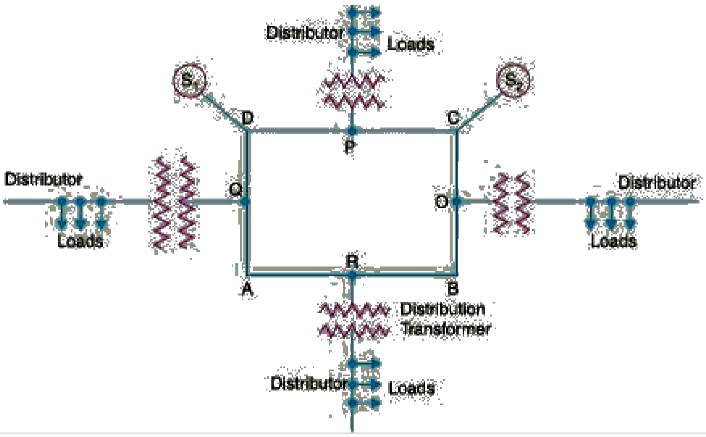
(b) two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point *F* of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers *via* the feeder *SRQPONM*.



(iii) Interconnected system.

When the feeder ring is energised by two or more than two gener- ating stations or substations, it is called inter-connected system.

Fig. 1.45 shows the single line diagram of interconnected system where the closed feeder ring *ABCD* is supplied by two substations $S1$ and $S2$ at points *D* and *C* respectively.



Distributors are connected to points *O*, *P*, *Q* and *R* of the feeder ring through distribution transformers.

The intercon- nected system has the following advantages :

(a) It increases the service reliability.

(b) Any area fed from one generating station during peak load hours can be fed from the other generating station. This reduces reserve power capacity and increases efficiency of the system.

8. Compare EHVAC and HVDC transmission system. (ND16)

Comparison of HVDC and EHVAC Transmission

The relative merits of the two modes of transmission which need to be considered by a system is based on the following factors:

1. Economics of transmission
2. Technical performance
3. Reliability

1. Economics of transmission

(i) Investment cost
(ii) Operational cost

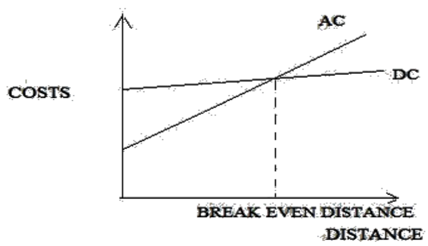
Investment Cost

It includes cost of right of way, transmission towers, conductors, insulators and terminal equipment.

Operational Cost

Mainly includes the cost of losses.

- The characteristics of insulators vary with the type of voltage applied.
- DC line can carry power with two conductors whereas AC needs three conductors.
- For a given power level, DC line requires less Right of Way, simpler and cheaper towers and reduced conductor and insulator costs.
- Power losses are also reduced in DC as there are only two conductors.
- Absence of skin effect with DC is also beneficial in reducing power losses.
- Corona effects tend to be less significant on DC conductors than for AC
- AC tends to be more economical for less than breakeven distance and costlier for longer distances
- Breakeven distances can vary from 500 to 800km in overhead lines depending on the per unit line costs

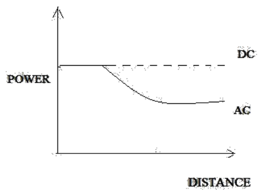


2. Technical Performance

- Full control over power transmitted.
- Ability to enhance transient and dynamic stability in associated AC networks.
- Fast control to limit fault currents in DC lines. This makes it feasible to avoid DC breakers.

Stability Limits

- Power transfer in AC lines is dependent on the angle difference between voltage phasors at two ends.
- Maximum power transfer is limited by the considerations of steady state and transient stability



Voltage Control

- Voltage control in AC is complicated by line charging and inductive voltage drops.
- Voltage profile in AC is relatively flat only for a fixed level of power transfer corresponding to surge impedance loading.
- Voltage profile varies with the loading
- Reactive power requirements increase with the increase in line lengths
- DC converter stations require reactive power related to the line loadings, the line itself does not require reactive power.

Line Compensation

- AC line requires shunt and series compensation in long distance transmission, mainly to overcome the problems of line charging and stability limitations
- Increase in power transfer and voltage control is possible through the use of static VAR systems
- In AC cable transmission, it is necessary to provide shunt compensation at regular intervals. It is a serious problem in underground cables.

Problems of AC Interconnection

- When two power systems are connected through AC ties, the automatic generation control of both systems have to be coordinated using tie line power and frequency signals.
- Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to presence of large power oscillations which can lead to frequent tripping, increase in fault level, transmission of disturbances from one system to another
- Controllability of power flow in DC lines eliminates all the above problems.

Ground Impedance

- In AC transmission the existence of ground current cannot be permitted in steady-state due to high magnitudes of ground impedance which will not only affect efficient power transfer but also telephone interference
- This is negligible for DC currents and a DC link can operate using one conductor with ground return

- While operating in mono polar mode, the AC network feeding the DC converter station operates with balanced voltages and currents.

3. Reliability

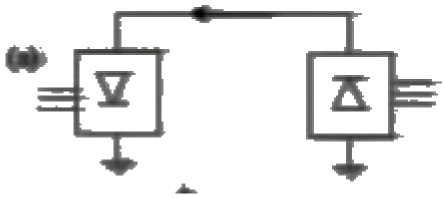
- Reliability of DC system is quite good and comparable to that of AC
- Performance of thyristor values is much more reliable than mercury arc values and further developments in devices, control and protection is likely to improve the reliability level

9. Describe the different types of HVDC links. (ND11, ND12, MJ16, ND16)

Types of HVDC links

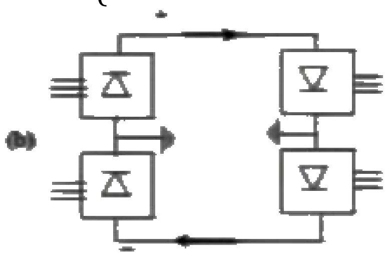
(i)Mono polar system:

One pole, one conductor for transmission and current return path is through earth. Mainly used for submarine cable transmission.



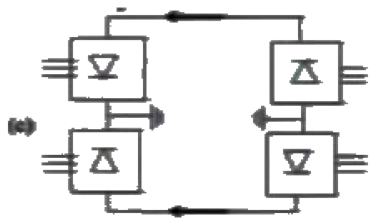
(ii)Bipolar System:

Two poles, two conductors in transmission line, one positive with respect to earth & other negative. The midpoint of Bi-poles in each terminal is earthed via an electrode line and earth electrode. In normal condition power flows through lines & negligible current through earth electrode. (in order of less than 10 Amps.)



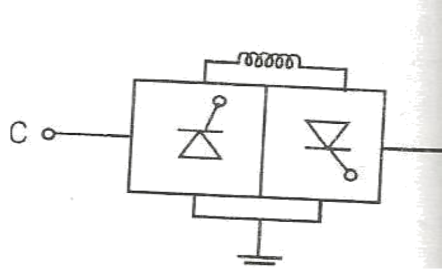
(iii) Homo Polar System:

Two poles at same polarity & current return path is through ground. This system was used earlier for combination of cable & over head transmission.



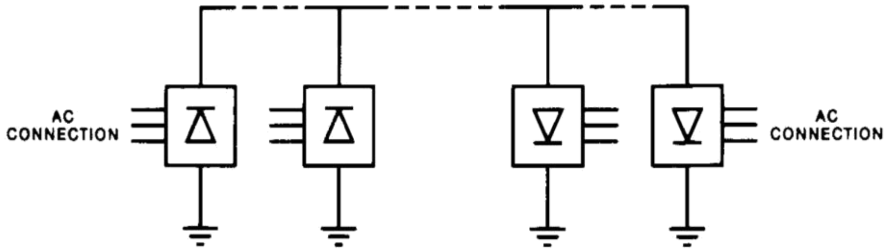
(iv) Back to Back HVDC Coupling:

Usually bipolar without earth return. Converter & inverters are located at the same place. No HVDC Transmission line. Provides Asynchronous tie between two electrical network. Improves system stability. Power transfer can be in either direction.



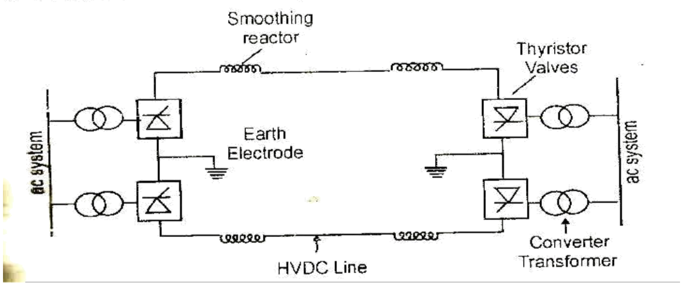
(v) Multi terminal HVDC system:

Three or more terminal connected in parallel, some feed power and some receive power from HVDC Bus. Provides Inter connection between the three or more AC network. System stability of AC network can be improved



10. Discuss in detail the various equipments used in HVDC converter station. (ND10)

Various Equipments used in HVDC Converter Station



Alternator (A.C Generator): It is a device which converts mechanical energy into electrical energy (Alternating Current).

Convertor transformer at the sending end: It is used to side step-up the generated A.C voltage at receiving end, it steps down the HVAC into distribution voltage

Surge Arrester: It is a Protective device, used to protect the equipments during lightning.

Rectifier: In sending end converter station, rectifier converts high voltage A.C into high voltage direct current (HVDC). Rectifier at receiving end is called inverter.

Filter: Both A.C and D.C Harmonics are injected into the A.C system and D.C harmonics are injected into the D.C line. These harmonics are minimized by using A.C and D.C filters.

Shunt Capacitors: To maintain the voltage at the receiving end, shunt capacitors are used.

Applications of HVDC Transmission.

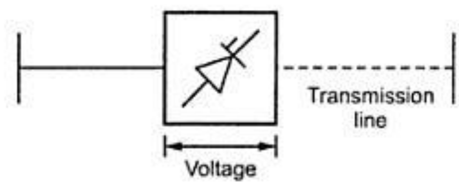
- Long distance bulk power transmission
- Underground or under water cables
- Asynchronous interconnection of AC system operating at different frequencies or where independent control of system is desired
- Control and stabilization of power flows in AC ties in an integrated power system.
- Testing of HVAC cables of long length
- Electrostatic precipitation of aching in thermal power plants
- Electrostatic painting
- Cement industry and Communication systems

11. Explain the different types of FACTS controllers. (MJ16, ND14)

Types of FACTS Controllers

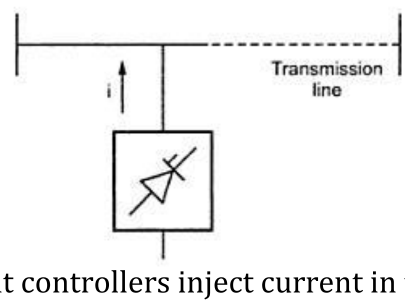
1. Series controller
2. Shunt controller
3. Combined series - series controllers
4. Combined series – shunt controller

1. Series controllers



i) Inject voltage in series with the line.
ii) The current multiplied by variable impedance represents injected series voltage in the line.
iii) Till the time the voltage is in phase quadrature with the line current, these controllers only supply variable reactive power.
iv) If there phase relationship between voltage and current is different then real power is also handled in addition to reactive power.
v) The series controller is normally of variable impedance type such as capacitor, reactor or power electronics based variable source of main, subsynchronous and harmonic to satisfy the requirement.

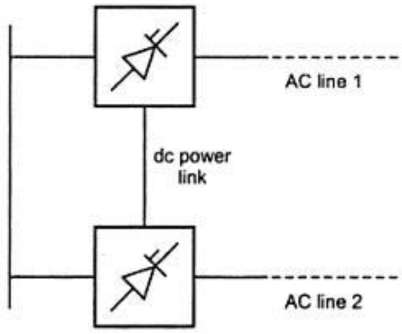
2. Shunt controllers



i) Shunt controllers inject current in the system at the point of connection.
ii) shunt controllers are of variable impedance type, variable source type or a combination.
iii) If a variable shunt impedance is connected to line voltage, variable current flows and current is injected in the line.

iv) There is quadrature relationship between voltage and current, these controllers either supply or deal with reactive power.

3. Combined series – series controllers



i) These type of controllers, series controllers are controlled in co ordinate manner in case of multiline transmission system

ii) It is alternatively unified controller in which series controllers individually supply reactive power compensating independently for every line and also transfer real power among the lines through power link.

iii) The meaning of the term unified indicates that the dc terminals of all the controller converters are all connected together for transferring real power.

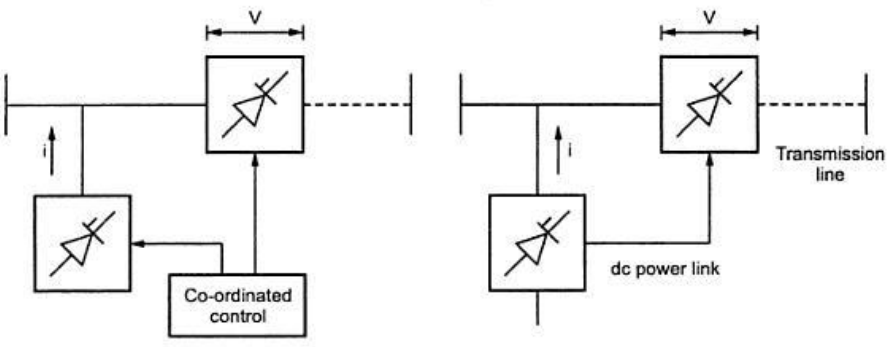
iv) The capacity of these controllers to transfer real power makes maximized utilization of transmission system as it is possible to balance both real and reactive power flow in the lines.

4. Combined shunt – series controllers

i) Combination of separate series and shunt controllers which are controlled in a co ordinate manner as shown in fig (a) or a unified power flow controller with series and shunt elements as shown in the fig (b)

ii) In these type of controllers, current is injected in the system through shunt part of the controller while voltage is injected in the line through series part of the controller.

iii) In unified series-shunt controller, it is possible to exchange real power between series and shunt controllers through dc power link

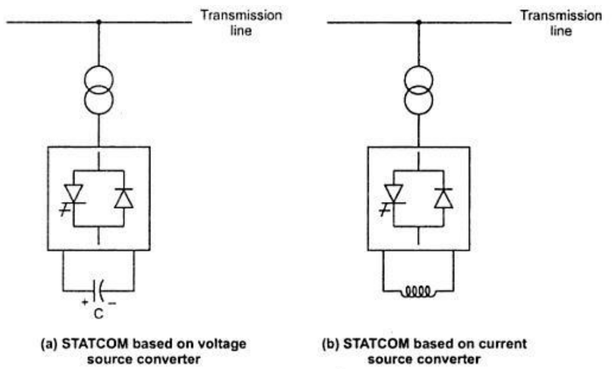


(a) Co-ordinated series-shunt controller **(b) Unified series-shunt controller**

FACTS devices:

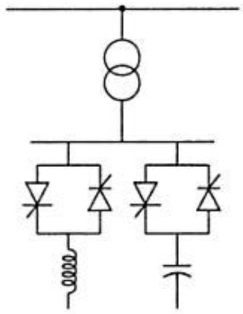
- Static synchronous compensator (STATCOM)
- Static synchronous Generator (SSG)
- Static VAR compensator (SVC)
- Thyristorized switched or controlled reactor(TSR/TCR)
- Thyristor switched capacitor
- Static VAR Generator or absorber (SVG)
- Static VAR system (SVS)
- Thyristor controlled braking Resistor (TCBR)
- Static Synchronous series compensator (SSSC)
- Interline power flow Controller (IPFC)
- Thyristor controlled or switched series capacitor or series reactor (TCSC/TSSC/TCSR/TSSR)
- Unified Power Flow controller (UPFC)
- Thyristor controlled phase shifting transformer(TCPST)
- Interphase power controller (IPC)
- Thyristor controlled voltage limiter(TCVL)
- Thyristor controlled voltage regulator (TCVR)

Static Synchronous Compensator (STATCOM)



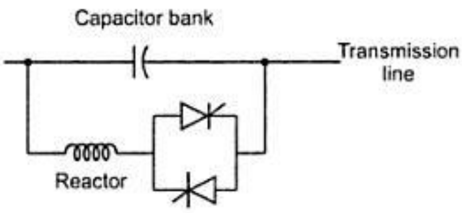
- It is shunt connected static VAR compensator whose capacitive or inductive output current can be controlled independently of the ac system voltage.
- In case of voltage source converter, the ac output voltage is controlled in such a way as the proper reactive current will flow for any bus voltage.
- The dc capacitor voltage is automatically adjusted as per the requirement so that it acts as voltage source for the converter.
- The harmonics in the system can be absorbed by designing STATCOM as an active filter.
- It is a three phase inverter driven by voltage across capacitor and the three phase output voltage are in phase with ac system voltages.
- The reactive power and its polarity can be changed by controlling the voltage.
- The performance of STATCOM is better than SVC.
- With depression in voltage, STATCOM will still supply high reactive power by using its over current capability.
- The large capacitor present acts as storage device and can continue to deliver some energy for shunt duration just like synchronous condenser.
- The use of STATCOM needs Gate turn off (GTO) thyristors which are costly as compared to normal thyristors.

Static VAR Compensator (SVC)



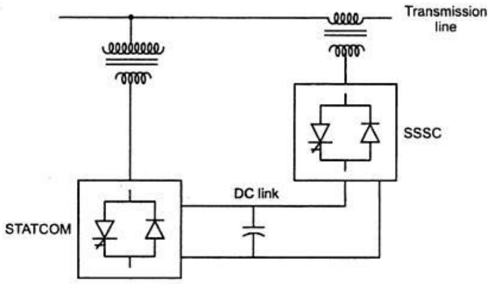
- In STATCOM, converters are used while in SVC thyristors without gate turn off capability are used.
- It is shunt connected static VAR generator or absorber.
- The output of SVC is adjusted to control capacitive or inductive current in order to control or maintain certain parameters, normally magnitude of bus voltage of the power systems.
- The separate equipments are present in SVC for lagging and leading VARs.
- It is a low cost substitute for STATCOM.
- In STATCOM, the most reactive power that is delivered is product of voltage and current whereas in case of SVC, it is the square of voltage divided by the impedance.
- The reactive power capability steeply falls off as a function of square of voltage in this case.

Thyristor controlled series capacitor (TSCS)



- It is a capacitive reactance type of compensator consisting of a series capacitor bank connected in parallel with a thyristor controlled reactor so as to provide smooth variable capacitive reactance.
- It is important type of FACTS controller based on thyristors without the gate turn off capability.
- The thyristor controlled reactor (TCR) is connected across a series capacitor. When the firing angle of TCR is 180_{o}, the reactor is non conducting and the series capacitor has its normal impedance.
- If the firing angle is decreased from 180_{o}, the capacitive impedance increases.
- The reactor is fully conducting when the firing angle is 90_{o}. In this case, the total impedance is inductive as the designed value of reactor impedance is less than the impedance of series capacitor.
- The TCSC helps in limiting fault current for firing angle of 90_{o}.
- For getting best performance from TCSC, it has different sized smaller capacitors or several equal capacitors instead of a single large unit.

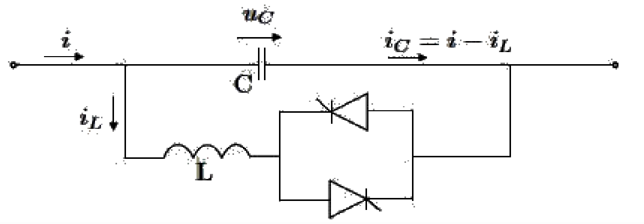
Unified Power flow controller (UPFC)



- It is a combination of static synchronous compensator (STATCOM) and static synchronous series compensator(SSSC).
- These two are coupled through a dc link and allows bidirectional flow of real power between series output terminals of SSSC and shunt output terminals of the STATCO.
- These can be controlled to provide real and reactive series line compensation without an electrical energy source.
- The meaning of UPFC is angular, unconstrained injection of series voltage to control selectively the line voltage, impedance and angle.
- Alternatively, real and reactive power flow in the line is controlled.
- The independent controllable shun compensation is also provided by UPFC.
- UPFC can be made more effective by connecting additional storage shunt as a super conducting magnet connected to the dc link through the electronic interface.
- The controlled exchange of real power is possible in case of UPFC.

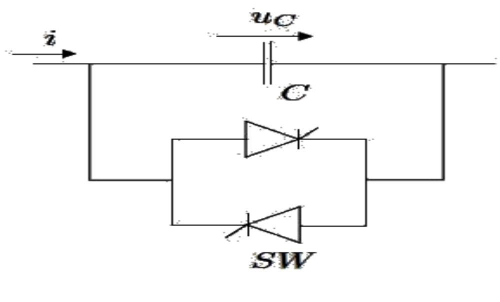
Thyristor-Controlled Series Capacitor (TCSC)

A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.



