



SATHYABAMA

INSTITUTE OF SCIENCE AND TECHNOLOGY
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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

Transmission and Distribution – SEEA1402
UNIT 1- STRUCTURE OF ELECTRIC POWER SYSTEM

I. STRUCTURE OF ELECTRIC POWER SYSTEM

Single Line Diagram - Distributors with Concentrated and Uniform Loading - DC Two Wire and Three Wire Systems - AC Distributors - Radial and Ring Distributors - Interconnectors - Electrical Layout & Bus Bar Arrangement in Generating Sub Stations and Bulk Power Substation - Kelvin's Law for the Design of Feeders and its Limitations.

1.1 Single Line Diagram

The large network of conductors between the power station and the consumers can be broadly divided into two parts viz., transmission system and distribution system. Each part can be further sub-divided into two—primary transmission and secondary transmission and primary distribution and secondary distribution. Fig. 1.1 shows the layout of a typical a.c. power supply scheme by a single line diagram. It may be noted that it is not necessary that all power schemes include all the stages shown in the figure. For example, in a certain power scheme, there may be no secondary transmission and in another case, the scheme may be so small that there is only distribution and no transmission.

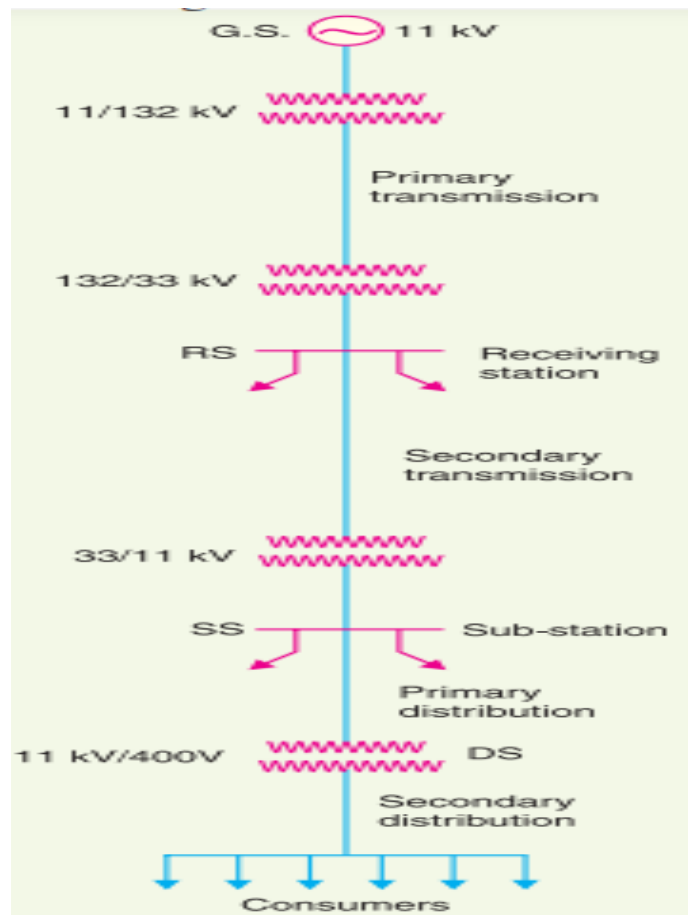


Fig. 1.1 Structure of Electric Power System

- (i) **Generating station** : In Figure G.S. represents the generating station where electric power is produced by 3-phase alternators operating in parallel. The usual generation voltage is ∇ 11 kV. For economy in the transmission of electric power, the generation voltage (i.e., 11 kV)

is stepped upto 132 kV (or **more) at the generating station with the help of 3-phase transformers. The transmission of electric power at high voltages has several advantages including the saving of conductor material and high transmission efficiency. It may appear advisable to use the highest possible voltage for transmission of electric power to save conductor material and have other advantages. But there is a limit to which this voltage can be increased. It is because increase in transmission voltage introduces insulation problems well as the cost of switchgear and transformer equipment is increased. Therefore, the choice of proper transmission voltage is essentially a question of economics. Generally the primary transmission is carried at 66 kV, 132 kV, 220 kV or 400 kV.

- (ii) **Primary transmission.** The electric power at 132 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. This forms the primary transmission.
- (iii) **Secondary transmission.** The primary transmission line terminates at the receiving station (RS) which usually lies at the outskirts of the city. At the receiving station, the voltage is reduced to 33kV by step-down transformers. From this station, electric power is transmitted at 33kV by 3-phase, 3-wire overhead system to various sub-stations (SS) located at the strategic points in the city. This forms the secondary transmission
- (iv) **Primary distribution.** The secondary transmission line terminates at the sub-station (SS) where voltage is reduced from 33 kV to 11kV, 3-phase, 3-wire. The 11 kV lines run along the important road sides of the city. This forms the primary distribution. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations
- (v) **Secondary distribution.** The electric power from primary distribution line (11 kV) is delivered to distribution sub-stations (DS). These sub-stations are located near the consumers' localities and step down the voltage to 400 V, 3-phase, 4-wire for secondary distribution. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single-phase residential lighting load is connected between any one phase and neutral, whereas 3-phase, 400 V motor load is connected across 3-phase lines directly.

It may be worthwhile to mention here that secondary distribution system consists of feeders, distributors and service mains. Fig. shows the elements of low voltage distribution system. Feeders (SC or SA) radiating from the distribution sub-station (DS) supply power to the distributors (AB, BC, CD and AD). No consumer is given direct connection from the feeders. Instead, the consumers are connected to the distributors through their service mains.

1.2 Comparison of D.C. and A.C. Transmission

The electric power can be transmitted either by means of d.c. or a.c. Each system has its own merits and demerits. It is, therefore, desirable to discuss the technical advantages and disadvantages of the two systems for transmission of electric power.

1.2.1 D.C. transmission. For some years past, the transmission of electric power by d.c. has been receiving the active consideration of engineers due to its numerous advantages.

Advantages.

The high voltage d.c. transmission has the following advantages over high voltage a.c. transmission :

- (i) It requires only two conductors as compared to three for a.c. transmission.
- (ii) There is no inductance, capacitance, phase displacement and surge problems in d.c.

transmission.

- (iii) Due to the absence of inductance, the voltage drop in a d.c. transmission line is less than the a.c. line for the same load and sending end voltage. For this reason, a d.c. transmission line has better voltage regulation.
- (iv) There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilised.
- (v) For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation.
- (vi) A d.c. line has less corona loss and reduced interference with communication circuits.
- (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

1.2.2 A.C. transmission.

Now-a-days, electrical energy is almost exclusively generated, transmitted and distributed in the form of a.c.

Advantages

- (i) The power can be generated at high voltages.
- (ii) The maintenance of a.c. sub-stations is easy and cheaper.
- (iii) The a.c. voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

Disadvantages

- (i) An a.c. line requires more copper than a d.c. line.
- (ii) The construction of a.c. transmission line is more complicated than a d.c. transmission line.
- (iii) Due to skin effect in the a.c. system, the effective resistance of the line is increased.
- (iv) An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open.

1.3 Advantages of High Transmission Voltage

The transmission of electric power is carried at high voltages due to the following reasons :

- (i) **Reduces volume of conductor material.** Consider the transmission of electric power by a three-phase line. Let P = power transmitted in watts V = line voltage in volts $\cos \phi$ = 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

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

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

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

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

Total volume of conductor material required

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

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,

$$a = l / J$$

$$\begin{aligned} \therefore \text{Input power} &= P + \frac{P^2 \rho l J}{V^2 \cos^2 \phi I} = P + \frac{P^2 \rho l J}{V^2 \cos^2 \phi} \times \frac{1}{I} \\ &= P + \frac{P^2 \rho l J}{V^2 \cos^2 \phi} \times \frac{\sqrt{3} V \cos \phi}{P} \\ &= P + \frac{\sqrt{3} P J \rho l}{V \cos \phi} = P \left[1 + \frac{\sqrt{3} J \rho l}{V \cos \phi} \right] \end{aligned}$$

$$\begin{aligned} \text{Transmission efficiency} &= \frac{\text{Output power}}{\text{Input power}} = \frac{P}{P \left[1 + \frac{\sqrt{3} J \rho l}{V \cos \phi} \right]} = \frac{1}{\left[1 + \frac{\sqrt{3} J \rho l}{V \cos \phi} \right]} \\ &= \left[1 - \frac{\sqrt{3} J \rho l}{V \cos \phi} \right] \text{ approx.} \quad \dots(ii) \end{aligned}$$

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

(iii) Decreases percentage line drop

$$\begin{aligned}
 \text{Line drop} &= IR = I \times \frac{\rho l}{a} \\
 &= I \times \rho l \times J/I = \rho l J \quad [\because a = l/J] \\
 \% \text{age line drop} &= \frac{J \rho l}{V} \times 100 \quad \dots(iii)
 \end{aligned}$$

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 advisable 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. Hence, the choice of proper transmission voltage is essentially a question of economics

1.4 Various Systems of Power Transmission

It has already been pointed out that for transmission of electric power, 3-phase, 3-wire a.c. system is universally adopted. However, other systems can also be used for transmission under special circumstances. The different possible systems of transmission are

1. D.C. system
 - (i) D.C. two-wire.
 - (ii) D.C. two-wire with mid-point earthed.
 - (iii) D.C. three-wire.
2. Single-phase A.C. system
 - (i) Single-phase two-wire.
 - (ii) Single-phase two-wire with mid-point earthed.
 - (iii) Single-phase three-wire.
3. Two-phase A.C. system
 - (i) Two-phase four-wire.
 - (ii) Two-phase three wire.
4. Three-phase A.C. system
 - (i) Three-phase three-wire.
 - (ii) Three-phase four-wire.

1.5 CLASSIFICATION OF DISTRIBUTION SYSTEMS

A distribution system may be classified according to ;

i) Nature of current

According to nature of current, distribution system may be classified as

- (a) d.c. Distribution system
- (b) a.c. Distribution system

Now-a-days, a.c. system is universally adopted for distribution of electric power as it is simpler and more economical than direct current method

ii) Type of construction

According to type of construction distribution system may be classified as

- (a) Overhead system
- (b) Underground system.

The overhead system is generally employed for distribution as it is 5 to 10 times cheaper than the equivalent underground system. In general, the underground system is used at places where overhead construction is impracticable or prohibited by the local laws

(iii) Scheme of connection

According to scheme of connection, the distribution system may be classified as

- (a) Radial system
- (b) Ring main system
- (c) Inter-connected system

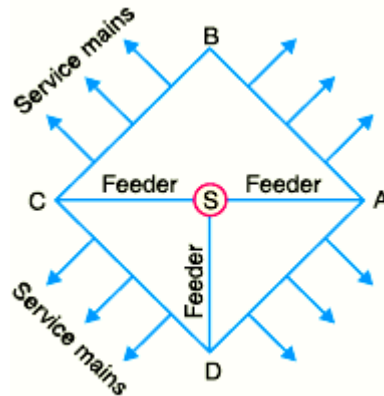


Fig.1.2 Distribution Systems

1.6 AC DISTRIBUTION

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating current. One important reason for the widespread use of alternating current in preference to direct current is the fact that alternating voltage can be conveniently changed in magnitude by means of a transformer. Transformer has made it possible to transmit a.c. power at high voltage and utilise it at a safe potential. High transmission and distribution voltages have greatly reduced the current in the conductors and the resulting line losses.

There is no definite line between transmission and distribution according to voltage or bulk capacity. However, in general, the a.c. distribution system is the electrical system between the

step- down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into

primary distribution system and
Secondary distribution system.

i) Primary distribution system.

It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average low- voltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance of the substation required to be fed. The most commonly used primary distribution voltages are 11 kV, 6.6 kV and 3.3 kV.

Due to economic considerations, primary distribution is carried out by 3- phase, 3-wire system Fig. shows a typical primary distribution system Electric power from the generating station is transmitted at high voltage to the substation located in or near the city.