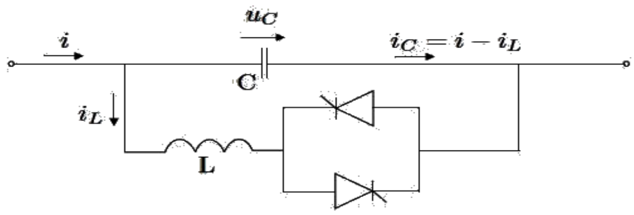
Thyristor-Switched Series Capacitor (TSSC)

TSSC is a capacitive reactance compensator, which consists of a series capacitor bank shunted by a thyristor-switched reactor to provide a stepwise control of series capacitive reactance.



Thyristor-Controlled Series Capacitor (TCSC)

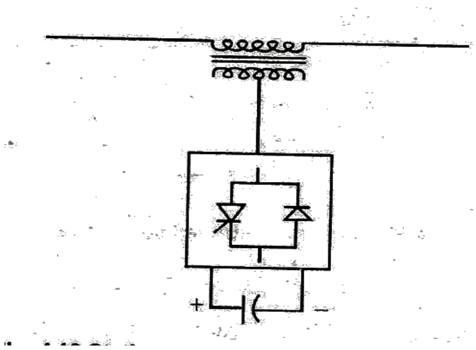
A capacitive reactance compensator which consists of a series capacitor bank shunted by a thyristor-controlled reactor in order to provide a smoothly variable series capacitive reactance.



Static-Synchronous Series Compensator (SSSC)

- A static synchronous generator operated without an external electric energy source as a series compensator whose output voltage is in quadrature with, and controllable independently of, the line current for the purpose of increasing or decreasing the overall reactive voltage drop across the line and thereby controlling the transmitted electric power.

- The SSSC may include transiently rated energy storage or energy absorbing devices to enhance the dynamic behavior of the power system by additional temporary active power compensation, to increase or decrease momentarily, the overall active (resistive) voltage drop across the line.



EE6402 – TRANSMISSION AND DISTRIBUTION

UNIT - II

1. Derive the expression for inductance of a single phase transmission line.(ND14, MJ15)

Inductance of a Single Phase Two-wire Line

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

The conductors are spaced several metres and the length of the line is several kilometres. Therefore, the loop has a large X-sectional area.

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

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

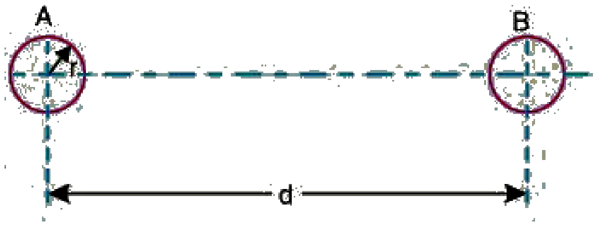


Fig.2.6

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

Flux linkages with conductor *A* due to its own current

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

Flux linkages with conductor *A* due to current I_B

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

Total flux linkages with conductor A is

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\therefore \quad L_A = 2\times10^{-7}\log_e \frac{d}{r\,e^{-1/4}}$$

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

$$L_A = 2\times10^{-7}\log_e \frac{d}{r'} \text{ H/m} \quad \text{...}(iii)$$

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

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

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

$$\text{Loop inductance} = 2\,L_A = 2\times2\times10^{-7}\log_e \frac{d}{r'} \text{H/m}$$

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

2. Derive the expression for inductance of 3 – phase transmission line. (ND10, MJ13, ND15)

Inductance of a 3-Phase Overhead Line

Fig.2.7 shows the three conductors *A*, *B* and *C* of a 3-phase line carrying currents I_A, I_B and I_C respectively. Let d_1, d_2 and d_3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced *i.e.* $I_A + I_B + I_C = 0$. Consider the flux linkages with conductor *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.

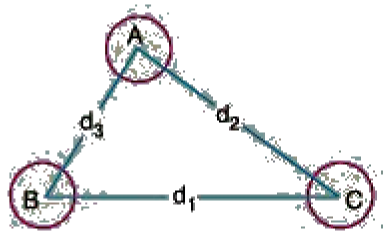


Fig.2.7

Flux linkages with conductor *A* due to its own current

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

Flux linkages with conductor *A* due to current I_B

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

Flux linkages with conductor A due to current I_C

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

Total flux linkages with conductor A is

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

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

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

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

As $I_A + I_B + I_C = 0,$

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

(i)Symmetrical spacing. If the three conductors *A, B* and *C* are placed symmetrically at the corners of an equilateral triangle of side *d,* then, $d1 = d2 = d3 = d$. Under such conditions, the flux linkages with conductor *A* become :

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

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

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

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

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

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

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

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

(i)Unsymmetrical spacing. When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, the flux linkages and inductance of each phase are not the same. A different inductance in each phase results in unequal voltage drops in the three phases even if the currents in the conductors are balanced. There- fore, the voltage at the receiving end will not be the same for all phases. In order that voltage drops are equal in all conductors, we generally interchange the positions of the conductors at regular inter- vals along the line so that each conductor occupies the original position of every other conductor over an equal distance. Such an exchange of positions is known as *transposition.*

Fig. 9.9 shows the transposed line. The phase conductors are designated as *A, B* and *C* and the positions occupied are numbered 1, 2 and 3. The effect of transposition is that each conductor has the same average inductance

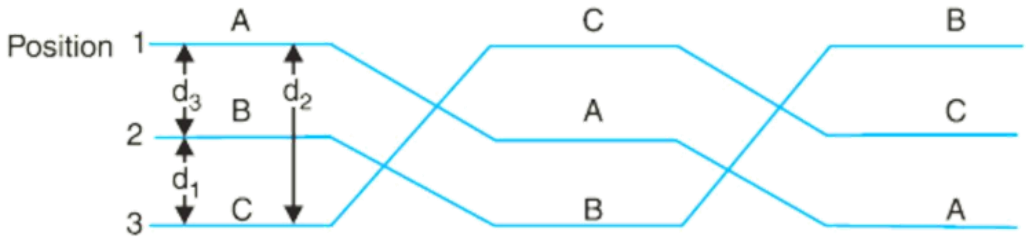


Fig.2.8

Fig. 2.8 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume that each of the three sections is 1 m in length. Let us further assume balanced conditions *i.e.,* $I_A + I_B + I_C = 0$. Let the line currents be :

$$I_A = I\,(1 + j\,0)$$

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

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

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

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

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

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

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

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

* $0{\cdot}5\,I\,(\log_e d_3 + \log_e d_2) = 0{\cdot}5\,I\log_e d_2 d_3 = I\log_e (d_2 d_3)^{0{\cdot}5} = I\log_e \sqrt{d_2 d_3}$

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

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

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

∴ Inductance of conductor *A* is

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

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

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

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

Similarly inductance of conductors B and C will be :

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

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

Inducance of each line conductor

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

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

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

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

Problems:

Inductance Formulas in Terms of GMD

(i) Single phase line

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

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

(ii) Single circuit 3-φ line

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

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

(iii) Double circuit 3-φ line

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

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

3. A single phase line has two parallel conductors 2 metres apart. The diameter of each conductor is 1·2 cm. Calculate the loop inductance per km of the line. (ND08)

Solution.

Spacing of conductors, d = 2 m = 200 cm

Radius of conductor, r = 1·2/2 = 0·6 cm Loop inductance per metre length of the line

$$= 10^{-7} (1 + 4 \log_e d/r) \text{ H}$$
$$= 10^{-7} (1 + 4 \log_e 200/0{\cdot}6) \text{ H}$$
$$= 24{\cdot}23 \times 10^{-7} \text{ H}$$

Loop inductance per km of the line

$$= 24{\cdot}23 \times 10^{-7} \times 1000 = 24{\cdot}23 \times 10^{-4} \text{ H} = \mathbf{2{\cdot}423\ mH}$$

4. A single phase transmission line has two parallel conductors 3 m apart, the radius of each conductor being 1 cm. Calculate the loop inductance per km length of the line if the material of the conductor is (i) copper (ii) steel with relative permeability of 100. (ND09)

Solution:

Spacing of conductors, $d = 300$ cm

Radius of conductor, $r = 1$ cm

Loop inductance $= 10^{-7}(\mu_r + 4 \log_e d/r)$ H/m

(i) With copper conductors, $\mu_r = 1$

$\therefore$ Loop inductance/m $= 10^{-7}(1 + 4 \log_e d/r)$ H $= 10^{-7}(1 + 4 \log_e 300/1)$ H

$= 23{\cdot}8 \times 10^{-7}$ H

Loop inductance/km $= 23{\cdot}8 \times 10^{-7} \times 1000 = 2{\cdot}38 \times 10^{-3}$ H $=$ **2·38 mH**

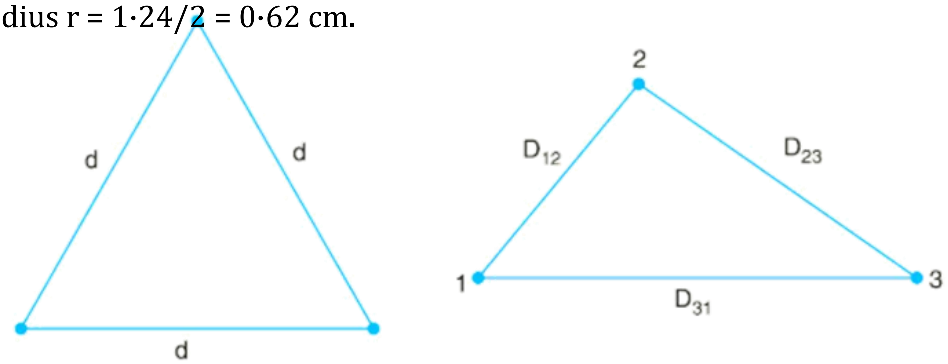
(ii) With steel conductors, $\mu_r = 100$

$\therefore$ Loop inductance/m $= 10^{-7}(100 + 4 \log_e 300/1)$ H $= 122{\cdot}8 \times 10^{-7}$ H

Loop inductance/km $= 122{\cdot}8 \times 10^{-7} \times 1000 = 12{\cdot}28 \times 10^{-3}$ H $=$ **12·28 mH**

5. Find the inductance per km of a 3-phase transmission line using 1·24 cm diameter conductors when these are placed at the corners of an equilateral triangle of each side 2 m. (ND13, MJ15)

Solution. Fig. shows the three conductors of the three phase line placed at the corners of an equilateral triangle of each side 2 m. Here conductor spacing d = 2 m and conductor radius r = 1·24/2 = 0·62 cm.



Inductance/phase/m $= 10^{-7}(0{\cdot}5 + 2 \log_e d/r)$ H

$= 10^{-7}(0{\cdot}5 + 2 \log_e 200/0{\cdot}62)$ H

$= 12 \times 10^{-7}$ H

Inductance/phase/km $= 12 \times 10^{-7} \times 1000$

$= 1{\cdot}2 \times 10^{-3}$ H $=$ **1·2 mH**

6. Derive the expression for capacitance of a single phase transmission line. (MJ13,ND15)

Capacitance of a Single Phase Two-wire Line

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

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

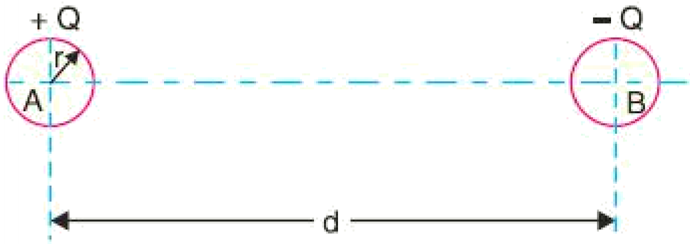


Fig 2.11

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

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

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

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

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

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

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

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

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

Capacitance to neutral. Equation (*i*) gives the capacitance between the conductors of a two-wire line Often it is desired to know the capacitance between one of the conductors and a neutral point between them. Since potential of the mid-point between the conductors is zero, the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the *capacitance to ground* or capacitance to neutral for the two- wire line is *twice* the line-to-line capacitance (capacitance between conductors as shown in Fig 2.12).

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

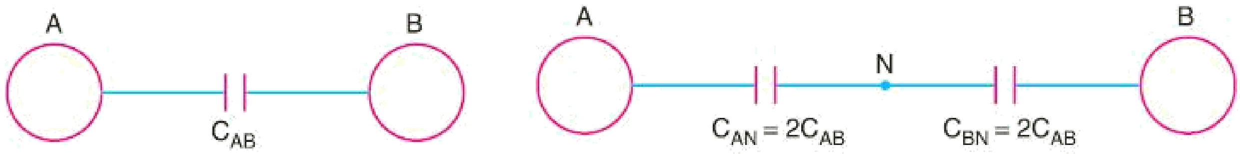


Fig.2.12

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

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

7. Derive the expression for capacitance of a three – phase transmission line. (ND12, ND13, MJ14, ND14, ND15, MJ16)

Capacitance of a 3-Phase Overhead Line

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

Symmetrical Spacing. Fig. 2.13. shows the three conductors *A*, *B* and *C* of the 3-phase overhead transmission line having charges Q_A, Q_B and Q_C per metre length respectively. Let the conductors be equidistant (*d* metres) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line.

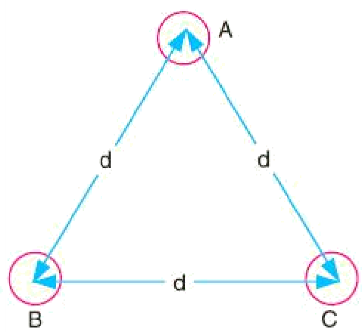


Fig 2.13

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

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

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

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

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

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

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

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

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

IN

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

Unsymmetrical spacing. Fig. 2.14. shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions *i.e.* $QA + QB + QC = 0$.

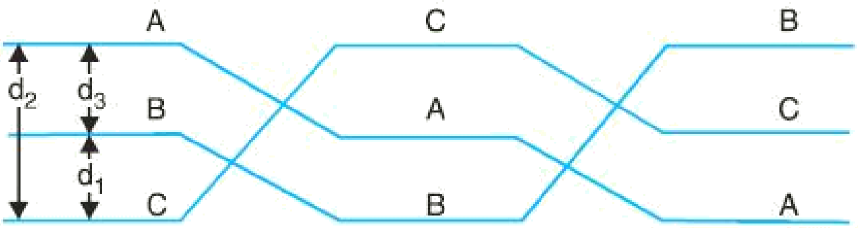


Fig.2.14

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

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

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

Average voltage on condutor A is

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

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

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

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

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

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

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

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

$\therefore$ Capacitance from conductor to neutral is

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

8. A single-phase transmission line has two parallel conductors 3 metres apart, radius of each conductor being 1 cm. Calculate the capacitance of the line per km. Given that ε0= v=8·854 × 10^{-12} F/m. (ND09)

Solution:

Conductor radius, r = 1 cm

Spacing of conductors, d = 3 m = 300 cm

Capacitance of the line $= \frac{\pi\varepsilon_0}{\log_e d/r}$ F/m $= \frac{\pi \times 8\cdot854 \times 10^{-12}}{\log_e 300/1}$ F/m

$= 0\cdot4875 \times 10^{-11}$ F/m $= 0\cdot4875 \times 10^{-8}$ F/km

$= $ **$0\cdot4875 \times 10^{-2}$ μF/km**

9. A 3-phase overhead transmission line has its conductors arranged at the corners of an equilateral triangle of 2 m side. Calculate the capacitance of each line conductor per km. Given that diameter of each conductor is 1·25 cm. (ND14)

Solution.

Conductor radius,r = 1·25/2 = 0·625 cm

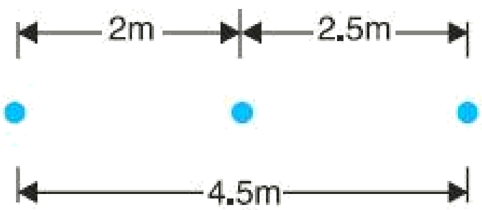
Spacing of conductors,d = 2 m = 200 cm

Capacitance of each line conductor

$$= \frac{2\pi\varepsilon_0}{\log_e d/r} \text{ F/m} = \frac{2\pi \times 8\cdot854 \times 10^{-12}}{\log_e 200/0\cdot625} \text{ F/m}$$

$= 0\cdot0096 \times 10^{-9}$ F/m $= 0\cdot0096 \times 10^{-6}$ F/km = **0·0096 μF/km**

10. A 3-phase, 50 Hz, 66 kV overhead line conductors are placed in a horizontal plane as shown in Fig. The conductor diameter is 1·25 cm. If the line length is 100 km,calculate (i) capacitance per phase, (ii) charging current per phase, assuming complete transposition of the line. (ND15)



Solution. Fig shows the arrangement of conductors of the 3-phase line. The equivalent equilateral spacing is

Conductor radius, r = 1·25/2 = 0·625 cm

Conductor spacing , d = 2·82 m = 282 cm

(*i*) Line to neutral capacitance$= \frac{2\pi\varepsilon_0}{\log_e d/r} \text{ F/m} = \frac{2\pi \times 8\cdot854 \times 10^{-12}}{\log_e 282/0\cdot625} \text{ F/m}$

$= 0\cdot0091 \times 10^{-9}$ F/m $= 0\cdot0091 \times 10^{-6}$ F/km $= 0\cdot0091$ μF/km

∴ Line to neutral capacitance for 100 km line is

$$C = 0\cdot0091 \times 100 = \mathbf{0\cdot91\ \mu F}$$

(*ii*) Charging current per phase is

$$I_C = \frac{V_{ph}}{X_C} = \frac{66{,}000}{\sqrt{3}} \times 2\pi f C$$

$$= \frac{66{,}000}{\sqrt{3}} \times 2\pi \times 50 \times 0\cdot91 \times 10^{-6} = \mathbf{10\cdot9\ A}$$

11. Derive the expression for voltage induced in communication lines due to current in power lines. (ND11, ND13)

Introduction:

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

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

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

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

1) Because of harmonics in power circuit, their frequency range and magnitudes.

2) Electromagnetic coupling between power and telephone conductor.

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

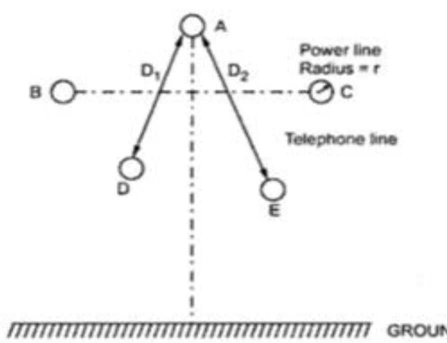
3) Due to unbalance in power circuits and in telephone circuits.

4) Type of return telephone circuit i.e. either metallic or ground return.

5) Screening effects.

Electro Magnetic Effect

Consider a line transmitting power with 3 conductors A, B and C. Consider a telephone line with two conductors D and E below the power line conductors. The two lines are running on the same supports. This is shown in the Fig. 2.18.



Consider the loop formed by the conductors A and D. Let the radius of each power line conductor be r. Let the distance between conductors A and D be whereas the distance between conductors A and E be D_2. Assuming that in loop AD, A is contributing to the e.m.f. induced in D. If we neglect the internal flux linkages then the inductance of this loop is given by,

$$L_{AD} = 2\times10^{-7}\, ln\left(\frac{D_1}{r}\right) H/m$$

The inductance of the loop AE is given by,

$$L_{AE} = 2\times10^{-7}\, ln\left(\frac{D_2}{r}\right) H/m$$

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

$$M_A = L_{AE} - L_{AD} = 2\times10^{-7}\left[ln\left(\frac{D_2}{r}\right) - ln\left(\frac{D_1}{r}\right)\right]$$

$$= 2\times10^{-7}\, ln\left(\frac{D_2}{D_1}\right) H/m$$

Similarly the mutual inductance between conductors B and C and loop DE can be obtained. Let these mutual inductances be M_B and M_C respectively. These mutual inductances are due to fluxes which have a phase displacement of 120^o. Hence the net effect of the magnetic field will be

$M = M_A + M_B + M_C$

Here M is the net mutual inductance which is the phasor sum of the three inductances. If the current flowing through the power line conductors is I and the supply frequency is f then the voltage induced in the communication conductors D and E is given by, $V = 2\ \omega\ f\ I\ M$ volts/m

From the above expression, it can be seen that with increase in distance between power and communication line, the values of M_A, M_B and M_C nearly becomes equal in magnitude and with the result that the net inductance M becomes very very small. As a consequence the voltage induced in telephone lines also diminshes.

The voltage induced in the neighbouring telephone line is directly proportional to frequency. If third harmonic is present then voltage equal to 3 times the voltage due to harmonic currents in power line is additive. In unbalanced condition i.e. during fault the flux linkage and corresponding voltage induced is very high which may prove to be dangerous for telephone circuits.

The presence of harmonics and multiples of third harmonics will not cancel as they are in phase in all power line conductors. In balanced condition the total induced voltage due to harmonic currents in power line is additive. In unbalanced condition i.e. during fault the flux linkage and corresponding voltage induced is very high which may prove to be dangerous for telephone circuits.

If the distance between power line and the telephone line is increased then the induced voltage in telephone line van be reduced. It can also be reduced by transposing the line.

Electrostatic Effect

Consider the line conductor A running parallel to infinite plane (i.e. earth). Let D be the conductor from neighbouring telephone line. Conductor A' is the image of conductor A below ground as shown in the Fig. 2.19 The potential distribution between the conductor and earth is exactly same as that of its image and the plane.

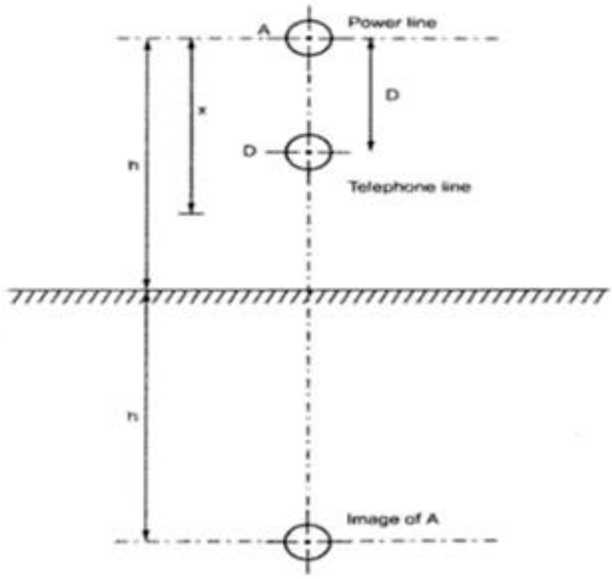


Fig.2.19

The potential of point A with respect to the earth is given by,

$$V_A = \frac{1}{2\pi\varepsilon}\int_r^h \left(\frac{q}{x}+\frac{q}{2h-x}\right)dx = \frac{q}{2\pi\varepsilon}\left[\int_r^h \frac{dx}{x}+\int_r^h \frac{dx}{2h-x}\right]$$

$$= \frac{q}{2\pi\varepsilon}\left\{(ln\, x)_r^h + [-ln\,(2h-x)]_r^h\right\}$$

$$= \frac{q}{2\pi\varepsilon}\left[ln\, h - ln\, r - ln\, h + ln(2h-r)\right]$$

$$= \frac{q}{2\pi\varepsilon}\left[ln(2h-r) - ln\, r\right]$$

$$V_A = \frac{q}{2\pi\varepsilon}\, ln\left(\frac{2h-r}{r}\right) \text{ volts}$$

The potential of point D due to conductor A is given by,

$$V_{DA} = \frac{1}{2\pi\varepsilon}\int_{d}^{h}\left(\frac{q}{x}+\frac{q}{2h-x}\right)dx$$

$$= \frac{q}{2\pi\varepsilon}\left[\int_{d}^{h}\frac{dx}{x}+\int_{d}^{h}\frac{dx}{2h-x}\right]$$

$$= \frac{q}{2\pi\varepsilon}\left\{(\ln x)_{d}^{h}+[-\ln(2h-x)]_{d}^{h}\right\}$$

$$= \frac{q}{2\pi\varepsilon}\left[\ln h - \ln d - \ln h + \ln(2h-d)\right]$$

$$= \frac{q}{2\pi\varepsilon}\ln\left(\frac{2h-d}{d}\right)$$

Multiplying and dividing by $\ln\left(\frac{2h-r}{r}\right)$

$$= \frac{q}{2\pi\varepsilon}\ln\left(\frac{2h-r}{r}\right)\frac{\ln(2h-d/d)}{\ln(2h-r/r)}$$

$$\therefore \quad V_{DA} = V_A\frac{\ln(2h-d/d)}{\ln(2h-r/r)} \text{ volts}$$

In the similar fashion, the voltages and can be calculated. Finally the resultant potential of point D with respect to earth is given by,

$V_D = V_{DA} + R_2 + R_2$

The above addition is the phasor addition.

Similarly the resultant potential of point E, V_E can be calculated using the same procedure.

12. **Explain corona formation, factors affecting corona and methods to reduce the corona (ND12, MJ15)**

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 sur- rounding the wires if the applied voltage is low. 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.

(i) Corona formation

Some ionisation is always present in air due to cosmic rays, ultraviolet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles (*i.e.,* free electrons and +ve ions) and neutral molecules.

When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons.

When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cummulative.The result of this ionisation is that either corona is formed or spark takes place between the conductors.

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 ionsiation 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 dis- tance between conductors reduces the electro-static stresses at the conductor surface, thus avoiding corona formation.

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

Methods of Reducing Corona Effect

Intense corona effects are observed at a working voltage of 33 kV or above. Therefore, careful design should be made to avoid corona on the sub-stations or bus-bars rated for 33 kV and higher voltages otherwise highly ionised air may cause flash-over in the insulators or between the phases, causing considerable damage to the equipment.

The corona effects can be reduced by the following methods :

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

13. Explain the following i) Critical disruptive voltage ii) visual critical voltage iii) power ' loss due to corona iv) Advantages and disadvantages of corona (MJ15, ND16, MJ17)

(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 g_O. If V_C is the phase-neutral potential required under these conditions, then,

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

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

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

The above expression for disruptive voltage is under standard conditions *i.e.,* at 76 cm of Hg and 25ºC. However, if these conditions vary, the air density also changes, thus altering the value of 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*ºC becomes $\delta\, g_O$

where

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

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

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

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.

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

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

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

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

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

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

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

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

where f = supply frequency in Hz

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

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

2.6.4 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 neighbouring communication lines.

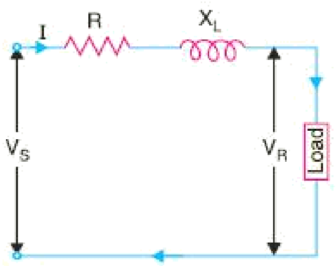
EE6402 – TRANSMISSION AND DISTRIBUTION
UNIT - III

1. Derive the expression for voltage regulation and transmission efficiency of short transmission line. (MJ13)

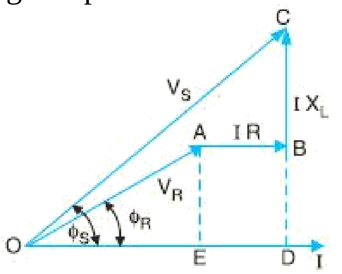
Performance of single phase Short Transmission Lines:

- The effects of line capacitance are neglected for a short transmission line.
- Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account.
- The equivalent circuit of a single phase short transmission line is shown in Fig.3.1 (i).
- Here the total resistance and inductance are shoen as concentrared or lumped instead of being distributed. The circuit is a simple ac series circuit.

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



(i)



(ii)

Fig.3.1

The *phasor diagram of the line for lagging load power factor is shown in Fig. 3.1 (*ii*). From the right angled traingle *ODC*, we get,

* **Phasor diagram.** Current I is taken as the reference phasor. OA represents the receiving end voltage VR leading I by ϕ_R. AB represents the drop IR in phase with I. BC represents the inductive drop IXL and leads I by 90$_S$°. OC represents the sending end voltage V and leads I by ▯ .

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

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

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

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

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

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

Line losses $= I^2 R$

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

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

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

Anapproximate expression for the sending end voltage VS can be obtained as follows. Draw perpendicular from *B* and *C* on *OA* produced as shown in Fig. 3.2. Then *OC* is *nearly* equal to *OF i.e.,*

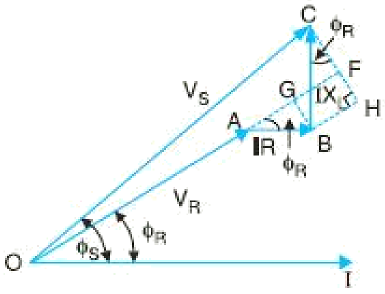


Fig.3.2

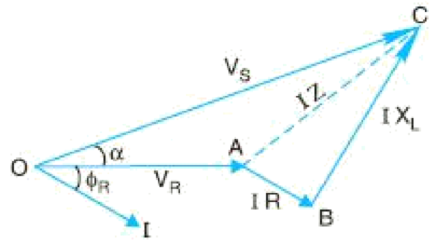


Fig.3.3

$$OC = OF = OA + AF = OA + AG + GF$$
$$= OA + AG + BH$$
$$\therefore \quad V_S = V_R + IR\cos\phi_R + IX_L\sin\phi_R$$

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

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

$$^*\overrightarrow{V_R} = V_R + j\,0$$
$$\vec{I} = \vec{I}\,\angle -\phi_R = I(\cos\phi_R - j\sin\phi_R)$$
$$\vec{Z} = R + jX_L$$
$$\therefore \quad \overrightarrow{V_S} = \overrightarrow{V_R} + \vec{I}\,\vec{Z}$$
$$= (V_R + j\,0) + I(\cos\phi_R - j\sin\phi_R)(R + jX_L)$$
$$= (V_R + IR\cos\phi_R + IX_L\sin\phi_R) + j(IX_L\cos\phi_R - IR\sin\phi_R)$$
$$\therefore \quad V_S = \sqrt{(V_R + IR\cos\phi_R + IX_L\sin\phi_R)^2 + (IX_L\cos\phi_R - IR\sin\phi_R)^2}$$

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

$$VS = VR + I\,R\cos\phi R + I\,XL\sin\phi R$$

The following poins may be noted :

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

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

2. Derive the expression for voltage regulation and transmission efficiency of medium transmission line (MJ13)

Medium Transmission Lines:

- In short transmission line calculations, the effects of the line capacitance are neglected because such lines have smaller lengths and transmit power at relatively low voltages (<20kV).
- However, as the length and voltage of the line increase4, the capacitance gradually becomes of greater importance.
- Since medium transmission lines have sufficient length (50-150 km) and usually operate at voltages greater than 20kV, the effects of capacitance cannot be neglected.
- Therefore, in order to obtain reasonable accuracy in medium transmission line calculations, the line capacitance must be taken into consideration.
- The capacitance is uniformly distributed over the entire length of the line.
- The most commonly used methods (known as localized capacitance methods) for the solution of medium transmission lines are:

(i) End condenser method

(ii) Nominal T method

(iii) Nominal π method.

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

End condenser method

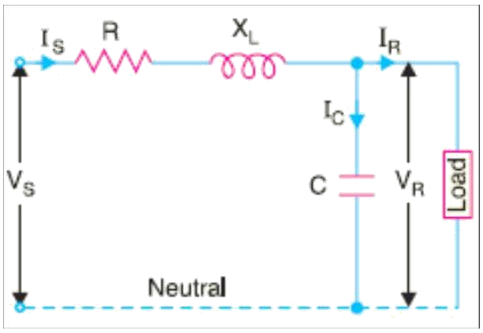
In this method, the capacitance of the line is lumped or concentrated at the receiving or load end as shown in Fig. 3.5(i). This method of localizing the line capacitance at the load end overestimates the effects of capacitance. In Fig. 10.8, one phase of the 3-phase transmission line is shown as it is more convenient to work in phase instead of line-to-line values.

Let I_R = load current per phase

R = resistance per phase

C = capacitance per phase

cos ϕ_R = receiving end power factor (*lagging*)



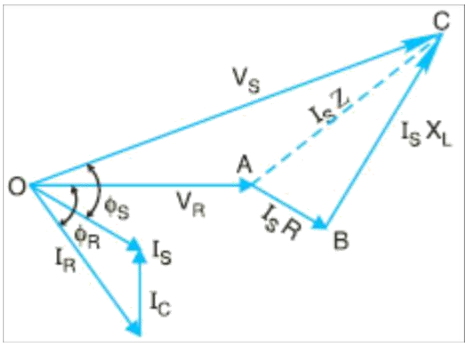


Fig.3.5(i) Fig.3.5(ii)

VS = sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig 3.5(ii)

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Nominal T Method

- In this method, the whole line capacitance is assumed to be concentrated at the middle point of the line and half the resistance and reactance are lumped on its either side as shown in Fig. 3.6.
- Therefore, in this arrangement, full charging current flows over half the line.
- In Fig. 3.6, one phase of 3-phase transmission line is shown as it is advantageous to work in phase instead of line-to-line values.

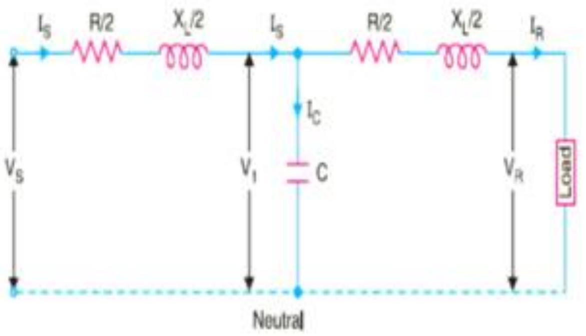


Fig.3.6(i)

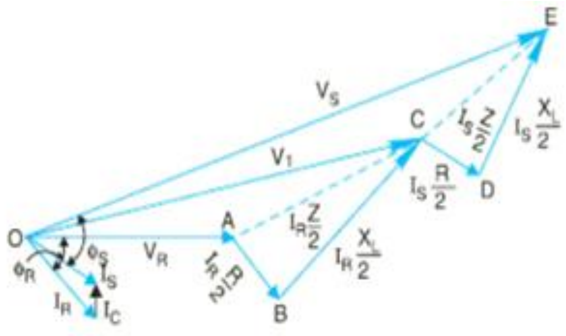


Fig.3.6(ii)

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

X_L = inductive reactance per phase ; C = capacitance per phase

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

V_1 = voltage across capacitor C

The *phasor diagram for the circuit is shown in Fig 3.6(ii).

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

we have,

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

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

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

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

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

Capacitive current, $\vec{I_C} = j\omega C\vec{V_1} = j2\pi f C\vec{V_1}$

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

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

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

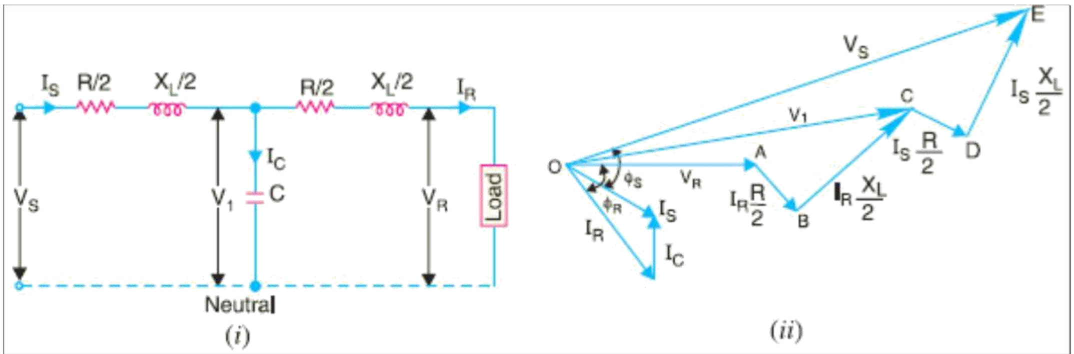
Resistance/km/phase = 0.1 Ω

Inductive reactance/km/phase = 0·2 Ω

Capacitive susceptance/km/phase = 0·04 × 10^{-4} siemen

Determine (i) the sending end current (ii) sending end voltage (iii) sending end power factor and (iv) transmission efficiency when supplying a balanced load of 10,000 kW at 66 kV, p.f. 0·8 lagging. Use nominal T method. (MJ16)

Solution:



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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

∴ Sending end current $=$ **100 A**

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

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

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

∴ Line value of sending end voltage

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

(iii) Referring to phasor diagram in Fig.

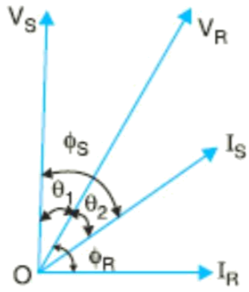
θ_1 = angle between $\vec{V_R}$ and $\vec{V_S} = 1°40'$

θ_2 = angle between $\vec{V_R}$ and $\vec{I_S} = 29°\,47'$

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

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

∴ Sending end power factor, $\cos\phi_S = \cos 31°27' =$ **0·853 lag**



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

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

Power delivered $= 10{,}000$ kW

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

4. Derive the expression for voltage regulation and transmission efficiency of medium transmission line by nominal π Method. (ND10)

Nominal π Method

In this method, capacitance of each conductor (*i.e.,* line to neutral) is divided into two halves; one half being lumped at the sending end and the other half at the receiving end as shown in Fig. 3.7(i). It is obvious that capacitance at the sending end has no effect on the line drop. However, its charging current must be added to line current in order to obtain the total sending end current

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

cos φ_R = receiving end power factor (*lagging*)

V_S = sending end voltage per phase

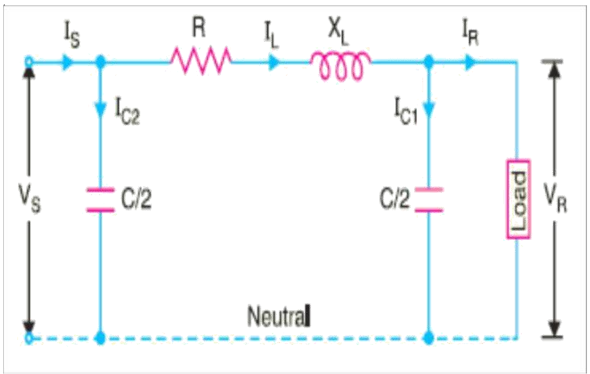


Fig.3.7(i)

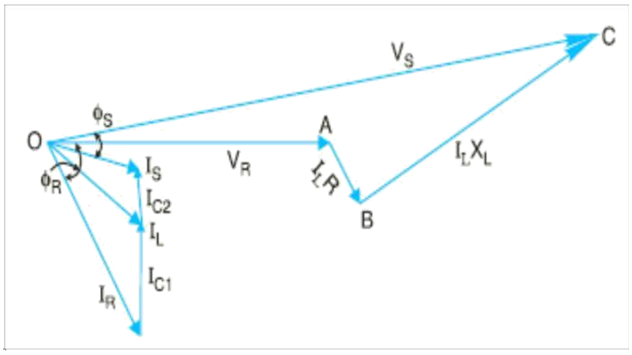


Fig.3.7(ii)

The *phasor diagram for the circuit is shown in Fig. 3.7(ii). Taking the receiving end voltage as the reference phasor, we have,

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

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

Charging current at load end is

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

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

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

Charging current at the sending end is

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

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

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

5. Derive the expression for voltage regulation and transmission efficiency of long transmission line by rigorous method. (ND12, ND15)

Analysis of Long Transmission Line (Rigorous method)

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

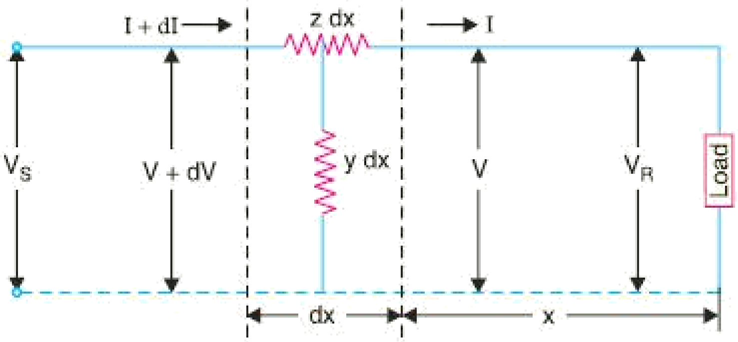


Fig.3.9

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

Let *z* = series impedance of the line per unit length

y = shunt admittance of the line per unit length

V = voltage at the end of element towards receiving end

V + *dV* = voltage at the end of element towards sending end *I* + *dI* = current entering the element *dx*

I = current leaving the element *dx*

Then for the small element *dx*,

z dx = series impedance

y dx = shunt admittance

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

or $$\frac{dV}{dx} = I z \quad \text{...}(i)$$

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

dI = Current through shunt admittance of element = $V\,y\,dx$

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

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

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

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

The solution of this differential equation is

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

Differentiating exp. (*iv*) *w.r.t.* *x*, we have,

$$\frac{dV}{dx} = k_1 \sqrt{y\,z}\,\sinh(x\sqrt{y\,z}) + k_2 \sqrt{y\,z}\,\cosh(x\sqrt{y\,z})$$

But $$\frac{dV}{dx} = I\,z \qquad \text{[from exp. (}i\text{)]}$$

$$\therefore \quad I\,z = k_1 \sqrt{y\,z}\,\sinh(x\sqrt{y\,z}) + k_2 \sqrt{z\,y}\,\cosh(x\sqrt{y\,z})$$

or $$I = \sqrt{\frac{y}{z}}\left[k_1 \sinh\,(x\sqrt{y\,z}) + k_2 \cosh\left(x\sqrt{y\,z}\right)\right] \qquad \text{...(}v\text{)}$$

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

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

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

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

$$\therefore \quad V_R = k_1$$

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

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

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

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

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

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

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

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

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

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

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

where Y = total shunt admittance of the line

Z = total series impedance of the line

Therefore, expressions for V_S and I_S become :

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

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

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

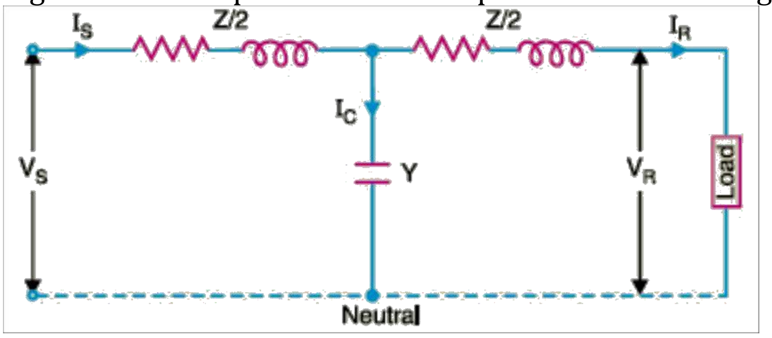
$$\cosh\sqrt{Y\,Z} = \left(1 + \frac{Z\,Y}{2} + \frac{Z^2Y^2}{24} + \ldots\ldots\right)$$

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

6. A balanced 3-phase load of 30 MW is supplied at 132 kV, 50 Hz and 0·85 p.f. lagging by means of a transmission line. The series impedance of a single conductor is (20 + j52) ohms and the total phase-neutral admittance is 315×10^{-6} siemen. Using nominal T method, deter- mine: (i) the A, B, C and D constants of the line (ii) sending end voltage (iii) regulation of the line. (ND11, MJ15)

Solution:

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



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

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

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

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

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

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

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

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

(ii) **Sending end voltage.**

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

Receiving end current, $I_R = \dfrac{30 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0{\cdot}85} = 154$ A

$\cos\phi_R = 0{\cdot}85\ ;\quad \sin\phi_R = 0{\cdot}53$

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

$$\vec{V_R} = V_R + j0 = 76210 \text{ V}$$

$$\vec{I_R} = I_R(\cos\phi_R - j\sin\phi_R) = 154(0{\cdot}85 - j\,0{\cdot}53) = 131 - j\,81{\cdot}62$$

Sending end voltage per phase is

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

$$= (0{\cdot}992 + j\,0{\cdot}0032)\,76210 + (19{\cdot}84 + j\,51{\cdot}82)(131 - j\,81{\cdot}62)$$

$$= 82{,}428 + j\,5413$$

∴ Magnitude of sending end voltage is

$$V_S = \sqrt{(82{,}428)^2 + (5413)^2} = 82{\cdot}6 \times 10^3 \text{V} = 82{\cdot}6 \text{ kV}$$

∴ Sending end line-to-line voltage

$$= 82{\cdot}6 \times \sqrt{3} = \mathbf{143\ kV}$$

***(iii)* Regulation.** Regulation is defined as the change in voltage at the receiving end when full-load is thrown off.