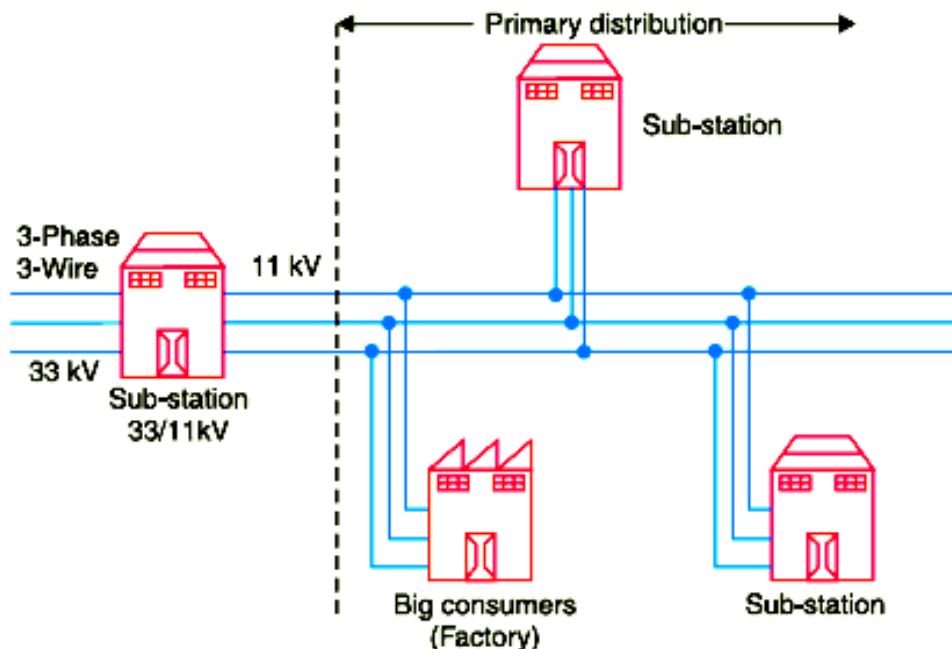


Fig. 1.3 Primary Distribution Systems

ii) Secondary distribution system

It is that part of a.c. distribution system. These secondary distribution employs 400/230V, 3-phase, 4-wire system. Fig shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution sub-stations. The substations are situated near the consumers' localities and contain step-down transformers. At each distribution substation, the voltage is stepped down to 400V and power is delivered by 3-phase, 4-wire a.c. system. The voltage between any two phases is 400V and between any phase and neutral is 230V. The single phase domestic loads are reconnected between any one phase and the neutral, whereas 3-phase 400V motor loads are reconnected across 3-phase lines directly.

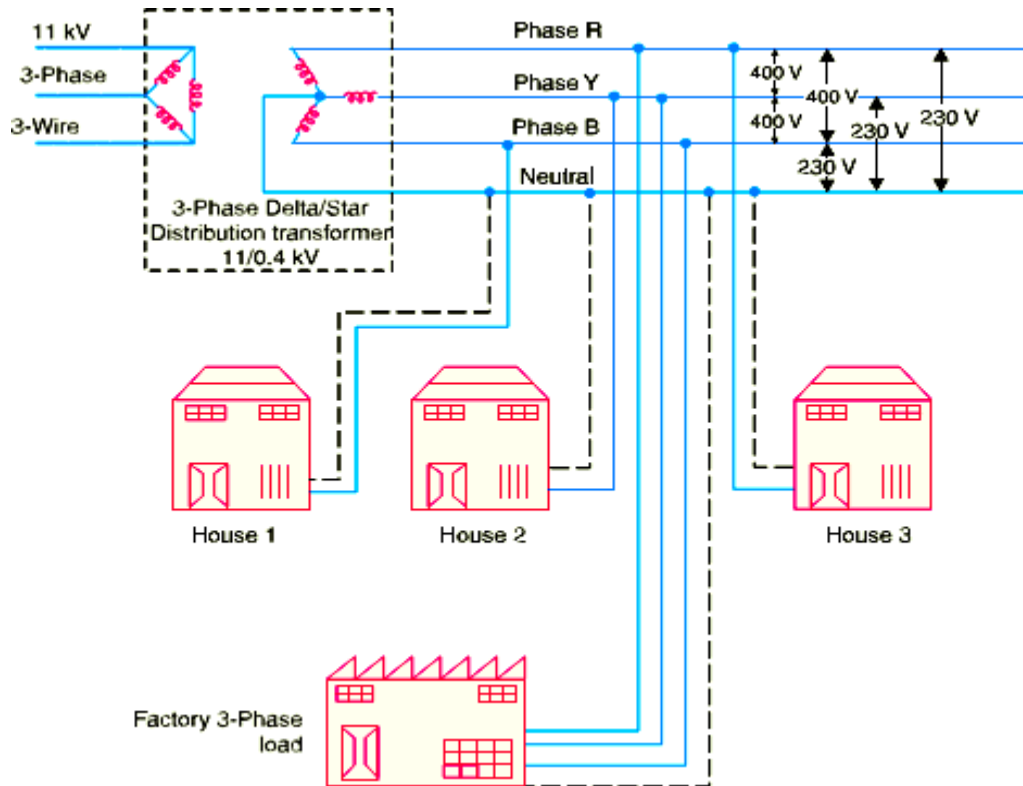


Fig. 1.4 Secondary Distribution Systems

1.7 D.C. DISTRIBUTION

It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery (d.c. motors), for electro-chemical work and for congested areas where storage battery reserves are necessary. For this purpose, a.c. power is converted into d.c. power at the substation by using converting machinery e.g., mercury arc rectifiers, rotary converters and motor-generator sets.

The d.c. supply from the substation may be obtained in the form of

- (i) 2-wire
- (ii) 3-wire for distribution.

(i) 2-wire d.c. system.

As the name implies, this system of distribution consists of two wires. One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires as shown in Fig. This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.

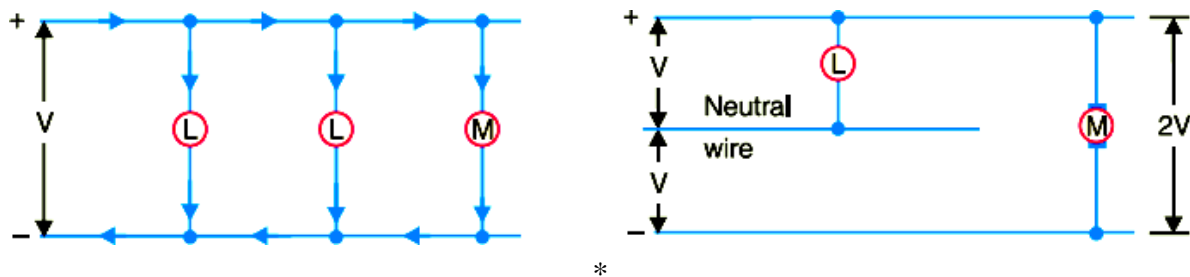


Fig.1.5 a) DC 2 wire system b) DC three wire system

(ii) 3-wire d.c. system.

It consists of two outers and a middle or neutral wire which is earthed at the substation. The voltage between the outers is twice the voltage between either outer and neutral wire as shown in Fig.. The principal advantage of this system is that it makes available two voltages at the consumer terminals viz., V between any outer and the neutral and $2V$ between the outers. Loads requiring high voltage (e.g., motors) are connected across the outers, whereas lamps and heating circuits requiring less voltage are connected between either outer and the neutral. The methods of obtaining 3-wire system are discussed in the following article.

1.8 OVERHEAD VERSUS UNDERGROUND SYSTEM

The distribution system can be overhead or underground. Overhead lines are generally mounted on wooden, concrete or steel poles which are arranged to carry distribution transformers in addition to the conductors. The underground system uses conduits, cables and manholes under the surface of streets and sidewalks. The choice between overhead and underground system depends upon a number of widely differing factors. Therefore, it is desirable to make a comparison between the two.

(i) Public safety.

The underground system is more safe than overhead system because all distribution wiring is placed underground and there are little chances of any hazard.

(ii) Initial cost.

The underground system is more expensive due to the high cost of trenching, conduits, cables, manholes and other special equipment. The initial cost of an underground system may be five to ten times than that of an overhead system.

(iii) Flexibility.

The overhead system is much more flexible than the underground system. In the latter case, manholes, duct lines etc., are permanently placed once installed and the load expansion can only be met by laying new lines. However, on an overhead system, poles, wires, transformers etc., can be easily shifted to meet the changes in load conditions.

(iv) Faults.

The chances of faults in underground system are very rare as the cables are laid underground and are generally provided with better insulation.

(v) Appearance.

The general appearance of an underground system is better as all the distribution lines are invisible. This factor is exerting considerable public pressure on electric supply companies to switch over to underground system.

(vi) **Fault location and repairs.**

In general, there are little chances of faults in an underground system. However, if a fault does occur, it is difficult to locate and repair on this system. On an overhead system, the conductors are visible and easily accessible so that fault locations and repairs can be easily made.

(vii) **Current carrying capacity and voltage drop.**

An overhead distribution conductor has a considerably higher current carrying capacity than an underground cable conductor of the same material and cross-section. On the other hand, underground cable conductor has much lower inductive reactance than that of an overhead conductor because of closer spacing of conductors.

(viii) **Useful life.**

The useful life of underground system is much longer than that of an overhead system. An overhead system may have a useful life of 25 years, whereas an underground system may have a useful life of more than 50 years.

(ix) **Maintenance cost.**

The maintenance cost of underground system is very low as compared with that of overhead system because of less chances of faults and service interruptions from wind, ice, lightning as well as from traffic hazards.

(x) **Interference with communication circuits.**

An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable level. However, there is no such interference with the underground system.

It is clear from the above comparison that each system has its own advantages and disadvantages. However, comparative economics (i.e., annual cost of operation) is the most powerful factor influencing the choice between underground and overhead system. The greater capital cost of underground system prohibits its use for distribution. But sometimes non- economic factors (e.g., general appearance, public safety etc.) exert considerable influence on choosing underground system. In general, overhead system is adopted for distribution and the use of underground system is made only where overhead construction is impracticable or prohibited by local laws.

1.9 CONNECTION SCHEMES OF DISTRIBUTION SYSTEM

All distribution of electrical energy is done by constant voltage system. In practice, the following distribution circuits are generally used :

(i) **Radial System.**

In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig. shows a single line diagram of a radial system for d.c. distribution where a feeder OC supplies a distributor A B at point A . Obviously, the distributor is fed at one end only i.e., point A is this case. Fig (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.

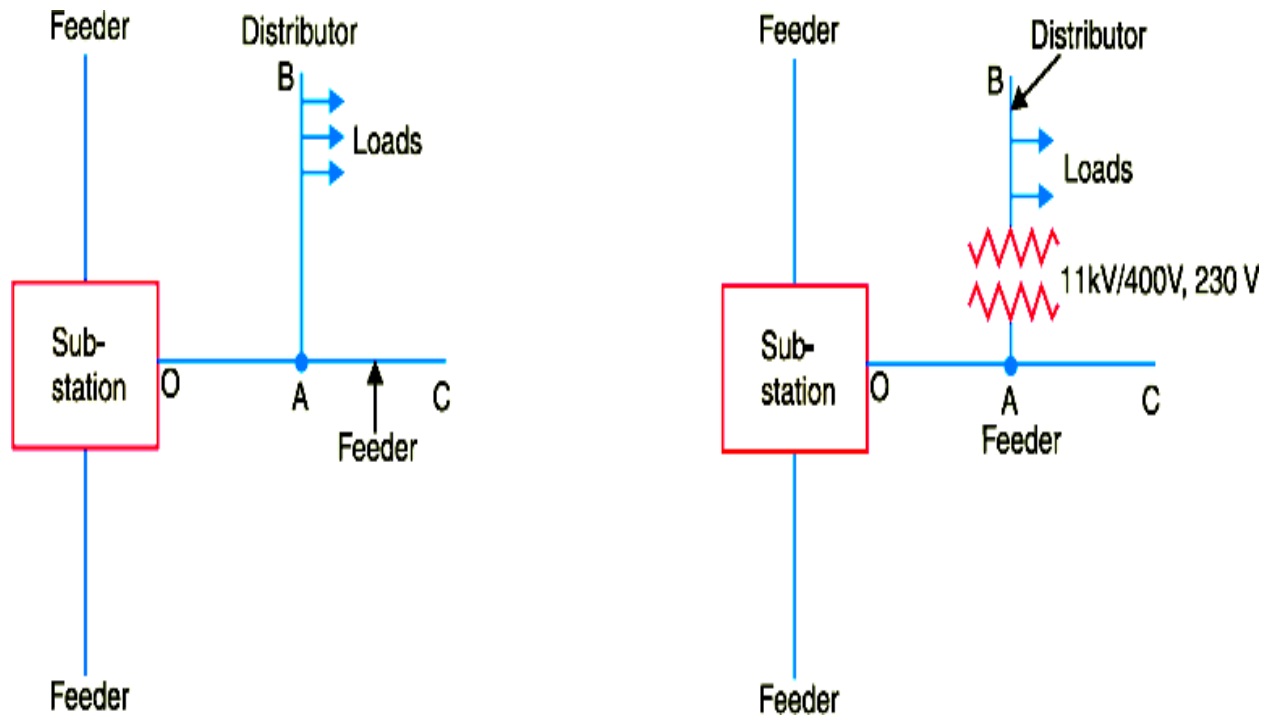


Fig.1.6 Radial Distribution system

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. shows the single line diagram of ring main system for a.c. distribution where substation supplies to the closed feeder LMNOPQRS.