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

At no load, $\vec{I_R} = 0$

∴ $\vec{V_S} = \vec{A}\,\vec{V_{R0}}$

where $\vec{V_{R0}}$ = voltage at receiving end at no load

or $\vec{V_{R0}} = \vec{V_S}/\vec{A}$

or $V_{R0} = V_S/A$ (in magnitude)

∴ $$\%\text{ Regulation} = \frac{(V_S/A - V_R)}{V_R} \times 100 = \frac{(82{\cdot}6/0{\cdot}992) - 76{\cdot}21}{76{\cdot}21} \times 100 = \mathbf{9{\cdot}25\%}$$

7. A 132 kV, 50 Hx, 3-phase transmission line delivers a load of 50 MW at 0·8 p.f. lagging at the receiving end. The generalised constants of the transmission line are :

A = D = 0·95∠1·4° ; B = 96∠78° ; C = 0·0015∠90°

Find the regulation of the line and charging current. Use Nominal-T method. (ND12)

Solution:

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

Receiving end current, $$I_R = \frac{50 \times 10^6}{\sqrt{3} \times 132 \times 10^3 \times 0{\cdot}8} = 273 \text{ A}$$

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

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

$$\vec{V_R} = V_R + j\,0 = 76210\,\angle 0°$$

$$\vec{I_R} = I_R\,\angle -\phi_R = 273\,\angle -36{\cdot}9°$$

Sending end voltage per phase is

$$\vec{V_S} = \vec{A}\ \vec{V_R} + \vec{B}\ \vec{I_R}$$
$$= 0{\cdot}95\ \angle 1{\cdot}4° \times 76210\ \angle 0° + 96\ \angle\ 78° \times 273\ \angle{-36{\cdot}9°}$$
$$= 72400\ \angle 1{\cdot}4° + 26208\ \angle 41{\cdot}1°$$
$$= 72400\ (\cos 1{\cdot}4° + j \sin 1{\cdot}4°) + 26208\ (\cos 41{\cdot}1° + j \sin 41{\cdot}1°)$$
$$= 72400\ (0{\cdot}9997 + j\ 0{\cdot}0244) + 26208\ (0{\cdot}7536 + j\ 0{\cdot}6574)$$
$$= (72378 + j\ 1767) + (19750 + j\ 17229)$$
$$= 92128 + j\ 18996 = 94066\ \angle 11{\cdot}65°\ \text{V}$$

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

$$= 0{\cdot}0015\ \angle 90° \times 76210\ \angle 0° + 0{\cdot}95\ \angle 1{\cdot}4° \times 273\ \angle{-36{\cdot}9°}$$
$$= 114\ \angle\ 90° + 260\ \angle{-35{\cdot}5°}$$
$$= 114\ (\cos 90° + j \sin 90°) + 260\ (\cos 35{\cdot}5° - j \sin 35{\cdot}5°)$$
$$= 114\ (\ 0 + j) + 260\ (0{\cdot}814 - j\ 0{\cdot}58)$$
$$= j\ 114 + 211 - j\ 150\ = 211 - j\ 36$$

Charging current, $\vec{I_C} = \vec{I_S} - \vec{I_R} = (211 - j36) - 273\ \angle{-36{\cdot}9°}$

$$= (211 - j\ 36) - (218 - j\ 164) = -7 + j\ 128 = \mathbf{128{\cdot}2\ \angle 93{\cdot}1°\ A}$$

$$\%\ \text{Regulation} = \frac{(V_S/A) - V_R}{V_R} \times 100 = \frac{94066/0{\cdot}95 - 76210}{76210} \times 100 = \mathbf{30\%}$$

8. Find the following for a single circuit transmission line delivering a load of 50 M VA at 110 kV and p.f. 0·8 lagging : i) sending end voltage (ii) sending end current (iii) sending end power (iv) efficiency of transmission. Given A = D = 0·98 ∠3°; B = 110 ∠75° ohm ; C = 0·0005 ∠80° siemen. (ND14)

Solution:

Receiving end voltage/phase,

$$V_R = \frac{110}{\sqrt{3}} = 63{\cdot}5\ \text{kV}$$

Receiving end current, $I_R = \dfrac{50 \times 10^6}{\sqrt{3} \times 110 \times 10^3} = 262{\cdot}4$ A

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

$$\vec{V_R} = (63500 + j0)$$

$$\vec{I_R} = 262{\cdot}4\ \angle{-\cos^{-1} 0{\cdot}8} = 262{\cdot}4\ (0{\cdot}8 - j\ 0{\cdot}6) = (210 - j\ 157{\cdot}5)\ \text{A}$$

(i) Now sending-end voltage per phase is

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

Here $\vec{A}\,\vec{V_R} = 0{\cdot}98\ \angle 3^\circ \times 63500\ \angle 0^\circ = 62230\ \angle 3^\circ = (62145 + j\,3260)$ V

and $\vec{B}\,\vec{I_R} = 110\ \angle 75^\circ \times 262{\cdot}4\ \angle -36{\cdot}86^\circ$

$= 28865\ \angle 38{\cdot}14^\circ = (22702 + j\,17826)$ V

$\therefore\quad \vec{V_S} = (62145 + j\,3260) + (22702 + j\,17826)$

$= 84847 + j\,21086 = 87427\ \angle 14^\circ$ V

$\therefore$ Magnitude of sending-end voltage/phase = **87427 V**

(*ii*) Sending-end current is given by ;

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

Here $\vec{C}\,\vec{V_R} = 0{\cdot}0005\ \angle 80^\circ \times 63500\ \angle 0^\circ = 31{\cdot}75\ \angle 80^\circ = (5{\cdot}5 + j\,31{\cdot}3)$ A

and $\vec{D}\,\vec{I_R} = 0{\cdot}98\ \angle 3^\circ \times 262{\cdot}4\ \angle -36{\cdot}86^\circ$

$= 257{\cdot}15\ \angle -33{\cdot}8^\circ = (213{\cdot}5 - j\,143{\cdot}3)$ A

$\therefore\quad \vec{I_S} = (5{\cdot}5 + j\,31{\cdot}3) + (213{\cdot}5 - j\,143{\cdot}3)$

$= 219 - j\,112 = 246\ \angle -27^\circ$ A

$\therefore$ Magnitude of sending-end current = **246 A**

(*iii*) Sending-end power $= 3\,V_S I_S \cos\phi_S$

Here $V_S = 87427$ V ; $I_S = 246$ A ; $\cos\phi_S = \cos(-27^\circ - 14^\circ)$

$\therefore$ Sending-end power $= 3 \times 87427 \times 246 \times \cos(-27^\circ - 14^\circ)$

$= 48{\cdot}6 \times 10^6$ W = **48·6 MW**

(*iv*) Receiving end power $= 50 \times 0{\cdot}8 = 40$ MW

Transmission efficiency, $\eta = \dfrac{40}{48{\cdot}6} \times 100 =$ **82·3%**

9. Derive the expression for real and reactive power flow through transmission lines. (MJ15, ND15, ND16)

Power Flow through Transmission Line

- The flow of power at any point along a transmission line can be determined with voltage, current and power factor. This power can be derived in terms of the transmission or ABCD parameters. These equations can be applied to any two terminal pair network.
- Fig. 3.13. shows, a transmission line with sending end quantities represented by subscript '5' and receiving end quantities represented by subscript 'R'.

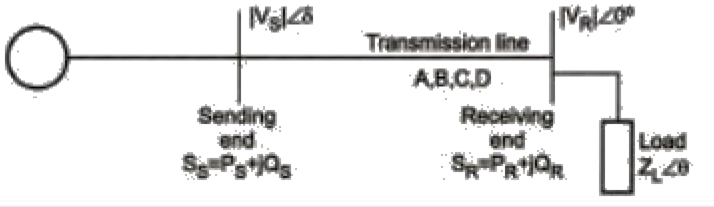


Fig.3.13

The complex power delivered by the receiving end and that received by the sending end of the transmission line is given as,

$$S_R = P_R + jQ_R = V_R I_R^*$$

$$S_S = P_S + jQ_S = V_S I_S^*$$

Here I_R^* and I_S^* are complex conjugate of currents I_R and I_S. Consider the Fig. 4.36.

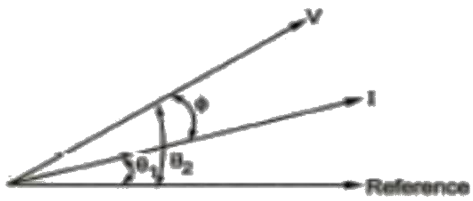


Fig.3.14

$$P + jQ = VI^*$$

where $\quad V = V[\cos\theta_2 + j\sin\theta_2]$

$$I = I[\cos\theta_1 + j\sin\theta_1]$$

and $\quad I^* = I[\cos\theta_1 - j\sin\theta_1]$

$$P + jQ = [V(\cos\theta_2 + j\sin\theta_2)][I(\cos\theta_1 - j\sin\theta_1)]$$

$$= VI\{[\cos\theta_2\cos\theta_1 + \sin\theta_1\sin\theta_2] + j[\sin\theta_2\cos\theta_1 - \cos\theta_2\sin\theta_1]\}$$

$$= VI[\cos(\theta_2 - \theta_1) + j\sin(\theta_2 - \theta_1)] = VI[\cos\phi + j\sin\phi]$$

$$= VI\cos\phi + j\,VI\sin\phi$$

Consider the following equation for sending end voltage in terms of ABCD parameters.

$$\bar{V}_S = \bar{A}\bar{V}_R + \bar{B}\bar{I}_R$$

$$\therefore \quad \bar{I}_R = \frac{\bar{V}_S - \bar{A}\bar{V}_R}{\bar{B}}$$

Let $\bar{A} = |A| \angle\alpha$, $\bar{B} = |B| \angle\beta$, $\bar{V}_R = |V_R| \angle 0^\circ$

$$\bar{V}_S = |V_S| \angle\delta$$

Substituting these values in the equation for $\bar{I}_R$

$$\bar{I}_R = \frac{|V_S| \angle\delta - [|A| \angle\alpha][|V_R| \angle 0^\circ]}{|B| \angle\beta}$$

$$\therefore \quad \bar{I}_R = \frac{|V_S|}{|B|} \angle\delta-\beta - \frac{|A||V_R|}{|B|} \angle\alpha-\beta$$

The complex power at the receiving end is given by,

$$P_R + jQ_R = V_R I_R^* = \frac{|V_R||V_S|}{|B|} \angle\beta-\delta - \frac{|A||V_R|^2}{|B|} \angle\beta-\alpha$$

The real and reactive power at receiving end are,

$$P_R = \frac{|V_S|\ |V_R|}{|B|} \cos(\beta-\delta) - \frac{|A|\ |V_R|^2}{|B|} \cos(\beta-\alpha)$$

$$Q_R = \frac{|V_S|\ |V_R|}{|B|} \sin(\beta-\delta) - \frac{|A|\ |V_R|^2}{|B|} \sin(\beta-\alpha)$$

Similarly the sending end complex power is given by

$$P_S + jQ_S = \frac{|D|}{|B|} |V_S|^2 \angle\beta-\alpha - \frac{|V_S|\ |V_R|}{|B|} \angle\beta+\delta$$

The real and reactive power at sending end are,

$$P_S = \frac{|D|\ |V_S|^2}{|B|} \cos(\beta-\alpha) - \frac{|V_S|\ |V_R|}{|B|} \cos(\beta+\delta)$$

$$Q_S = \frac{|D|\ |V_S|^2}{|B|} \sin(\beta-\alpha) - \frac{|V_S|\ |V_R|}{|B|} \sin(\beta+\delta)$$

The receiving end power will be maximum when $\beta = \delta$ as seen from above equation.

Substituting $\beta = \delta$ in the expression for P_R we get

$$P_{R\,max} = \frac{|V_S|\ |V_R|}{|B|} - \frac{|A|\ |V_R|^2}{|B|} \cos(\beta-\alpha)$$

The corresponding Q_R when P_R is maximum is given by,

$$Q_R = -\frac{|A|\ |V_R|^2}{|B|} \sin(\beta-\alpha)$$

- Thus maximum real power will be received if the load draws the leading reactive power given by above equation.

- Thus it can be seen that there is limit to the power that can be transmitted to the receiving end of the line for specified magnitudes of sending and receiving end voltages.

- When angle 8 becomes equal to 13, maximum power will be transferred or delivered.

- Further increase in 8 results in less power received.

- For achieving the condition of maximum power the load must draw a large amount of leading current which is not practicable. But by using leading VAR compensation the power transfer can be improved.

10. Describe the concept and procedure to draw the power circle diagram. (ND15)

POWER CIRCLE DIAGRAM

- By taking either V_S, V_R, I_S or I_R as a reference these characteristics can be plotted. These characteristics are nothing but representing circles. Hence such diagrams are called circle diagram.
- A circle diagram is drawn with real power P on X-axis and Q on Y axis on complex plane. The circle diagram can be drawn at the sending end as well as at the receiving end.
- These diagrams are helpful for determination of active power P, reactive power Q, power angle 8, power factor for given load conditions, voltage conditions and impedance Z of the line.

Receiving End Circle Diagram

The complex power at the receiving end is given by,

$$S_R = P_R + jQ_R$$

$$= \frac{|V_S|\,|V_R|}{|B|} \angle \beta - \delta - \frac{|A|\,|V_R|^2}{|B|} \angle \beta - \alpha$$

$$P_R = \frac{|V_S|\,|V_R|}{|B|} \cos(\beta - \delta) - \frac{|A|\,|V_R|^2}{|B|} \cos(\beta - \alpha)$$

$$Q_R = \frac{|V_S|\,|V_R|}{|B|} \sin(\beta - \delta) - \frac{|A|\,|V_R|^2}{|B|} \sin(\beta - \alpha)$$

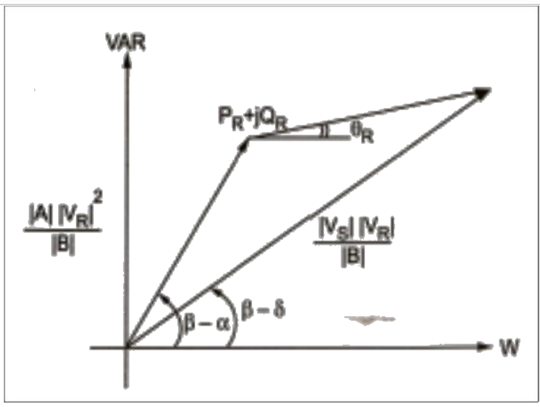


Fig.3.14

The real component of $(P_R + jQ_R)$ is,

$P_R = |V_R|\ |I_R| \cos \theta_R$

where θ_R is p.f. at the receiving end

The imaginary component of $(P_R + jQ_R)$ is,

$Q_R = |V_R|\ |I_R| \sin\theta_R$

Here θ_R is the phase angle by which I_R lags behind V_R. the inductive load draws positive reactive power. Now the phasor diagram is redrawn with the origin of the co-ordinates axes shifted, the resultant figure is shown in Fig.3.15

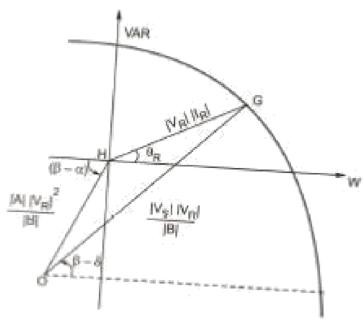


Fig.3.15

It can be shown that for constant values of V_R and V_S and for variable values of I_R the point G moves on a circle with centre O.

In Δ OGH

$$V_S = |A|\ |V_R|\left[-\cos(\beta-\alpha)+j\sin(\beta-\alpha)\right]+|B|\ |I_R|\left[\cos\theta_R - j\sin\theta_R\right]$$

$$= |A|\ |V_R|\left[-\cos(\beta-\alpha)\right]+|B|\ |I_R|\cos\theta_R + j\left[|A|\ |V_R|\sin(\beta-\alpha)-|B|\ |I_R|\sin\theta_R\right]$$

Let $|A|\ |V_R|\left[\cos(\beta-\alpha)\right] = -x_1$

$|B|\ |I_R|\cos\theta_R = x_2$

$|A|\ |V_R|\sin(\beta-\alpha) = y_1$

$|B|\ |I_R|\sin\theta_R = -y_2$

The above equations are now reduced as,

$$V_S = (x_1+x_2)+j(y_1+y_2) \quad \text{... (1)}$$

The conjugate of V_S can be written as,

$$V_S^* = (x_1+x_2)-j(y_1+y_2) \quad \text{... (2)}$$

Multiplying equations (1) and (2),

$$V_S^2 = (x_1+x_2)^2+(y_1+y_2)^2$$

The above equation represents a circle with its centre at O and having co-ordinates ($-x_1$,$-y_1$) All the phasors shown in Fig. represent voltage. In order to represent them as volt amperes, multiply each phasor by constant V_R/B, which represents a current phasor because B has dimensions of impedance.

The co-ordinates of the centre of the receiving end circle are given as

$$x_1 = -\frac{|A|\ |V_R|^2}{|B|}\cos(\beta-\alpha)$$

$$y_1 = -\frac{|A|\ |V_R|^2}{|B|}\sin(\beta-\alpha)$$

The radius OG of the circle is given by,

$$\text{Radius} = \frac{|V_S|\ |V_R|}{|B|}$$

The θ_R is the phase angle by which V_R leads I_R. The position of point O is independent of load current I_R and will not change as long as IVRI is constant. Furthermore if values of Vs and V_R are constant then distance OG remains constant.

Now with change in load, the distance between points Hand G goes on changing. As the values of Vs and V_R are fixed, distance between points O and G remains same which constrain point G to move on a circle with centre at *O* and radius as O*G.*

In order to keep point G on the circle it is required that with change in P_R, Q_R should also change. If values of sending end voltages are changed then for same values IVRI, the position of point O is unchanged but a new circle with different radius is obtained.

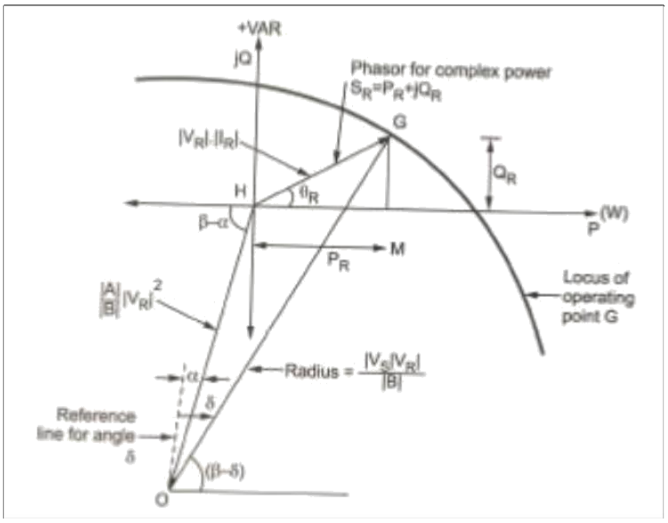


Fig.3.16

An increase in power delivered means that point G will move along the circle until the angle β – δ is zero. Thus so long as δ=β, maximum power is delivered. With further increase in δ, results in less power at receiving end. The equation for maximum power is given by,

$$P_{R\,max} = \frac{|V_S|\;|V_R|}{|B|} - \frac{|A|\;|V_R|^2}{|B|}\cos(\beta-\alpha)$$

11. Describe the different methods of voltage control. (MJ17)

Methods of Voltage Control

There are several methods of voltage control. In each method, the system voltage is changed in accordance with the load to obtain a fairly constant voltage at the consumer's end of the system. The following are the methods of voltage control in an *a.c. power system:

(i) By excitation control

(ii) By using tap changing transformers

(iii) Auto-transformer tap changing

(iv) Booster transformers

(v) Induction regulators

(vi) By synchronous condenser

Method (*i*) is used at the generating station only whereas methods (*ii*) to (*v*) can be used for transmission as well as primary distribution systems. However, methods (*vi*) is reserved for the voltage control of a transmission line. We shall discuss each method separately in the next sections.

(i) Excitation Control

When the load on the supply system changes, the terminal voltage of the alternator also varies due to the changed voltage drop in the synchronous reactance of the armature. The voltage of the alternator can be kept constant by changing the *field current of the alternator in accordance with the load. This is known as *excitation control* method. The excitation of alternator can be controlled by the use of automatic or hand operated regulator acting in the field circuit of the alternator. The first method is preferred in modern practice. There are two main types of automatic voltage regulators *viz*.

(vii) Tirril Regulator

(viii) Brown-Boveri Regulator

These regulators are based on the "overshooting the mark †principle" to enable them to respond quickly to the rapid fluctuations of load. When the load on the alternator increases, the regulator produces an increase in excitation more than is ultimately necessary. Before the voltage has the time to increase to the value corresponding to the increased excitation, the regulator reduces the excitation to the proper value.

(ii) Tap -Changing transformers:

The excitation control method is satisfactory only for relatively short lines. However, it is *not suitable for long lines as the voltage at the alternator terminals will have to be varied too much in order that the voltage at the far end of the line may be constant. Under such situations, the problem of voltage control can be solved by employing other methods. One important method is to use tap- changing transformer and is commonly employed where main transformer is necessary. In this method, a number of tappings are provided on the secondary of the transformer. The voltage drop in the line is supplied by changing the secondary e.m.f. of the transformer through the adjustment of its number of turns.

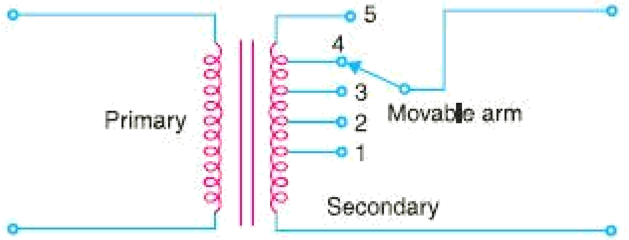


Fig 3.17

(a) Off load tap-changing transformer. Fig. 3.17. shows the arrangement where a number of tappings have been provided on the secondary. As the position of the tap is varied, the effective number of secondary turns is varied and hence the output voltage of the secondary can be changed. Thus referring to Fig. 3.17, when the movable arm makes contact with stud 1, the secondary voltage is minimum and when with stud 5, it is maximum. During

the period of light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on stud 1. When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at the previous value by placing the movable arm on to a higher stud. Whenever a tapping is to be changed in this type of transformer, the load is kept off and hence the name off load tap-changing transformer.

(b) On-load tap-changing transformer. In supply system, tap-changing has normally to be performed on load so that there is no interruption to supply. Fig. 15.5 shows diagrammatically one type of on-load tap-changing transformer. The secondary consists of two equal parallel windings which have similar tappings 1*a* ...... 5*a* and 1*b* .... 5*b*. In the normal working conditions, switches *a*, *b* and tappings with the same number remain closed and each secondary winding carries one-half of the total current. Referring to Fig. 3.18, the secondary voltage will be maximum when switches *a*, *b* and 5*a*, 5*b* are closed. However, the secondary voltage will be minimum when switches *a*, *b* and 1*a,* 1*b* are closed.

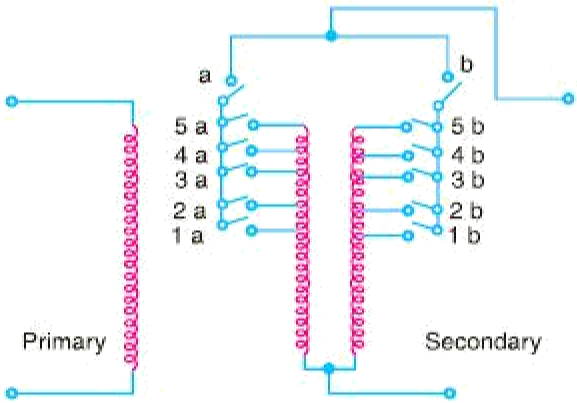


Fig.3.18

Suppose that the transformer is working with tapping position at 4*a*, 4*b* and it is desired to alter its position to 5*a*, 5*b*. For this purpose, one of the switches *a* and *b*, say *a*, is opened. This takes the secondary winding controlled by switch *a* out of the circuit. Now, the secondary winding controlled by switch *b* carries the total current which is twice its rated capacity. Then the tapping on the disconnected winding is changed to 5*a* and switch *a* is closed. After this, switch *b* is opened to disconnect its winding, tapping position on this winding is changed to 5*b* and then switch *b* is closed. In this way, tapping position is changed without interrupting the supply. This method has the following disadvantages :

- During switching, the impedance of transformer is increased and there will be a voltage surge.
- There are twice as many tappings as the voltage steps.

(iii) Auto-transformer tap changing

Fig. 3.19. shows diagrammatically auto-transformer tap changing. Here, a mid-tapped auto-transformer or reactor is used. One of the lines is connected to its mid-tapping. One end, say *a* of this transformer is connected to a series of switches across the odd tappings and the other end *b* is connected to switches across even tappings. A short-circuiting switch *S* is connected across the auto-transformer and remains in the closed position under normal operation. In the normal operation, there is *no inductive voltage drop across the auto-transformer. Referring to Fig. 3.19, it is clear that with switch 5 closed, minimum secondary turns are in the circuit and hence the output voltage will be the lowest. On the other hand, the output voltage will be maximum when switch 1 is closed.

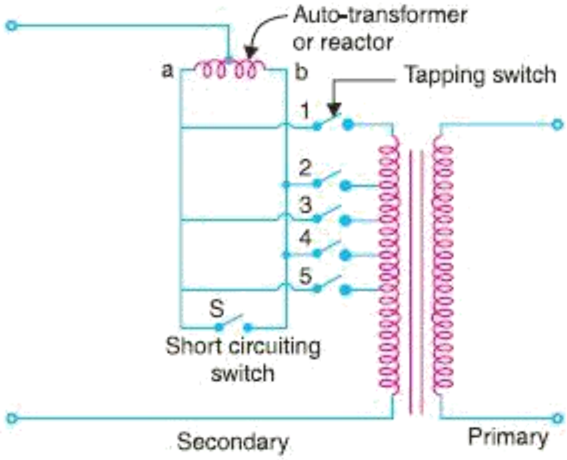


Fig.3.19

Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage. For this purpose, short-circuiting switch *S* is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed. In this way, tapping can be changed without interrupting the supply.

It is worthwhile to describe the electrical phenomenon occurring during the tap changing. When the short-circuiting switch is opened, the load current flows through one-half of the reactor coil so that there is a voltage drop across the reactor. When switch 4 is closed, the turns between points 4 and 5 are connected through the whole reactor winding. A circulating current flows through this local circuit but it is limited to a low value due to high reactance of the reactor.

(iv) Booster Transformer

Sometimes it is desired to control the voltage of a transmission line at a point far away from the main transformer. This can be conveniently achieved by the use of a booster transformer as shown in Fig.3.20. The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled. The primary of this transformer is supplied from a regulating transformer *fitted with on-load tap-changing gear. The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.

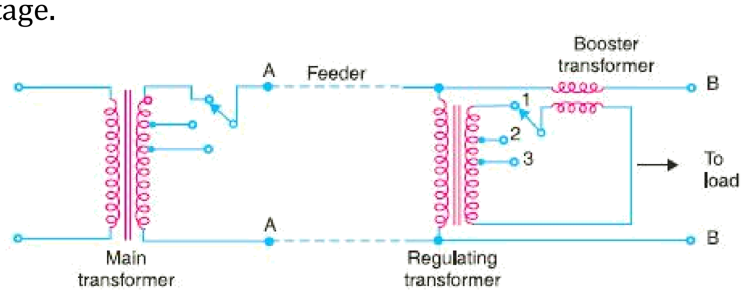


Fig.3.20

The voltage at *AA* is maintained constant by tap-changing gear in the main transformer. However, there may be considerable voltage drop between *AA* and *BB* due to fairly long feeder and tapping of loads. The voltage at *BB* is controlled by the use of regulating transformer and booster transformer. By changing the tap- ping on the regulating transformer, the magnitude of the voltage injected into the line can be varied. This permits to keep the voltage at *BB* to the desired value. This method of voltage control has three disadvantages. Firstly, it is more expensive than the on-load tap-changing transformer. Secondly, it is less efficient owing to losses in the booster and thirdly more floor space is required. Fig. 3.21. shows a three-phase booster transformer.

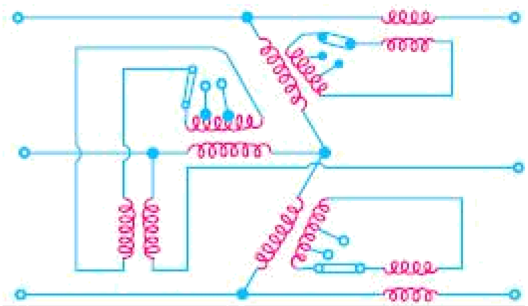


Fig. 3.21

(v)Induction Regulators

An induction regulator is essentially a constant voltage transformer, one winding of which can be moved *w.r.t.* the other, thereby obtaining a variable secondary voltage. The primary winding is connected across the supply while the secondary winding is connected in series with the line whose voltage is to be controlled. When the position of one winding is changed w.r.t. the other, the secondary voltage injected into the line also changes. There are two types of induction regulators *viz.* single phase and 3-phase.

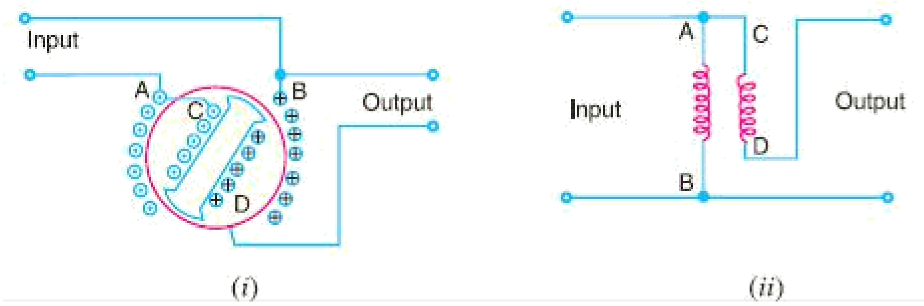


Fig. 3.22

(a) Single-phase induction regulator. A single phase induction regulator is illustrated in Fig.3.22. In construction, it is similar to a single phase induction motor except that the rotor is not allowed to rotate continuously but can be adjusted in any position either manually or by a small motor. The primary winding *AB* is wound on the *stator and is connected across the supply line. The secondary winding *CD* is wound on the rotor and is connected in series with the line whose voltage is to be controlled.

The primary exciting current produces an alternating flux that induces an alternating voltage in the secondary winding *CD*. The magnitude of voltage induced in the secondary depends upon its position *w.r.t.* the primary winding. By adjusting the rotor to a suitable position, the secondary volt- age can be varied from a maximum positive to a maximum negative value. In this way, the regulator can add or subtract from the circuit voltage according to the relative positions of the two windings. Owing to their greater flexibility, single phase regulators are frequently used for voltage control of distribution primary feeders.

(b) Three-phase induction regulator. In construction, a 3-phase induction regulator is similar to a 3-phase induction motor with wound rotor except that the rotor is not allowed to rotate continuously but can be held in any position by means of a worm gear. The primary windings either in star or delta are wound on the stator and are connected across the supply. The secondary windings are wound on the rotor and the six terminals are brought out since these windings are to be connected in series with the line whose voltage is to be controlled.

When polyphase currents flow through the primary windings, a rotating field is set up which induces an e.m.f. in each phase of rotor winding. As the rotor is turned, the magnitude of the rotating flux is not changed; hence the rotor e.m.f. per phase remains constant. However, the variation of the position of the rotor will affect the phase of the rotor e.m.f. *w.r.t.* the applied voltage as shown in Fig. 3.23.

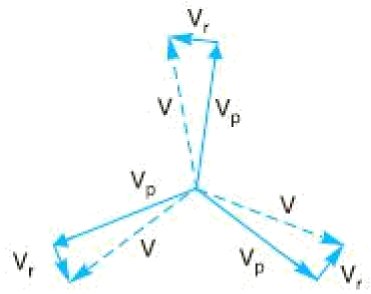


Fig. 3.23

The input primary voltage per phase is V_p and the boost introduced by the regulator is V_r. The output voltage V is the vector sum of V_p and V_r. Three phase induction regulators are used to regulate the voltage of feeders and in connection with high voltage oil testing transformers.

(vi) Voltage Control by Synchronous Condenser

The voltage at the receiving end of a transmission line can be controlled by installing specially designed synchronous motors called synchronous condensers at the receiving end of the line. The synchronous condenser supplies wattless leading kVA to the line depending upon the excitation of the motor. This wattless leading kVA partly or fully cancels the wattless lagging kVA of the line, thus controlling the voltage drop in the line. In this way, voltage at the receiving end of a transmission line can be kept constant as the load on the system changes.

For simplicity, consider a short transmission line where the effects of capacitance are neglected. Therefore, the line has only resistance and inductance. Let V_1 and V_2 be the per phase sending end and receiving end voltages respectively. Let I_2 be the load current at a lagging power factor of cos ϕ_2.

(a) Without synchronous condenser. Fig. 3.24 (*i*) shows the transmission line with resistance *R* and inductive reactance *X* per phase. The load current I_2 can be resolved into two rectangular components *viz* I_p in phase with V_2 and I_q at right angles to V_2 [See Fig. 3.24

(ii)]. Each component will produce resistive and reactive drops ; the resistive drops being in phase with and the reactive drops in quadrature leading with the corresponding currents.

The vector addition of these voltage drops to $V2$ gives the sending end voltage $V1$.

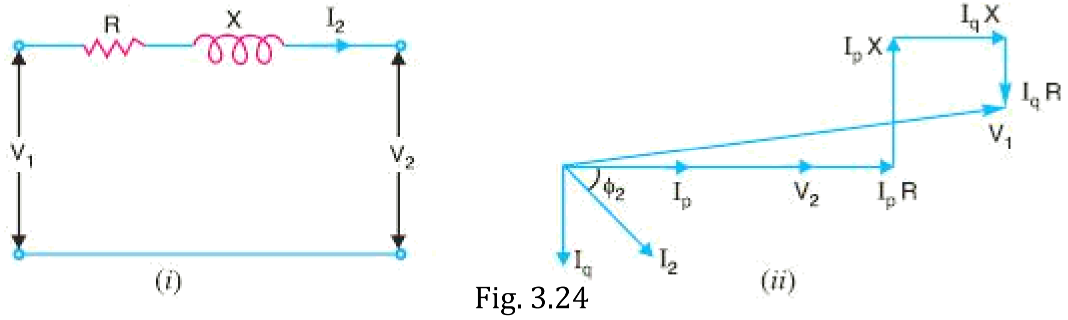


Fig. 3.24

(b)With synchronous condenser. Now suppose that a synchronous condenser taking a leading current Im is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. 3.25. Note that since Im and Iq are in direct opposition and that Im must be greater than Iq, the four drops due to these two currents simplify to :

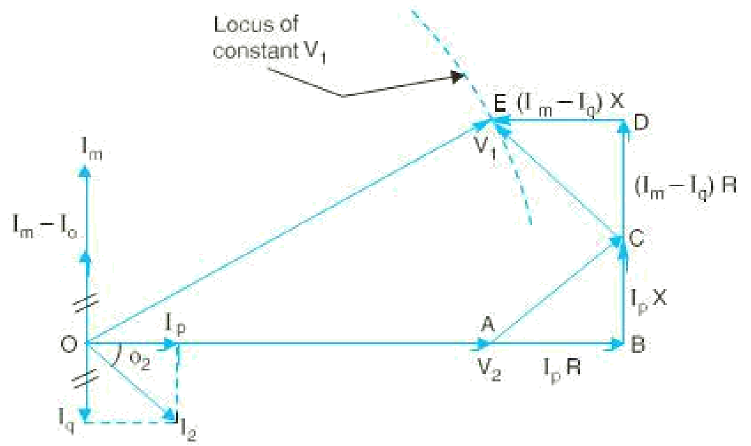


Fig. 3.25

$(I_m - I_q) R$ in phase with I_m

and $(I_m - I_q) X$ in quadrature leading with I_m

From the vector diagram, the relation between V_1 and V_2 is given by ;

$$OE^2 = (OA + AB - DE)^2 + (BC + CD)^2$$

or

$$V_1^2 = [V_2 + I_p R - (I_m - I_q) X]^2 + [I_p X + (I_m - I_q) R]^2$$

From this equation, the value of I_m can be calculated to obtain any desired ratio of V_1/V_2 for a given load current and power factor.

$$\text{kVAR capacity of condenser} = \frac{3\,V_2\,I_m}{1000}$$

12. Explain the Ferranti effect with relevant phasor diagram. (MJ15)

Ferranti Effect:

A long transmission line draws a substantial quantity of charging current. If such a line is open circuited or very lightly loaded at the receiving end, the voltage at receiving end may become greater than voltage at sending end. This is known as **Ferranti Effect** and is due to the voltage drop across the line inductance (due to charging current) being in phase with the sending end voltages.

Therefore both capacitance and inductance is responsible to produce this phenomenon The capacitance (and charging current) is negligible in short line but significant in medium line and appreciable in long line. Therefore this phenomenon occurs in medium and long lines. Represent line by equivalent π model.

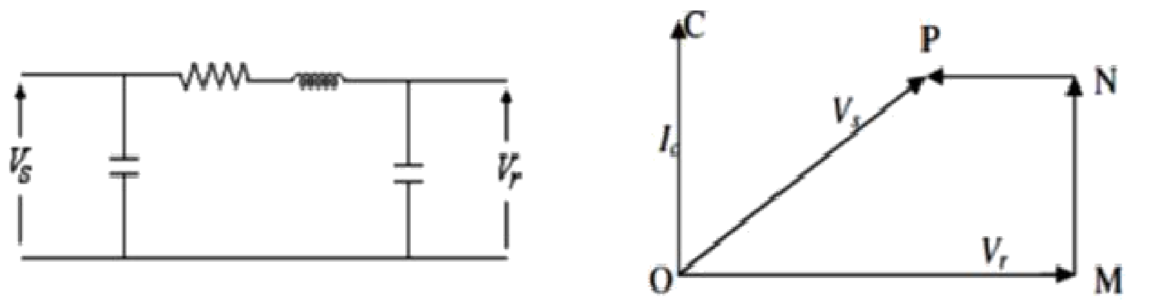


Fig. 3.26

Line capacitance is assumed to be concentrated at the receiving end.

OM = receiving end voltage Vr

OC = Current drawn by capacitance = Ic

MN = Resistance drop

NP = Inductive reactance drop

Therefore;

OP = Sending end voltage at no load and is less than receiving end voltage (Vr)

Since, resistance is small compared to reactance; resistance can be neglected in calculating Ferranti effect.

From π model,

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

For open circuit line; Ir = 0

$$\therefore \quad V_s = \left(1 + \frac{YZ}{2}\right)V_r$$

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

or; $$V_s - V_r = \left(\frac{YZ}{2}\right)V_r = \frac{(j\omega Cl)(r + j\omega L)l}{2}V_r$$

Neglecting resistance;

$$V_s - V_r = \frac{-V_r \omega^2 l^2 LC}{2}$$

Substituting the value in above equation;

$$LC = \frac{1}{(3\times 10^5)^2}$$

$$V_s - V_r = \frac{-V_r \omega^2 l^2}{2\,(3\times 10^5)^2}$$

$$\therefore \; V_s - V_r = \frac{-V_r \omega^2 l^2 \times 10^{-10}}{18}$$

$$\therefore \; V_s = V_r\left[1 - \frac{\omega^2 l^2 \times 10^{-10}}{18}\right]$$

Now, from above expression;

$$\left[1 - \frac{\omega^2 l^2 \times 10^{-10}}{18}\right] < 1$$

$$V_s < V_r \qquad or; \qquad V_r > V_s$$

i.e. receiving end voltage is greater than sending end voltage and this effect is called Ferranti Effect. It is valid for open circuit condition of long line.