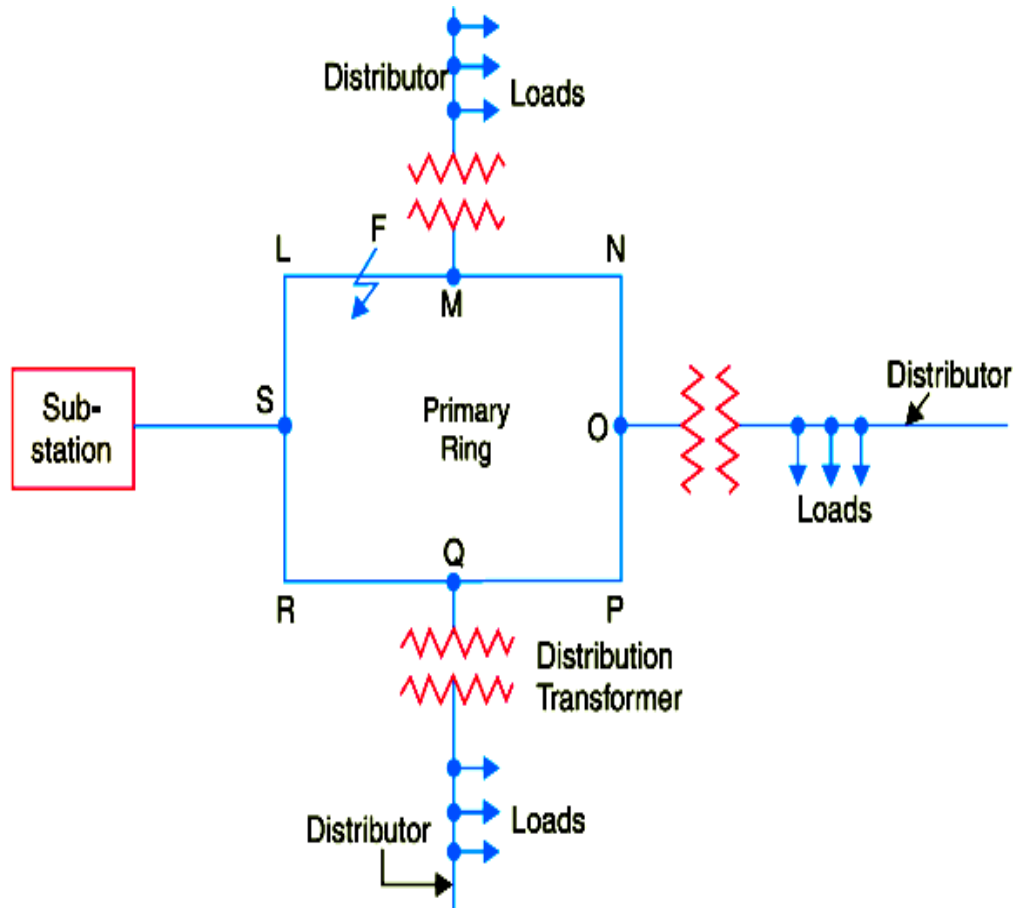


Fig. 1.7 Ring main distribution system

The distributors are tapped from different points M, O and Q of the feeder through distribution transformers. The ring main system has the following advantages :

- (a) There are less voltage fluctuations at consumer's terminals.
- (b) The system is very reliable as each distributor is fed via *two feeders. In the event of fault on any section of the feeder, the continuity of supply is maintained. For example, suppose that fault occurs at any point F of section SLM of the feeder. Then section SLM of the feeder can be isolated for repairs and at the same time continuity of supply is maintained to all the consumers via the feeder SRQPONM.

(iii) **Interconnected system.**

When the feeder ring is energised by two or more than two generating stations or substations, it is called inter-connected system. Fig. shows the single line diagram of interconnected system where the closed feeder ring ABCD is supplied by two substations S and S at points D and C respectively.

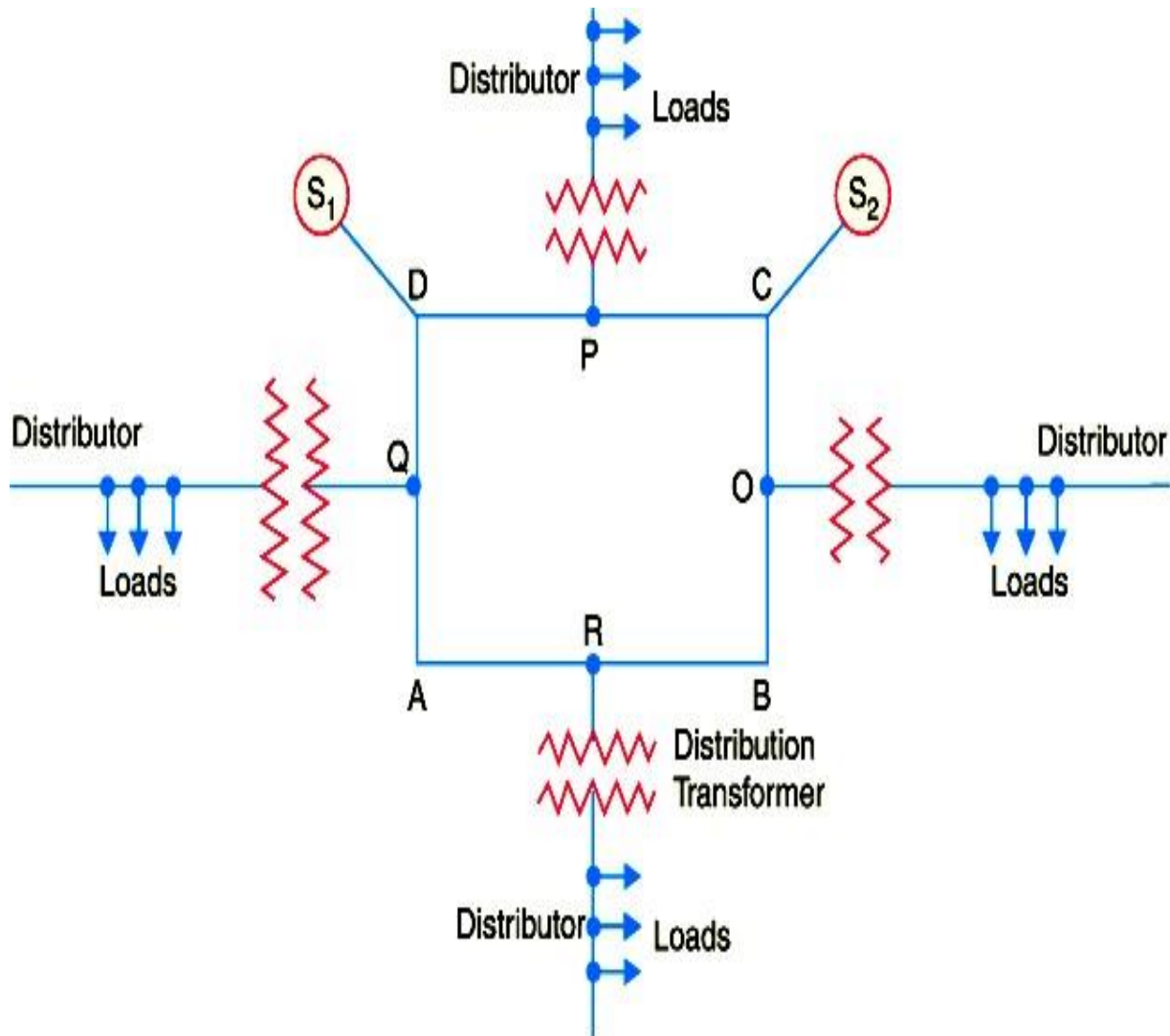


Fig.1.8 Interconnected System

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

1.10 REQUIREMENTS OF A DISTRIBUTION SYSTEM

A considerable amount of effort is necessary to maintain an electric power supply within the requirements of various types of consumers. Some of the requirements of a good distribution system are : proper voltage, availability of power on demand and reliability.

(i) Proper voltage.

One important requirement of a distribution system is that voltage variations at consumer's terminals should be as low as possible. The changes in voltage are generally caused due to the variation of load on the system. Low voltage causes loss of revenue, inefficient lighting and possible burning out of motors. High voltage causes lamps to burn out permanently and may cause failure of other appliances. Therefore, a good distribution system should ensure that the voltage variations at consumers terminals are within permissible limits. The statutory limit of voltage variations is $\pm 6\%$ of the rated value at the consumer's terminals. Thus, if the declared voltage is 230 V, then the highest voltage of the consumer should not exceed 244 V while the lowest voltage of the consumer should not be less than 216 V.

(ii) Availability of power on demand.

Power must be available to the consumers in any amount that they may require from time to time. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric supply company. As electrical energy cannot be stored, therefore, the distribution system must be capable of supplying load demands of the consumers. This necessitates that operating staff must continuously study load patterns to predict in advance those major load changes that follow the known schedules.

(iii) Reliability.

Modern industry is almost dependent on electric power for its operation. Homes and office buildings are lighted, heated, cooled and ventilated by electric power. This calls for reliable service. Unfortunately, electric power, like everything else that is man-made, can never be absolutely reliable. However, the reliability can be improved to a considerable extent by (a) interconnected system (b) reliable automatic control system (c) providing additional reserve facilities.

1.10.1 DESIGN CONSIDERATIONS IN DISTRIBUTION SYSTEM

Good voltage regulation of a distribution network is probably the most important factor responsible for delivering good service to the consumers. For this purpose, design of feeders and distributors requires careful consideration.

(i) Feeders.

A feeder is designed from the point of view of its current carrying capacity while the voltage drop consideration is relatively unimportant. It is because voltage drop in a feeder can be compensated by means of voltage regulating equipment at the substation.

(ii) Distributors.

A distributor is designed from the point of view of the voltage drop in it. It is because a distributor supplies power to the consumers and there is a statutory limit of voltage variations at the consumer's terminals ($\pm 6\%$ of rated value). The size and length of the distributor should be such that voltage at the consumer's terminals is within the permissible limits.

1.11 A.C. DISTRIBUTION -INTRODUCTION

In the beginning of electrical age, electricity was generated, transmitted and distributed as direct current. The principal disadvantage of d.c. system was that voltage level could not readily

be changed, except by the use of rotating machinery, which in most cases was too expensive. With the development of transformer by George Westinghouse, a.c. system has become so predominant as to make d.c. system practically extinct in most parts of the world. The presentday large power system has been possible only due to the adoption of a.c. system. Now-a-days, electrical energy is generated, transmitted and distributed in the form of alternating current as an economical proposition. The electrical energy produced at the power station is transmitted at very high voltages by 3-phase, 3-wire system to step-down sub-stations for distribution. The distribution system consists of two parts viz. primary distribution and secondary distribution. The primary distribution circuit is 3-phase, 3-wire and operates at voltages (3.3 or 6.6 or 11kV) somewhat higher than general utilization levels. It delivers power to the secondary distribution circuit through distribution transformers situated near consumers' localities. Each distribution transformer steps down the voltage to 400 V and power is distributed to ultimate consumers' by 400/230 V, 3-phase, 4-wire system. In this chapter, we shall focus our attention on the various aspects of a.c. distribution.

1.11.1 A.C. DISTRIBUTION CALCULATIONS

A.C. distribution calculations differ from those of d.c. distribution in the following respects :

(i) In case of d.c. system, the voltage drop is due to resistance alone. However, in a.c. system, the voltage drops are due to the combined effects of resistance, inductance and capacitance.