UNIT - IV

1. Explain with neat sketch, the different types of insulators.(ND10, MJ14, ND14, MJ15, ND16)

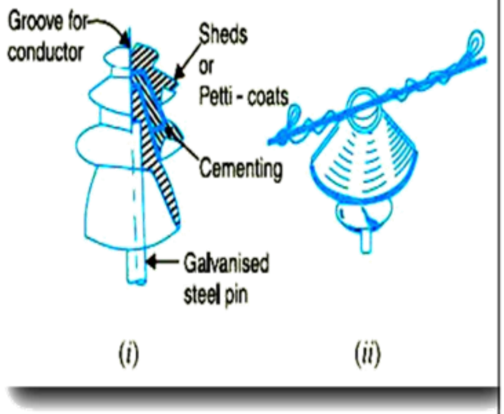
Types of Insulator

There are mainly three types of insulator likewise

1. Pin Insulator
2. Suspension Insulator
3. Stray Insulator

In addition to that there are other two types of electrical insulator available mainly for low voltage application, i.e stay insulator and shackle insulator.

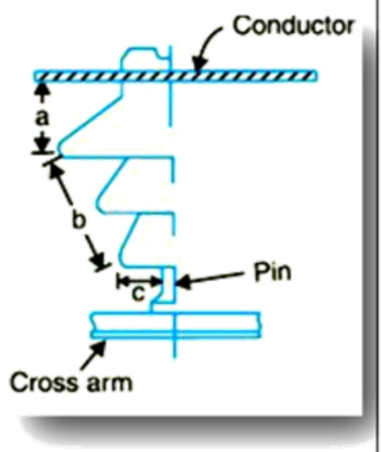
1. Pin Type Insulators



- 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 electric power at voltages up to 33 kV.

Fig.4.4

- Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.



- Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily due to line voltage and may cause the breakdown of the insulator.
- The electrical breakdown of the insulator can occur either by flash-over or puncture. In flashover, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the air gaps, following shortest distance.
- Figure 4.5 shows the arcing distance (i.e. a + b + c) for the insulator. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced Fig.4.5 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 flashover voltage is known as safety factor.

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

2. Suspension Type

- For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Figure.
- Consist of a number of porcelain discs connected in series by metal links in the form of a string.
- The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower.
- Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage.
- For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

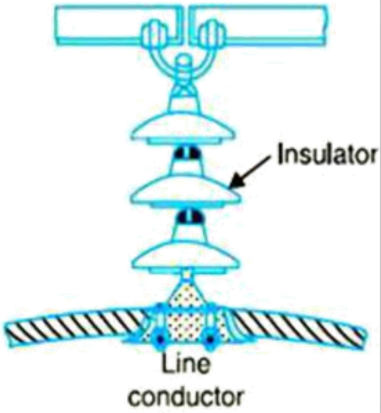


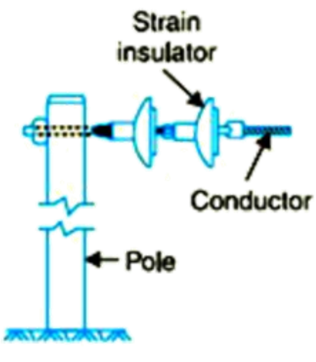
Fig.4.6

Advantages of suspension type:

- Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
- 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 series.
- If anyone disc is damaged, the whole string does not become useless because the damaged disc can be replaced.
- 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.
- In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.
- The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain Insulators

- When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used.
- For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Figure. 4.7
- The discs of strain insulators are used in the vertical plane.



When the tension in lines is exceedingly high, at long river Fig.4.7 spans, two or more strings are used in parallel.

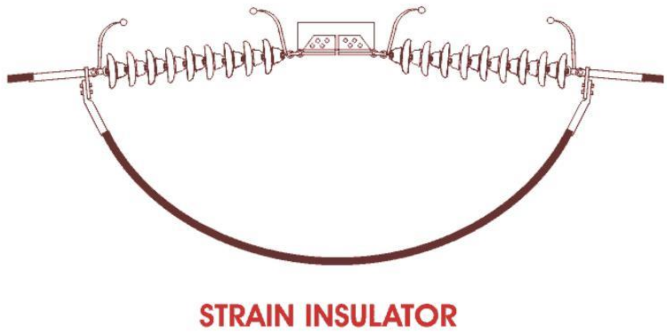


Fig.4.8

4. Shackle Insulators

- In early days, the shackle insulators were used as strain insulators. But now a day, 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.

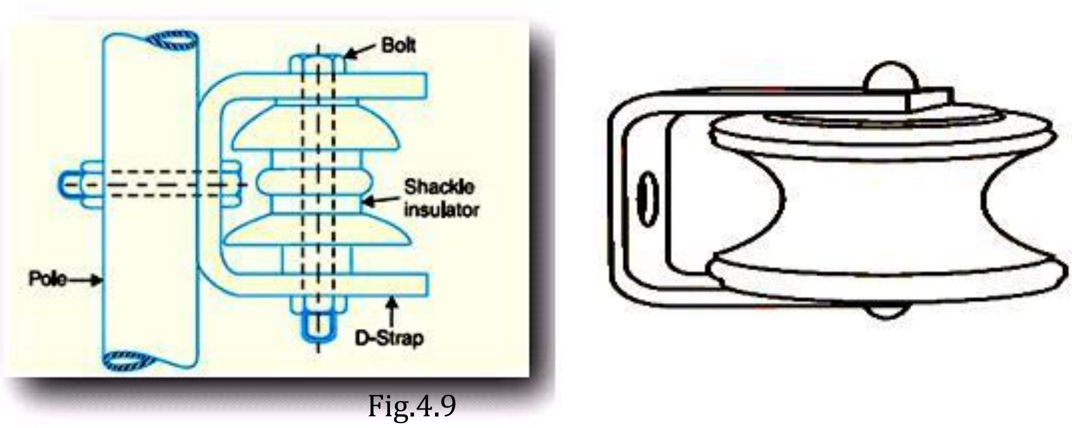


Fig.4.9

5. Stay Insulator

For low voltage lines, the stays are to be insulated from ground at a height. The insulator used in the stay wire is called as the **stay insulator** and is usually of porcelain and is so designed that in case of breakage of the insulator the guy-wire will not fall to the ground. There are several methods of increasing the string efficiency or improving voltage distribution across different units of a string.

Fig.4.10

2. Derive the expression for voltage distribution in insulator string and string efficiency. (ND13)

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.4.11(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 fig4.11.(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 Therefore, voltage across each disc will be different.
- Obviously, the disc nearest to the line conductor will have the maximum* voltage. Thus referring to Fig V3 will be much more than V2 or V1.

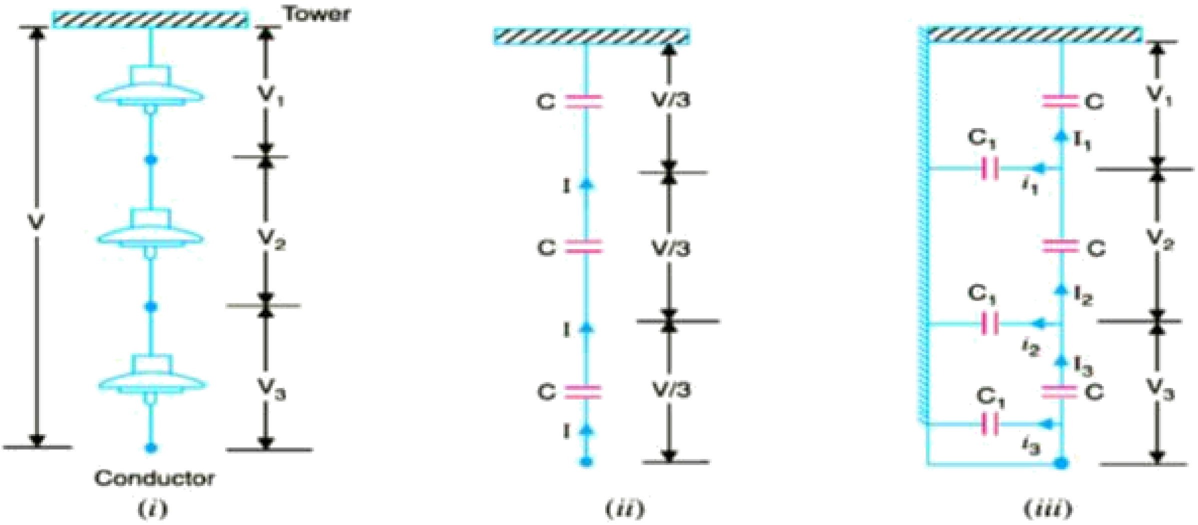


Fig. 4.11

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

- The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.
- The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.
- The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.
- If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective for d.c.

String Efficiency

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

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

where n = number of discs in the string.

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

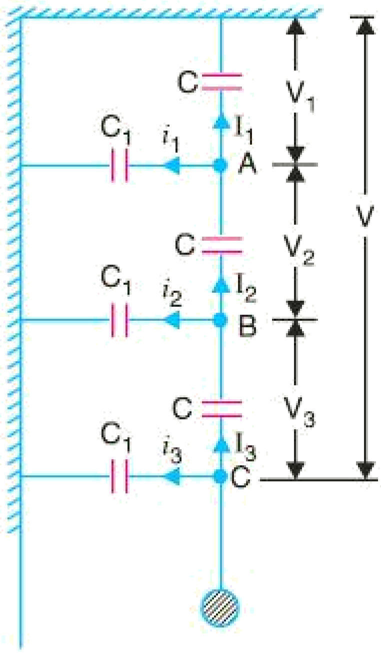


Fig. 4.12

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 voltage across each unit is V1,V2 and V3 respectively as shown.

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

$$I_2 = I_1 + i_1$$

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

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

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

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

$$I_3 = I_2 + i_2$$

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

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

or $$V_3 = V_2 + (V_1 + V_2) K$$

$$= K V_1 + V_2 (1 + K)$$

$$= K V_1 + V_1 (1 + K)^2 \quad [\because V_2 = V_1 (1 + K)]$$

$$= V_1 [K + (1 + K)^2]$$

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

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

$$V = V_1 + V_2 + V_3$$
$$= V_1 + V_1(1+K) + V_1(1+3K+K^2)$$
$$= V_1(3+4K+K^2)$$
$$\therefore \quad V = V_1(1+K)(3+K) \quad ...(iii)$$

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

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

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

$$\text{Voltage across second unit from top, } V_2 = V_1(1+K)$$
$$\text{Voltage across third unit from top, } V_3 = V_1(1+3K+K^2)$$
$$\text{\%age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$
$$= \frac{V}{3 \times V_3} \times 100$$

* Note that current through capacitor = $\frac{\text{Voltage}}{\text{Capacitive reactance}}$

† Voltage across second shunt capacitance C_1 from top = $V_1 + V_2$. It is because one point of it is connected to *B* and the other point to the tower.

Following Points May Be Noted From The Above Mathematical Analysis

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

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

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

3. Describe the various methods to improve string efficiency. (ND12, ND15, MJ16)

Methods of Improving String Efficiency

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

- 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.

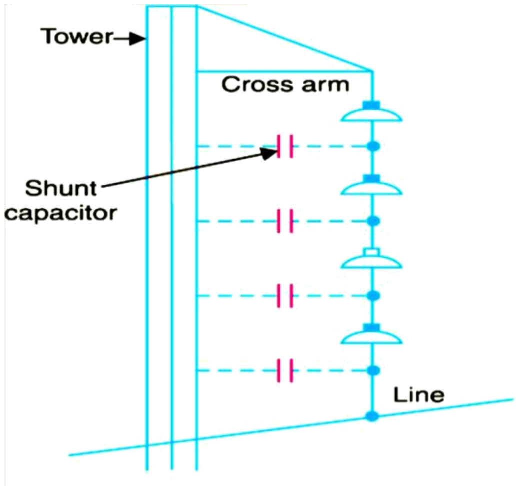


Fig.4.13

(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 equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig
- 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 i′1, i′2 etc.
- The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

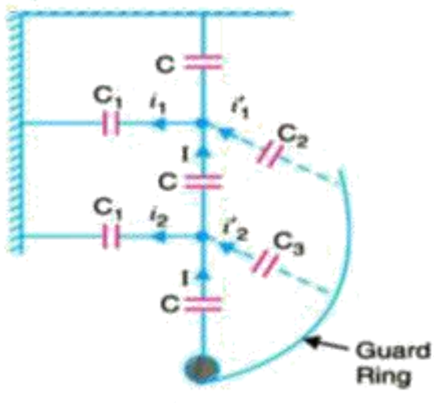
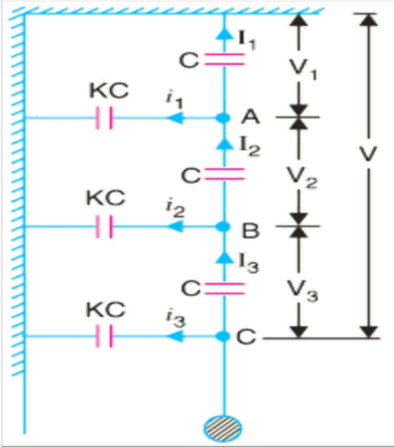


Fig.4.14

4. 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. (ND12)

Solution. 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 $$V_2 = 1{\cdot}11 \, V_1 \quad ...(i)$$

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) $$\text{String efficiency} = \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{19{\cdot}05}{3 \times 7{\cdot}4} \times 100 = \mathbf{85.8\%}$$

5. 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. (ND11)

Solution. The equivalent circuit of string insulators is the same as shown in previous Fig. It is given that 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 $= \sqrt{3} \times 37{\cdot}12 = 64{\cdot}28$ **kV**

(iii) String efficiency $$= \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{37{\cdot}12}{3 \times 18{\cdot}12} \times 100 = 68.28\%$$

6. Describe the different testing methods of insulators. (MJ17)

Insulator Testing Types

According to the British Standard, the electrical insulator must undergo the following tests

1. Flashover tests of insulator
2. Performance tests
3. Routine tests

1. FLASHOVER TEST

There are mainly three types of flashover test performed on an insulator and these are-

Power Frequency Dry Flashover Test of Insulator

- First the insulator to be tested is mounted in the manner in which it would be used practically.
- Then terminals of variable power frequency voltage source are connected to the both electrodes of the insulator.
- Now the power frequency voltage is applied and gradually increased up to the specified value. This specified value is below the minimum flashover voltage.
- This voltage is maintained for one minute and observe that there should not be any flash-over or puncher occurred.
- The insulator must be capable of sustaining the specified minimum voltage for one minute without flash over.

- In this test also the insulator to be tested is mounted in the manner in which it would be used practically.
- Then terminals of variable power frequency voltage source are connected to the both electrodes of the insulator.
- After that the insulator is sprayed with water at an angle of 45o in such a manner that its precipitation should not be more 5.08 mm per minute. The resistance of the water used for spraying must be between 9 kΩ 10 11 kΩ per cm3 at normal atmospheric pressure and temperature. In this way we create artificial raining condition.
- Now the power frequency voltage is applied and gradually increased up to the specified value.
- This voltage is maintained for either one minute or 30 second as specified and observe that there should not be any flash-over or puncher occurred. The insulator must be capable of sustaining the specified minimum power frequency voltage for specified period without flash over in the said wet condition.

Power Frequency Flashover Voltage test of Insulator

- The insulator is kept in similar manner of previous test.
- In this test the applied voltage is gradually increased in similar to that of previous tests.
- But in that case the voltage when the surroundings air breaks down, is noted.

Impulse Frequency Flashover Voltage Test of Insulator

- The overhead outdoor insulator must be capable of sustaining high voltage surges caused by lightning etc. So this must be tested against the high voltage surges.
- The insulator is kept in similar manner of previous test.
- Then several hundred thousands Hz very high impulse voltage generator is connected to the insulator.
- Such a voltage is applied to the insulator and the spark over voltage is noted.

- The ratio of this noted voltage to the voltage reading collected from power frequency flashover voltage test is known as impulse ratio of insulator.

$$\therefore \text{Impulse Ratio} = \frac{\text{Impulse Frequency Flashover Voltage}}{\text{Power Frequency Flashover Voltage}}$$

This ratio should be approximately 1.4 for pin type insulator and 1.3 for suspension type insulators.

2. PERFORMANCE TEST OF INSULATOR

Temperature Cycle Test of Insulator

- The insulator is first heated in water at 70oC for one hour.
- Then this insulator immediately cooled in water at 7oC for another one hour.
- This cycle is repeated for three times.
- After completion of these three temperature cycles, the insulator is dried and the glazing of insulator is thoroughly observed.
- After this test there should not be any damaged or deterioration in the glaze of the insulator surface

Puncture Voltage Test of Insulator

- The insulator is first suspended in an insulating oil.
- Then voltage of 1.3 times of flash over voltage, is applied to the insulator.
- A good insulator should not puncture under this condition

Porosity Test of Insulator

- The insulator is first broken into pieces.
- Then These broken pieces of insulator are immersed in a 0.5 % alcohol solution of fuchsine dye under pressure of about 140.7 kg / cm2 for 24 hours.
- After that the sample are removed and examine.
- The presence of a slight porosity in the material is indicated by a deep penetration of the dye into it.

Mechanical Strength Test of Insulator

- The insulator is applied by 2½ times the maximum working strength for about one minute.
- The insulator must be capable of sustaining this much mechanical stress for one minute without any damage in it.

3. ROUTINE TEST OF INSULATOR

- Each of the insulator must undergo the following routine test before they are recommended for using at site.

Proof Load Test of Insulator

- In proof load test of insulator, a load of 20% in excess of specified maximum working load is applied for about one minute to each of the insulator.
- The insulator with its galvanized or steel fittings is suspended into a copper sulfate solution for one minute.
- Then the insulator is removed from the solution and wiped, cleaned.

- Again it is suspended into the copper sulfate solution for one minute.
- The process is repeated for four times.
- Then it should be examined and there should not be any disposition of metal on it.

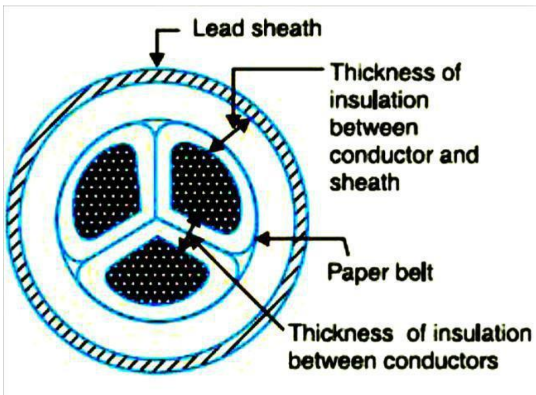
7. With neat diagrams, explain the constructional features of various types of cables. (ND12, MJ15)

Cable for 3-Phase

- The 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.3 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 (not shown in the figure).
- The belted type construction is suitable only for low and medium voltages as the electro static stresses developed in the cables for these voltages are more or less radial i.e., across the insulation. However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation.



- As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment.
- In order to overcome this difficulty, screened cables are used where leakage currents are conducted to earth through metallic screens.

2. Screened Cables

These cables are meant for use up to 33 kV, but in particular cases their use may be extended to operating voltages up to 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. Hochstetler 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.

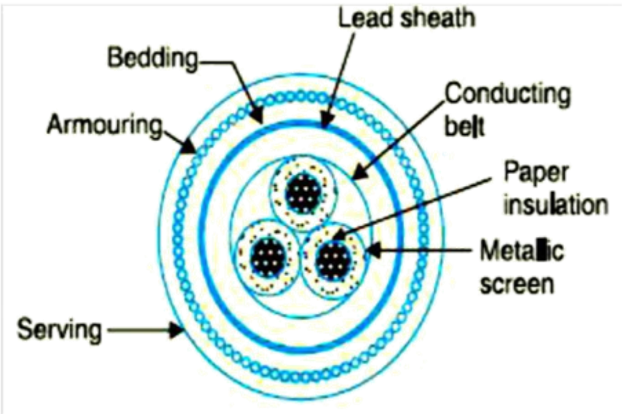


Fig. 4.18

- 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.
- The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation. Secondly, the metallic screens increase the heat dissipating power of the cable.

(ii) S.L. Type cables

- Fig. 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.

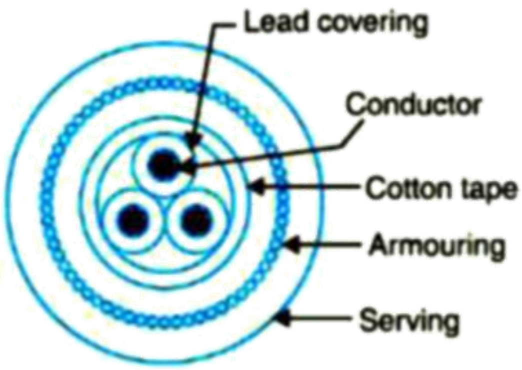


Fig.4.19

- 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 in to 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 up to 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.4.20 shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the center 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.

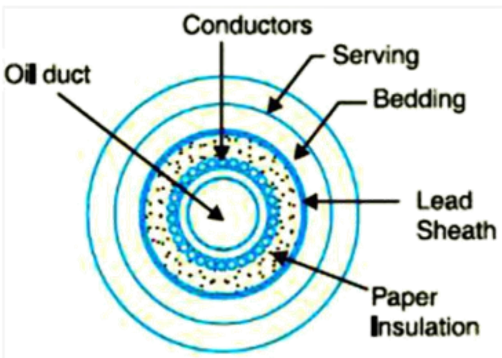


Fig.4.20

- 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.4.21. 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 them metallic sheath as shown. In the 3-core oil-filler cable shown in Fig.4.22. the oil ducts are located in the filler spaces. These channels are composed of perforated metal ribbon tubing and are at earth potential.

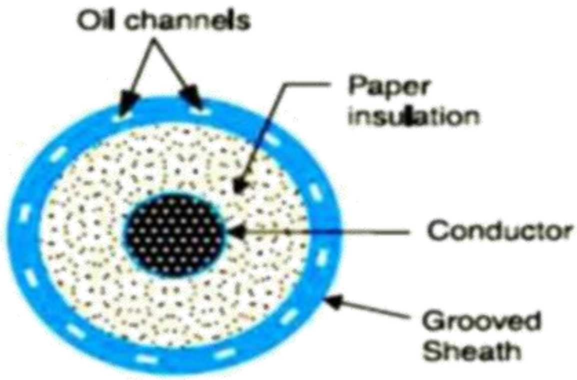


Fig.4.21

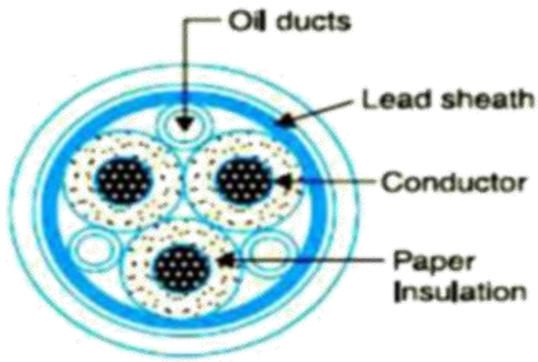


Fig.4.22

(ii)Gas Pressure Cable

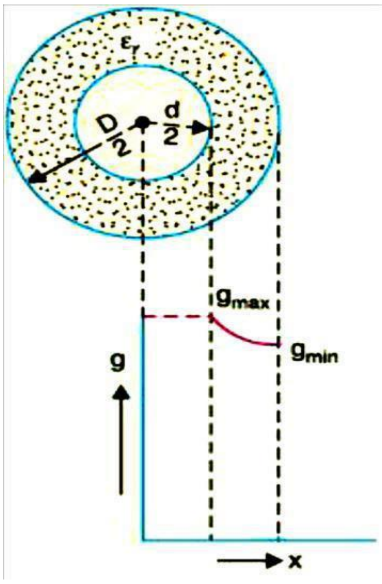
- The voltage required to set up ionization inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionization can be altogether eliminated.
- At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.
- Fig4.23. Shows the section of external pressure cable designed by Hochstetler, 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.

Fig.4.23

- 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.

8. Derive the expression for dielectric stress of a single core cable.(ND10, ND14)

Dielectric Stress in Cable



- Under operating conditions, the insulation of a cable is subjected to electrostatic forces. This is known as dielectric stress.
- The dielectric stress at any point in a cable is in fact the potential gradient (or electric intensity) at that point.
- Consider a single core cable with core diameter d and internal sheath diameter D.
- As proved in Art 8, the electric intensity at a point x metres from the centre of the cable is

$$E_x = \frac{Q}{2\pi \varepsilon_o \varepsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Fig 4.24

Therefore, potential gradient g at a point x meters from the Centre of cable is

$$g = E_x$$

or $$g = \frac{Q}{2\pi \varepsilon_o \varepsilon_r x} \text{ volts/m} \quad ...(i)$$

As proved, potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi \varepsilon_o \varepsilon_r} \log_e \frac{D}{d} \text{ volts}$$

or $$Q = \frac{2\pi \varepsilon_o \varepsilon_r V}{\log_e \frac{D}{d}} \quad ...(ii)$$

Substituting the value of Q from exp. (ii) in exp. (i), we get,

$$g = \frac{\frac{2\pi \varepsilon_o \varepsilon_r V}{\log_e D/d}}{2\pi \varepsilon_o \varepsilon_r x} = \frac{V}{x \log_e \frac{D}{d}} \text{ volts/m} \quad ...(iii)$$

It is clear from exp. (iii) that potential gradient varies inversely as the distance x. Therefore, potential gradient will be maximum when x is minimum i.e., when x = d/2 or at the surface of the conductor. On the other hand, potential gradient will be minimum at x = D/2 or at sheath surface.

Maximum potential gradient is

$$g_{max} = \frac{2V}{d \log_e \frac{D}{d}} \text{ volts/m} \quad \text{[Putting } x = d/2 \text{ in exp. (iii)]}$$

Minimum potential gradient is

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} \text{ volts/m} \quad \text{[Putting } x = D/2 \text{ in exp. (iii)]}$$

$$\therefore \quad \frac{g_{max}}{g_{min}} = \frac{\dfrac{2V}{d\log_e D/d}}{\dfrac{2V}{D\log_e D/d}} = \frac{D}{d}$$

- The variation of stress in the dielectric is shown in Fig.14. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor.
- It may be noted that maximum stress is an important consideration in the design of a cable. For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.

Most Economical size of conductor

- It has already been shown that maximum stress in a cable occurs at the surface of the conductor. For safe working of the cable, dielectric strength of the insulation should be more than the maximums tress. Rewriting the expression for maximum stress, we get,

$$g_{max} = \frac{2V}{d\log_e \frac{D}{d}} \text{ volts/m} \qquad \ldots(i)$$

- The values of working voltage V and internal sheath diameter D have to be kept fixed at certain values due to design considerations.
- This leaves conductor diameter d to be the only variable in exp.(i). For given values of V and D, the most economical conductor diameter will be one for which gmax has a minimum value.
- The value of gmax will be minimum when d loge D/d is maximum i.e.

$$\frac{d}{dd}\left[d\log_e \frac{D}{d}\right] = 0$$

$$\text{or} \quad \log_e \frac{D}{d} + d.\frac{d}{D}.\frac{-D}{d^2} = 0$$

$$\text{or} \quad \log_e (D/d) - 1 = 0$$

$$\text{or} \quad \log_e (D/d) = 1$$

$$\text{or} \quad (D/d) = e = 2{\cdot}718$$

Most economical conductor diameter is

$$d = \frac{D}{2.718}$$

and the value of *gmax* under this condition is

$$g_{max} = \frac{2V}{d} \text{ volts/m}$$

[Putting $\log_e D/d = 1$ in exp. (i)]

9. Enumerate the different methods of grading of cables. (MJ13, MJ14, MJ15, MJ16)

Grading of Cables

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

(i) Capacitance grading

(ii) Intersheath grading

(i)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 center.
- Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the center. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one.
- However, 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.4.25. There are three dielectrics of outer diameter d1, d2 and D and of relative permittivity 1, 2 and 3 respectively.

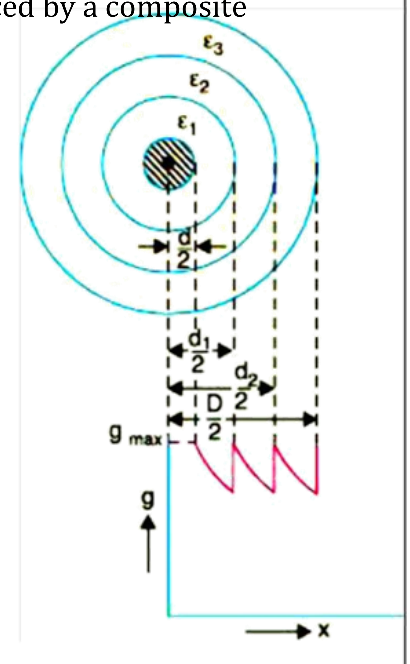


Fig.4.25

- If the permittivity are such that 1 > 2 > 3 and the three dielectrics are worked at the same maximum stress, then,

* As $\varepsilon_r \propto \frac{1}{x}$ $\therefore$ $\varepsilon_r = k/x$ where k is a constant.

Potential gradient at a distance x from the centre

$$= \frac{Q}{2\pi\varepsilon_0\varepsilon_r x} = \frac{Q}{2\pi\varepsilon_0 (k/x)x} = \frac{Q}{2\pi\varepsilon_0 k} = \text{Constant}$$

This shows that if the condition $\varepsilon_r \propto 1/x$ is fulfilled, potential gradient will be constant throughout the dielectric of the cable.

† $g_{1max} = \frac{Q}{\pi\varepsilon_0\, \varepsilon_1 d}$; $g_{2max} = \frac{Q}{\pi\varepsilon_0\, \varepsilon_2 d_1}$; $g_{3max} = \frac{Q}{\pi\varepsilon_0\, \varepsilon_3 d_2}$

If $g_{1max} = g_{2max} = g_{3max} = g_{max}$ (say), then,

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

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

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

Potential difference across the inner layer is

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

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

Similarly, potential across second layer (V2) and third layer (V3) 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 gmax, the permissible potential difference between core and earthed sheath would have been

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

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

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

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

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

(ii)Intersheath Grading

- In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic inters heaths between the core and lead sheath.
- The inter sheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves 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 inters heaths of diameters d1 and d2 are inserted into the homogeneous dielectric and maintained at some fixed potentials.

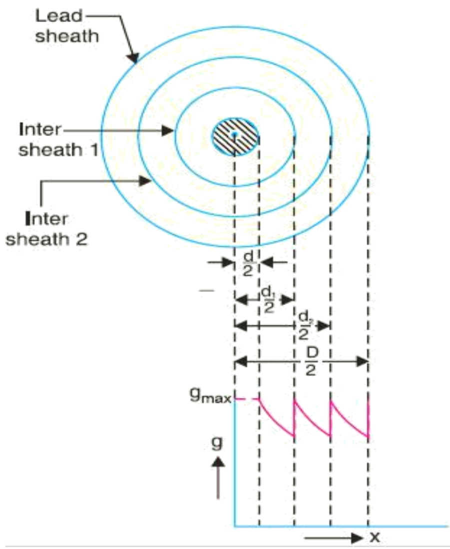


Fig.4.26

- Let V1,V2 and V3 respectively be the voltage between core and intersheath 1, between inter sheath 1 and 2 and between inter sheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each inter sheath, therefore, each sheath can be treated like a homogeneous single core cable Maximum stress between core and inter sheath 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

$$V = V_1 + V_2 + V_3$$

- Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials.
- Secondly, the inter sheaths 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 inter sheaths due to charging currents. For these reasons, inter sheath grading is rarely used.

10. A 33 kV single core cable has a conductor diameter of 1 cm and a sheath of inside diameter 4 cm. Find the maximum and minimum stress in the insulation. (ND13)

Solution.

The maximum stress occurs at the conductor surface and its value is given by;

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

Here, $V = 33$ kV (r.m.s) ; $d = 1$ cm ; $D = 4$ cm

Substituting the values in the above expression, we get,

$$g_{max} = \frac{2 \times 33}{1 \times \log_e 4} \text{ kV}^{\dagger}\text{/cm} = \mathbf{47{\cdot}61\ kV/cm}\ r.m.s.$$

The minimum stress occurs at the sheath and its value is give by ;

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} = \frac{2 \times 33}{4 \times \log_e 4} \text{ kV/cm} = \mathbf{11{\cdot}9\ kV/cm}\ r.m.s$$

Alternatively ;

$$g_{min} = g_{max} \times \frac{d}{D} = 47{\cdot}61 \times 1/4 = \mathbf{11{\cdot}9\ kV/cm}\ r.m.s.$$

11. Derive the expression for capacitance of a single core cable. (ND10, ND14)

Capacitance of a Single-Core Cable

A single-core cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a single core cable with conductor diameter d and inner sheath diameter D (Fig. 4.27). Let the charge per metre axial length of the cable be Q coulombs and ε be the permittivity of the insulation material between core and lead sheath.

Obviously *$\varepsilon = \varepsilon_0 \varepsilon_r$ where ε_r is the relative permittivity of the insulation.

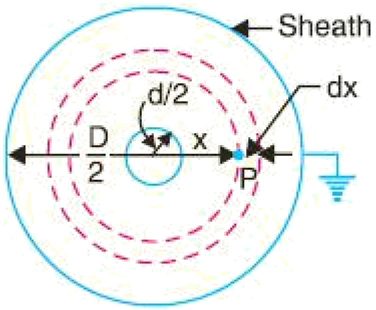


Fig.4.27

Consider a cylinder of radius x metres and axial length 1 metre.

The surface area of this cylinder is = $2\pi x \times 1 = 2\pi x\ m^2$

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

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

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

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

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

Capacitance of the cable is

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

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

$$= \frac{2\pi \times 8\cdot854 \times 10^{-12} \times \varepsilon_r}{2\cdot303\ \log_{10}(D/d)}\ \text{F/m}$$

$$= \frac{\varepsilon_r}{41\cdot4\ \log_{10}(D/d)} \times 10^{-9}\ \text{F/m}$$

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

$$C = \frac{\varepsilon_r\ l}{41\cdot4\ \log_{10}\frac{D}{d}} \times 10^{-9}\ \text{F}$$

EE6402 – TRANSMISSION AND DISTRIBUTION

PART - B

1. **Derive the expression for calculation of sag i)when supports are equal ii) When supports are not equal iii) Effect of ice and wind (ND12, ND13,ND15)**

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.
- Sag and tension of a conductor are calculated 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.5.2.
- It can be proved that lowest point will be at 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.
- 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 conductor Fig.5.2 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,

(ii) When supports are at unequal levels.

In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig.5.3 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

x 1 = Distance of support at lower level (i.e., A) from O

x 2 = Distance of support at higher level (i.e. B) from O

T = Tension in the conductor

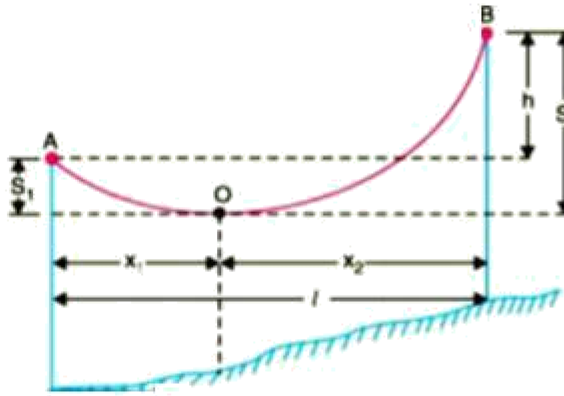


Fig.5.3

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 $$x_1 + x_2 = l \qquad \ldots(i)$$

$$*\,y = \frac{w\,x^2}{2T}$$

At support A, $x = x_1$ and $y = S_1$.

$$\therefore \quad S_1 = \frac{w\,x_1^2}{2T}$$

Now $$S_2 - S_1 = \frac{w}{2T}[x_2^2 - x_1^2] = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$$\therefore \quad S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

But $$S_2 - S_1 = h$$

$$\therefore \quad h = \frac{w\,l}{2T}(x_2 - x_1)$$

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 fig.5.4

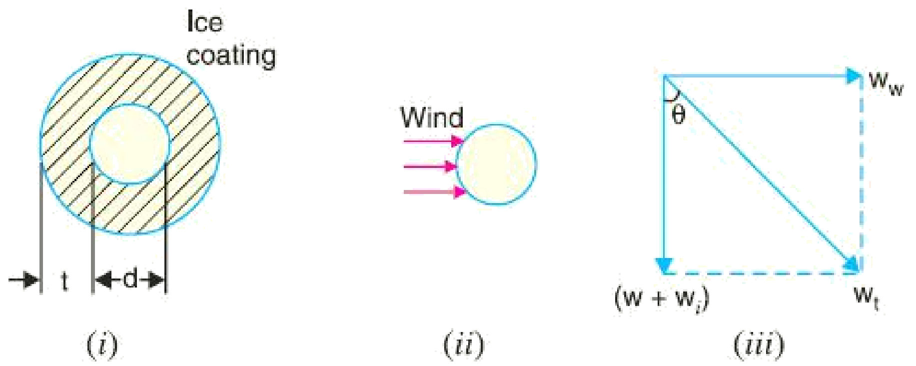


Fig.5.4

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 = weight of ice per unit length

= density of ice × 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 = wind force per unit length

= wind pressure per unit area × projected area per unit length

$= \text{wind pressure} \times [(d + 2t) \times 1]$

* Volume of ice per unit length $= \frac{\pi}{4}[(d + t)^2 - d^2] \times 1 = \frac{\pi}{4}[4dt + 4t^2] = \pi t (d + t)$

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 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 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 cosθ

2. 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 (ND12)

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

$\therefore$ $\text{Sag} = \dfrac{w\,l^2}{8T} = \dfrac{0\cdot 68 \times (260)^2}{8 \times 1550} = 3{\cdot}7$ m

$\therefore$ Conductor should be supported at a height of $10 + 3{\cdot}7 =$ **13·7 m**

3. A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm^2. The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9·9 gm/cm^3 and wind pressure is 1·5 kg/m length, calculate the sag. What is the vertical sag?(MJ14)

Solution.

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1{\cdot}5$ kg

Wt. of conductor/m length, w = Sp. Gravity × Volume of 1 m conductor

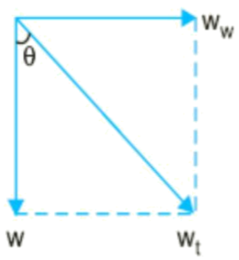
$= 9{\cdot}9 \times 2 \times 100 = 1980$ gm $= 1{\cdot}98$ kg

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 98)^2 + (1\cdot 5)^2} = 2{\cdot}48 \text{ kg}$$

$$\therefore \quad \text{Sag, } S = \frac{w_t\, l^2}{8T} = \frac{2\cdot 48 \times (150)^2}{8 \times 2000} = \mathbf{3{\cdot}48\ m}$$

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 ;



$$\tan\theta = w_w/w = 1{\cdot}5/1{\cdot}98 = 0{\cdot}76$$

$$\therefore \quad \theta = \tan^{-1} 0{\cdot}76 = 37{\cdot}23^\circ$$

$$\therefore \quad \text{Vertical sag} = S\cos\theta$$

$$= 3{\cdot}48 \times \cos 37{\cdot}23^\circ = \mathbf{2{\cdot}77\ m}$$

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.(ND14, MJ16)

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

$$= \pi\, t\, (d + t) \times 100 \text{ cm}^3$$

$$= \pi \times 1{\cdot}27 \times (1{\cdot}96 + 1{\cdot}27) \times 100 = 1288 \text{ cm}^3$$

Weight of ice per metre length of conductor is

$$w_i = 0{\cdot}91 \times 1288 = 1172 \text{ gm} = 1{\cdot}172$$

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

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

$$= \sqrt{(0{\cdot}865 + 1{\cdot}172)^2 + (1{\cdot}755)^2} = 2{\cdot}688 \text{ kg}$$

* Working stress $= \dfrac{\text{Ultimate Strength}}{\text{Safety factor}} = \dfrac{4218}{5}$

∴ Working Tension, $T =$ Working stress × conductor area = 4218 × 1·29/5

$$\therefore \quad \text{Sag} = \frac{w_t\, l^2}{8T} = \frac{2{\cdot}688 \times (275)^2}{8 \times 4030} = \mathbf{6{\cdot}3\ m}$$

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=2540kg/cm2

Wt. of conductor = 1·125 kg/m run (ND13)

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

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot125)^2 + (1\cdot5)^2} = 1\cdot875 \text{ kg}$$

If f is the factor of safety, then,

$$\text{Working tension, } T = \frac{\text{Breaking stress} \times \text{conductor area}}{\text{safety factor}} = 2540 \times 3\cdot225/f = 8191/f \text{ kg}$$

$$\text{Slant Sag, } S = \frac{\text{Vertical sag}}{{}^*\cos\theta} = \frac{2\cdot35 \times 1\cdot875}{1\cdot125} = 3\cdot92 \text{ m}$$

Now $$S = \frac{w_t l^2}{8T}$$

or $$T = \frac{w_t l^2}{8S}$$

$\therefore$ $$\frac{8191}{f} = \frac{1\cdot875 \times (214)^2}{8 \times 3\cdot92}$$

or Safety factor, $$f = \frac{8191 \times 8 \times 3\cdot92}{1\cdot875 \times (214)^2} = \mathbf{3}$$

6. An overhead line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm^2. The ultimate strength is 5000 kg/cm ^{2} and safety factor is 5. The specific gravity of the material is 8·9 gm/cc. The wind pressure is 1·5 kg/m. Calculate the height of the conductor above the ground level at which it should be supported if a minimum clearance of 7 m is to be left between the ground and the conductor.(MJ15)

Solution.

Span length, l = 150 m ; Wind force/m run, w_w = 1·5 kg

Wt. of conductor/m run, w = conductor area × 100 cm × sp. gravity

= 2 × 100 × 8·9 = 1780 gm = 1·78 kg

Working tension, T = 5000 × 2/5 = 2000 kg

Total weight of one metre length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1\cdot 78)^2 + (1\cdot 5)^2} = 2\cdot 33 \text{ kg}$$

$$\text{Slant sag, } S = \frac{w_t l^2}{8T} = \frac{2\cdot 33 \times (150)^2}{8 \times 2000} = 3\cdot 28 \text{ m}$$

Vertical sag = $S \cos \theta = 3\cdot 28 \times w/w_t = 3\cdot 28 \times 1\cdot 78/2\cdot 33 = 2\cdot 5$ m

Conductor should be supported at a height of 7 + 2·5 = **9·5 m**

* The slant sag makes an angle θ with the vertical.