(ii) In a d.c. system, additions and subtractions of currents or voltages are done arithmetically but in case of a.c. system, these operations are done vectorially.

(iii) In an a.c. system, power factor (p.f.) has to be taken into account. Loads tapped off from the distributor are generally at different power factors. There are two ways of referring power factor viz

(a) It may be referred to supply or receiving end voltage which is regarded as the reference vector.

(b) It may be referred to the voltage at the load point itself.

There are several ways of solving a.c. distribution problems. However, symbolic notation method has been found to be most convenient for this purpose. In this method, voltages, currents and impedances are expressed in complex notation and the calculations are made exactly as in d.c. distribution.

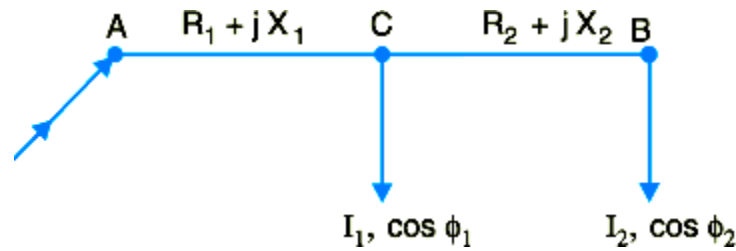
1.11.2 METHODS OF SOLVING A.C. DISTRIBUTION PROBLEMS

In a.c. distribution calculations, power factors of various load currents have to be considered since currents in different sections of the distributor will be the vector sum of load currents and not the arithmetic sum. The power factors of load currents may be given (i) w.r.t. receiving or sending end voltage or (ii) w.r.t. to load voltage itself. Each case shall be discussed separately.

(i) Power factors referred to receiving end voltage.

Consider an a.c. distributor AB with concentrated loads of I_1 and I_2 tapped off at points C and B as shown in Fig. Taking the receiving end voltage V_B as the reference vector, let

lagging power factors at C and B be $\cos \phi_1$ and $\cos \phi_2$ w.r.t. V_B . Let R_1, X_1 and R_2, X_2 be the resistance and reactance of sections AC and CB of the distributor.



Impedance of section AC , $\overrightarrow{Z_{AC}} = R_1 + j X_1$

Impedance of section CB , $\overrightarrow{Z_{CB}} = R_2 + j X_2$

Load current at point C , $\overrightarrow{I_1} = I_1 (\cos \phi_1 - j \sin \phi_1)$

Load current at point B , $\overrightarrow{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

Current in section CB , $\overrightarrow{I_{CB}} = \overrightarrow{I_2} = I_2 (\cos \phi_2 - j \sin \phi_2)$

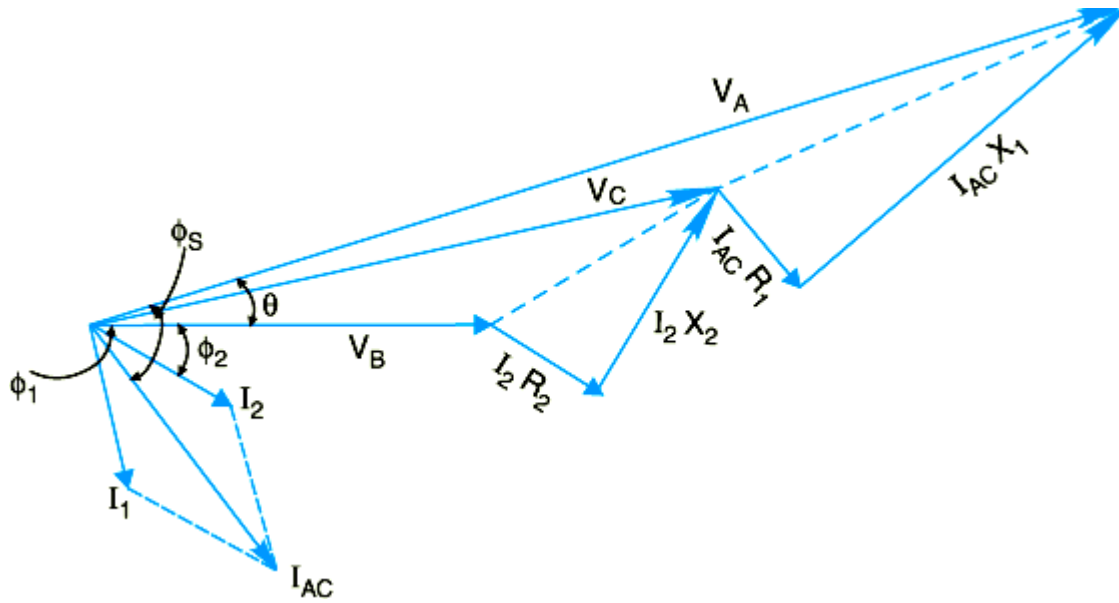
Current in section AC , $\overrightarrow{I_{AC}} = \overrightarrow{I_1} + \overrightarrow{I_2}$
 $= I_1 (\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)$

Voltage drop in section CB , $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}} \overrightarrow{Z_{CB}} = I_2 (\cos \phi_2 - j \sin \phi_2) (R_2 + j X_2)$

Voltage drop in section AC , $\overrightarrow{V_{AC}} = \overrightarrow{I_{AC}} \overrightarrow{Z_{AC}} = (\overrightarrow{I_1} + \overrightarrow{I_2}) Z_{AC}$
 $= [I_1 (\cos \phi_1 - j \sin \phi_1) + I_2 (\cos \phi_2 - j \sin \phi_2)] [R_1 + j X_1]$

Sending end voltage, $\overrightarrow{V_A} = \overrightarrow{V_B} + \overrightarrow{V_{CB}} + \overrightarrow{V_{AC}}$