∴ $\cos\theta = w/w_t = 1\cdot 125/1\cdot 875$

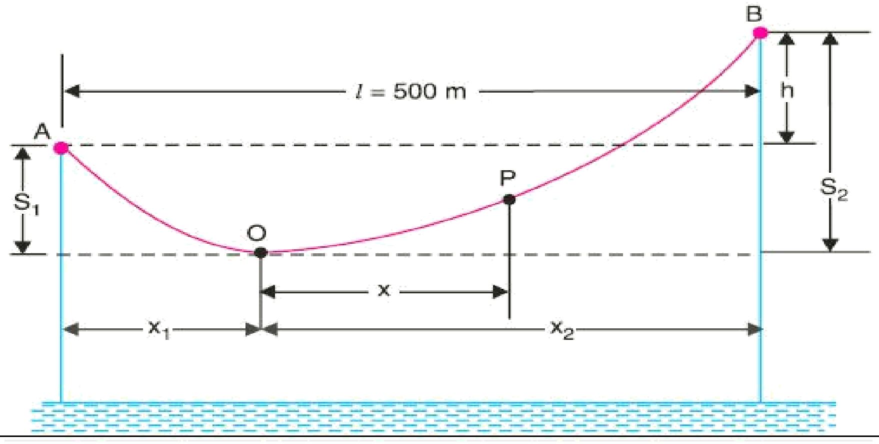
7. The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance betwen the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1·5 kg/m. Bases of the towers can be considered to be at water level. (ND10)

Solution. Fig. shows the conductor suspended between two supports *A* and *B* at different levels with *O* as the lowest point on the conductor.

Here, l = 500 m ; w = 1·5 kg ; T = 1600 kg.

Difference in levels between supports, h = 90 – 30 = 60 m. Let the lowest point *O* of the conductor be at a distance x_1 from the support at lower level (*i.e.*, support *A*) and at a distance x_2 from the support at higher level (*i.e.*, support *B*).

Obviously, $x_1 + x_2 = 500$ m ...(*i*)



Now Sag $S_1 = \dfrac{w\,x_1^2}{2T}$ and Sag $S_2 = \dfrac{w\,x_2^2}{2T}$

$\therefore$ $$h = S_2 - S_1 = \frac{w\,x_2^2}{2T} - \frac{w\,x_1^2}{2T}$$

or $$60 = \frac{w}{2T}(x_2 + x_1)(x_2 - x_1)$$

$\therefore$ $$x_2 - x_1 = \frac{60 \times 2 \times 1600}{1 \cdot 5 \times 500} = 256 \text{ m} \qquad ...(ii)$$

Solving exps. (*i*) and (*ii*), we get, $x_1 = 122$ m; $x_2 = 378$ m

Now, $$S_1 = \frac{w\,x_1^2}{2T} = \frac{1 \cdot 5 \times (122)^2}{2 \times 1600} = 7 \text{ m}$$

Clearance of the lowest point *O* from water level

$= 30 - 7 =$ **23 m**

Let the mid-point *P* be at a distance *x* from the lowest point *O*.

Clearly, $x = 250 - x_1 = 250 - 122 = 128$ m

Sag at mid-point *P*, $$S_{mid} = \frac{w\,x^2}{2T} = \frac{1 \cdot 5 \times (128)^2}{2 \times 1600} = 7{\cdot}68 \text{ m}$$

Clearance of mid-point *P* from water level

$= 23 + 7{\cdot}68 =$ **30·68 m**

8. Explain the sub station equipments . (ND13)

Classification of Sub-Stations

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

1.According to service requirement

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

(i)Transformer sub-stations.

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

(ii) Switching sub-stations

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

(iii) Power factor correction sub-stations.

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

(iv) Frequency changer sub-stations

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

(v) Converting sub-stations

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

(vi) Industrial sub-stations

Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

2. According to constructional features

A sub-station has many components (e.g. circuit breakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous and reliable 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 installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages upto 66 kV.

(ii) Outdoor sub-stations

For voltages beyond 66 kV, equipment is invariably installed out- door. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor.

(iii) Underground sub-stations

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

(iv) Pole-mounted sub-stations

This is an outdoor sub-station with equipment installed over- head on H-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such sub- stations.

Substation Layout

1.Substation Layout AIS

- **AIS Substation Description**

- An Air Insulated Switchgear substation (AIS substation) uses atmospheric air as the phase to ground insulation for the switchgear of an electrical substation.
- The main advantage of the AIS substation is the scope of the substation for future offloading, for this reason AIS substations tend to be the most popular 400kV substation type.

- The equipment of an AIS substation is easily sourced and has a short lead-time; this means that the required future offloading does not need to be built immediately, unlike GIS where it must be considered.
- The main disadvantage to the AIS substation is its overall size. At 400kV level these substations can have a significant footprint and require sensitive locating in any rural environment. AIS are usually installed outdoor.

- **AIS Substation Size**

- Based on the single line diagrams given in Appendix B the minimum size of an AIS substation for this project would be as follows:

1. Overall substation Compound Size 46,864.5m2(235.5m x 199m or approximately 11.6 acres)
2. Height of highest element of substation ~ 28m (lightning protection structures situated in the substation compound)

Note: The switchgear in an AIS substation is outdoors therefore no building sizes are considered.

AIS Maintenance Requirements

1. Ongoing maintenance requirements, all equipment exposed to weather conditions
2. Disconnect contacts must be cleaned regularly, operating mechanisms must be checked and maintained

2.Substation Layout GIS

- A gas insulated substation (GIS) is a **high voltage substation** in which the major structures are contained in a sealed environment with sulfur hexafluoride gas as the insulating medium.
- GIS technology originated in Japan, where there was a substantial need to develop technology to make substations as compact as possible.
- The clearance required for phase to phase and phase to ground for all equipment is much lower than that required in an air insulated substation; the total space required for a GIS is 10% of that needed for a conventional substation.

- Gas insulated substations offer other advantages in addition to the reduced space requirements. Because the substation is enclosed in a building, a GIS is less sensitive to pollution, as well as salt, sand or large amounts of snow.
- Although the initial cost of building a GIS is higher than building an air insulated substation, the operation and maintenance costs of a GIS are less.

The primary applications for gas insulated substations include:

High voltage installations

The higher the voltage, the more favorable gas insulated technology becomes. The footprint of 765kV conventional substation is enormous, and GIS technology allows a significant size reduction.

Urban Installations

GIS technology can be used for installations in areas where the cost of real estate or aesthetic appeal is a significant consideration.

Indoor Installations

Building an air insulated substation indoors is usually impractical, but a GIS can easily go inside buildings.

Environmentally Sensitive Installations

GIS technology is popular in desert and arctic areas because it can be enclosed in a building with environmental control. Gas insulated substations also contain the electrical components within a Faraday cage and are therefore totally shielded from lightning.

Comparison between AIS & GIS Substation:

AIS Substation	GIS Substation
Outdoor substation	Indoor substation.
During maintenance, disconnect contacts must be cleaned regularly.	Switchgear play an important role for maintenance.
Land area required is large	Land area required is less compared to that of AIS substation
Cost is high compared to that of GIS substation	Cost is less compared to that of AIS Substation.
Frequent maintenance should be done	Long term maintenance should be done
Considerable dismantling may be required if a main element fails .	Manufacturer super vision will be required for the 20 year full overhaul

9. Explain the different methods of grounding. (MJ13, MJ15, ND15, MJ16, ND16)

Introduction

- In power system, grounding or earthing means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth i.e. soil.
- This connection to earth may be through a conductor or some other circuit element (e.g. are resistor, a circuit breaker etc.) depending up on the situation, grounding or earthing offers two principal advantages. First, it provides protection to the power system.
- For example, If the neutral point of a star-connected system is grounded through a circuit breaker and phase to earth fault occurs on any one line, a large fault current will flow through the circuit breaker. The circuit breaker will open to isolate the faulty line.
- This protects the power system from the harmful effects of the fault. Secondly, earthing of electrical equipment ensures the safety of the persons handling the equipment. For example, if insulation fails, there will be a direct contact of the live conductor with the metallic part (i.e. frame) of the equipment.
- Any person in contact with the metallic part of this equipment will be subjected to a dangerous electrical shock which can be fatal. In this chapter, we shall discuss the importance of grounding or earthing in the line of power system with special emphasis on neutral grounding.

Concept of Grounding

- The process of connecting the metallic frame (i.e. non-current carrying part) of electrical equipment or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called grounding or earthing.
- It is strange but true that grounding of electrical systems is less understood aspect of power system. Nevertheless, it is a very important subject.
- If grounding is done systematically in the line of the power system, we can effectively prevent accidents and damage to the equipment of the power system and at the same time continuity of supply can be maintained.
- Grounding or earthing may be classified as:(i) Equipment grounding (ii) System grounding. Equipment grounding deals with earthing the non-current-carrying metal parts of the electrical equipment.
- On the other hand, system grounding means earthing some part of the electrical system e.g. earthing of neutral point of star-connected system in generating stations and substations.

Neutral Grounding

- The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element is called neutral grounding.

- Neutral grounding provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (e.g. a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig.5.8

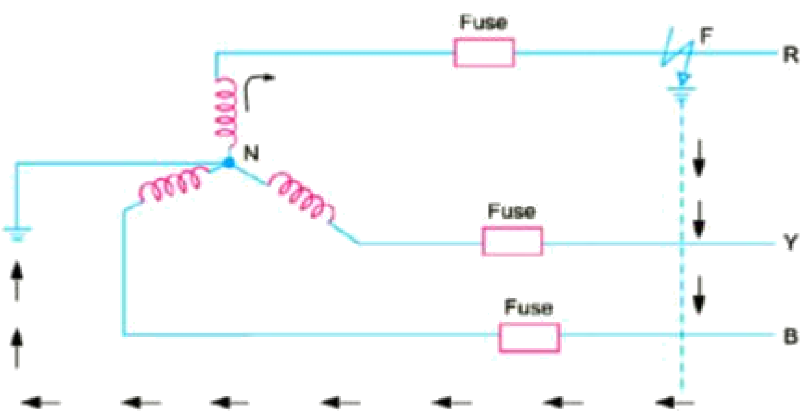


Fig.5.8

- Fig.5.8 shows a 3-phase, star-connected system with neutral earthed. Suppose a single line to ground fault occurs in line R at point F.
- This will cause the current to flow through ground path as shown in Fig.1. Note that current flows from R phase to earth, then to neutral point N and back to R-phase.
- Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in R-phase and isolate the faulty line R.
- This will protect the system from the harmful effects of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system i.e. it will remain nearly constant.

Advantages of Neutral Grounding

The following are the advantages of neutral grounding

(i) Voltages of the healthy phases do not exceed line to ground voltages i.e. they remain nearly constant.

(ii) The high voltages due to arcing grounds are eliminated

(iii)The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.

(iv) The over voltages due to lightning are discharged to earth.

(v) It provides greater safety to personnel and equipment.

(vi) It provides improved service reliability.

(vii) Operating and maintenance expenditures are reduced

Methods of Neutral Grounding

The methods commonly used for grounding the neutral point of a 3-phase system are :

(i) Solid or effective grounding

(ii) Resistance grounding

(iii) Reactance grounding

(iv) Peterson-coil grounding

The choice of the method of grounding depends upon many factors including the size of the system, system voltage and the scheme of protection to be used.

(i)Solid Grounding

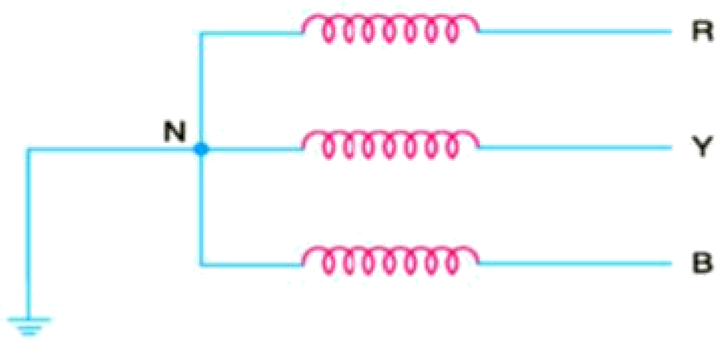


Fig.5.9

- When the neutral point of a 3-phase system (e.g. 3- phase generator, 3-phase transformer etc.) is directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called solid grounding or effective grounding.
- Fig.5.9. shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions.
- Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.

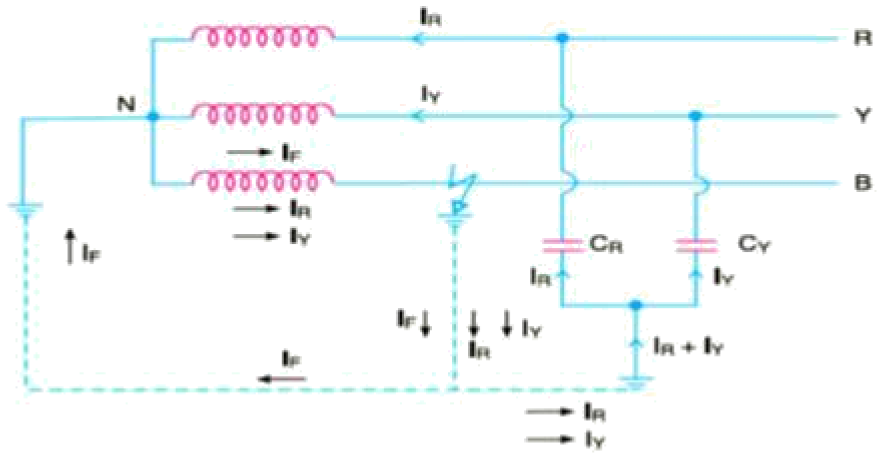


Fig.5.10

Advantages

The solid grounding of neutral point has the following advantages:

(i) The neutral is effectively held at earth potential.

(ii)When earth fault occurs on any phase, the resultant capacitive current IC is in phase opposition to the fault current I_F . The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur. Consider a line to ground fault in line B as shown in Fig.5.10. The capacitive currents flowing in the healthy phases R and Y are IR and IY respectively. The resultant capacitive current IC is the phasor sum of IR and IY . In addition to these capacitive currents, the power source also supplies the fault current IF . This fault current will go from fault point to earth, then to neutral point N and back to the fault point through the faulty phase. The path of I_C is capacitive and that of I_F is inductive. The two currents are in phase opposition and completely cancel each other. Therefore, no arcing ground phenomenon or over-voltage conditions can occur.

(iii)When there is an earth fault on any phase of the system, the phase to earth voltage of the faulty phase becomes zero. However, the phase to earth voltages of the remaining two healthy phases remain at normal phase voltage because the potential of the neutral is fixed at earth potential. This permits to insulate the equipment for phase voltage. Therefore, there is a saving in the cost of equipment.

(iv) It becomes easier to protect the system from earth faults which frequently occur on the system. When there is an earth fault on any phase of the system, large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth fault relay.

Disadvantages

The following are the disadvantages of solid grounding :
(i) Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.
(ii)The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.
(iii)The increased earth fault current results in greater interference in the neighboring communication lines.

Applications
Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages up to 33 kV with total power capacity not exceeding 5000 kVA.

(ii)Resistance Grounding

- In order to limit the magnitude of earth fault current, it is a common practice to connect the neutral point of a 3-phase system to earth through a resistor. This is called resistance grounding.
- When the neutral point of a 3-phase system (e.g. 3-phase generator, 3- phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called resistance grounding.
- Fig.5.11.shows the grounding of neutral point through a resistor R . The value of R should neither be very low nor very high. If the value of earthing resistance R is very low, the earth fault current will be large and the system becomes similar to the solid grounding system.

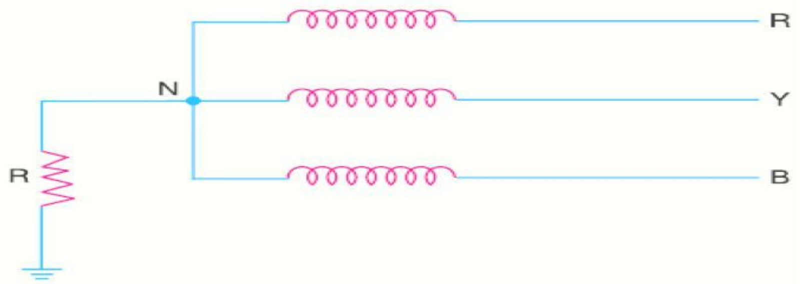


Fig.5.11

- On the other hand, if the earthing resistance R is very high, the system conditions become similar to ungrounded neutral system.
- The value of R is so chosen such that the earth fault current is limited to safe value but still sufficient to permit the operation of earth fault protection system.
- In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.

Advantages

The following are the advantages of resistance earthing:

i)The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.

ii)It improves the stability of the system.

Disadvantages

The following are the disadvantages of resistance grounding :

(i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.

(ii)This system is costlier than the solidly grounded system.

(iii)A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications

It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

(iii)Reactance Grounding

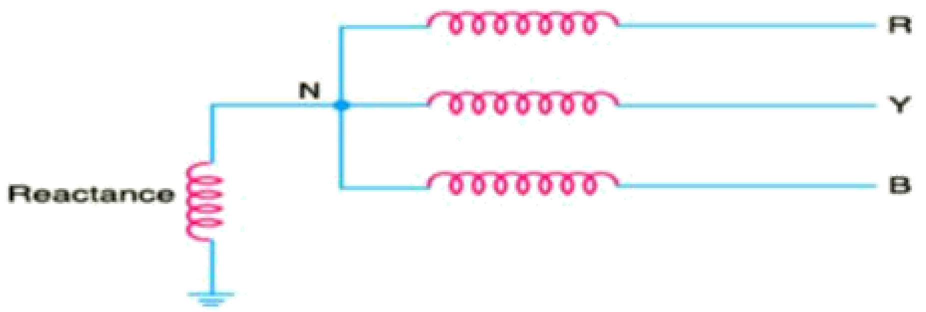


Fig.5.12

In this system, a reactance is inserted between the neutral and ground as shown in Fig.5.12. The purpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can to changed to obtain the conditions similar to that of solid grounding. This method is not used these days because of the following

Disadvantages

(i) In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.

(ii)High transient voltages appear under fault conditions.

(iv)Arc Suspension Grounding (Or Resonant Grounding)

- The capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth.
- If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current IF flowing through L will be in phase opposition to the capacitive current IC of the system.
- If L is so adjusted that IL= Ic then resultant current in the fault will be zero. This condition is known as resonant grounding.
- When the value of L of arc suppression coil is such that the fault current IF exactly balances the capacitive current Ic, it is called resonant grounding
- **Value of L for resonant grounding** . For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors CR and CY

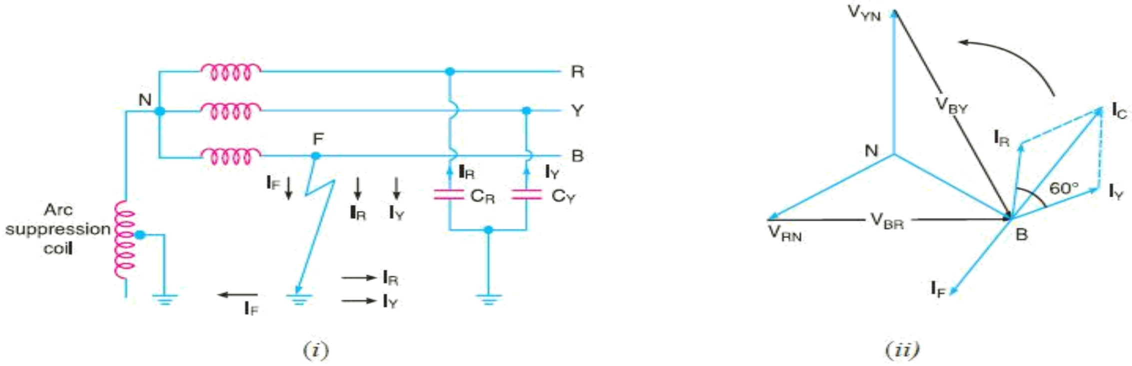


Fig.5.13

$$\therefore \quad I_R = I_Y = \frac{\sqrt{3}V_{ph}}{X_C}$$

$$\therefore \quad I_C = \sqrt{3}\, I_R = \sqrt{3} \times \frac{\sqrt{3}V_{ph}}{X_C} = \frac{3V_{ph}}{X_C}$$

Here, X_C is the line to ground capacitive reactance.

Fault current, $$I_F = \frac{V_{ph}}{X_L}$$

Here, X_L is the inductive reactance of the arc suppression coil.

For resonant grounding, $I_L = I_C$.

$$\text{or} \quad \frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$$

$$\text{or} \quad X_L = \frac{X_C}{3}$$

$$\text{or} \quad \omega L = \frac{1}{3\omega C}$$

$$\therefore \quad L = \frac{1}{3\omega^2 C} \quad \ldots(i)$$

Exp. (i) gives the value of inductance L of the arc suppression coil for resonant grounding.

Advantages

The Peterson coil grounding has the following advantages:

(i) The Peterson coil is completely effective in preventing any damage by an arcing ground.

(ii) The Peterson coil has the advantages of ungrounded neutral system.

Disadvantages

The Peterson coil grounding has the following disadvantages :

(i) Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance L of Peterson coil requires readjustment.

(ii) The lines should be transposed.