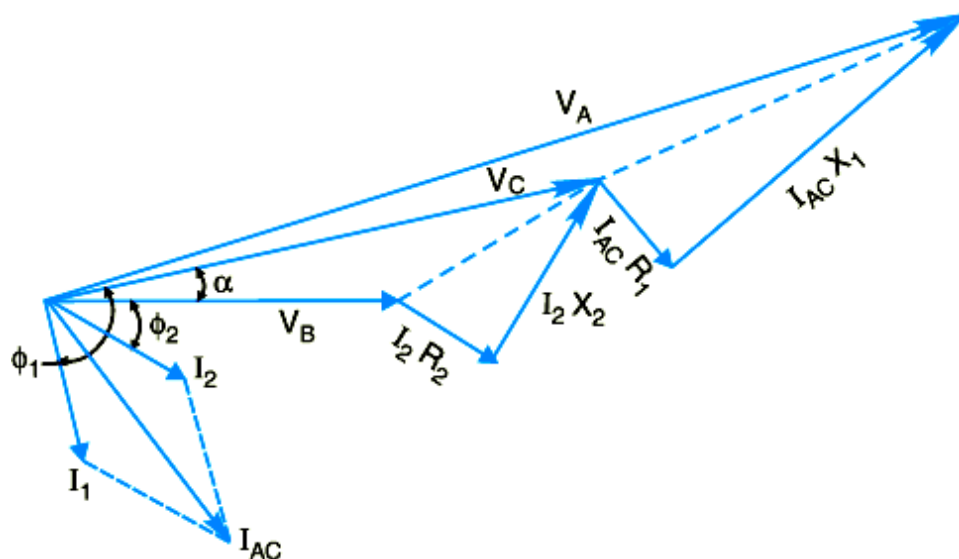
Sending end current, $\overrightarrow{I_A} = \overrightarrow{I_1} + \overrightarrow{I_2}$



The vector diagram of the a.c. distributor under these conditions is shown in Fig. Here, the receiving end voltage V_B is taken as the reference vector. As power factors of loads are given *w.r.t.* V_B , therefore, I_1 and I_2 lag behind V_B by ϕ_1 and ϕ_2 respectively.

(ii) **Power factors referred to respective load voltages.**

Suppose the power factors of loads in the previous Fig. are referred to their respective load voltages. Then ϕ_1 is the phase angle between V_C and I_1 and ϕ_2 is the phase angle between V_B and I_2 . The vector diagram under these conditions is shown in Fig



$$\text{Voltage drop in section } CB = \vec{I}_2 \vec{Z}_{CB} = I_2 (\cos \phi_2 - j \sin \phi_2) (R_2 + j X_2)$$

$$\text{Voltage at point } C = \vec{V}_B + \text{Drop in section } CB = V_C \angle \alpha \text{ (say)}$$

$$\text{Now } \vec{I}_1 = I_1 \angle -\phi_1 \text{ w.r.t. voltage } V_C$$

$$\therefore \vec{I}_1 = I_1 \angle -(\phi_1 - \alpha) \text{ w.r.t. voltage } V_B$$

$$\text{i.e. } \vec{I}_1 = I_1 [\cos (\phi_1 - \alpha) - j \sin (\phi_1 - \alpha)]$$

$$\begin{aligned} \text{Now } \vec{I}_{AC} &= \vec{I}_1 + \vec{I}_2 \\ &= I_1 [\cos (\phi_1 - \alpha) - j \sin (\phi_1 - \alpha)] + I_2 (\cos \phi_2 - j \sin \phi_2) \end{aligned}$$

$$\text{Voltage drop in section } AC = \vec{I}_{AC} \vec{Z}_{AC}$$

$$\therefore \text{Voltage at point } A = V_B + \text{Drop in } CB + \text{Drop in } AC$$

1.12 TYPES OF D.C. DISTRIBUTORS

The most general method of classifying d.c. distributors is the way they are fed by the feeders. On this basis, d.c. distributors are classified as:

- (i) Distributor fed at one end
- (ii) Distributor fed at both ends
- (iii) Distributor fed at the centre
- (iv) Ring distributor.

(i) Distributor fed at one end.

In this type of feeding, the distributor is connected to the supply at one end and loads are taken at different point along the length of the distributor.

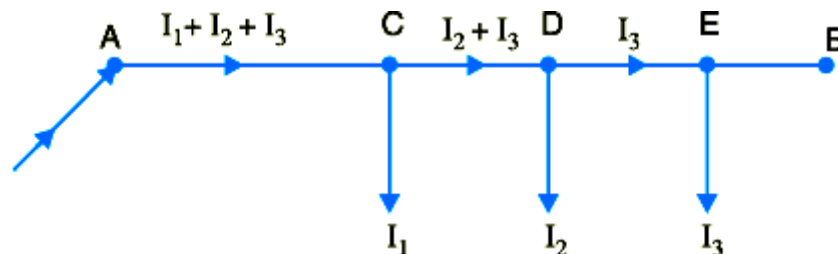


Fig. shows the single line diagram of a d.c. distributor A B fed at the end A (also known as singly fed distributor) and loads I_1 , I_2 and I_3 tapped off at points C, D and E respectively.

The following points are worth noting in a singly fed distributor:

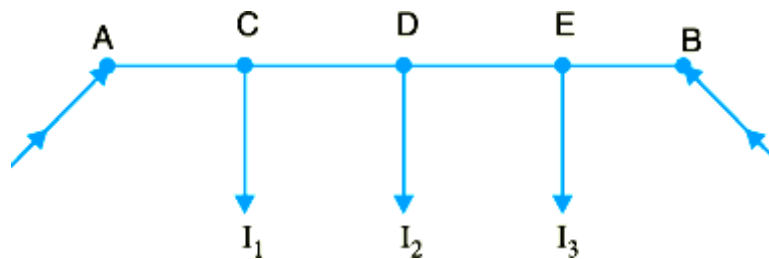
(a) The current in the various sections of the distributor away from feeding point goes on decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.

(b) The voltage across the loads away from the feeding point goes on decreasing. Thus in Fig. the minimum voltage occurs at the load point E.

(c) In case a fault occurs on any section of the distributor, the whole distributor will have to be disconnected from the supply mains. Therefore, continuity of supply is interrupted.

(ii) **Distributor fed at both ends.**

In this type of feeding, the distributor is connected to the supply mains at both ends and loads are tapped off at different points along the length of the distributor. The voltage at the feeding points may or may not be equal. Fig. shows a distributor A B fed at the ends A and B and loads of I_1 , I_2 and I_3 tapped off at points C, D and E respectively.



Here, the load voltage goes on decreasing as we move away from one feeding point say A , reaches minimum value and then again starts rising and reaches maximum value when we reach the other feeding point B. The minimum voltage occurs at some load point and is never fixed. It is shifted with the variation of load on different sections of the distributor.

Advantages

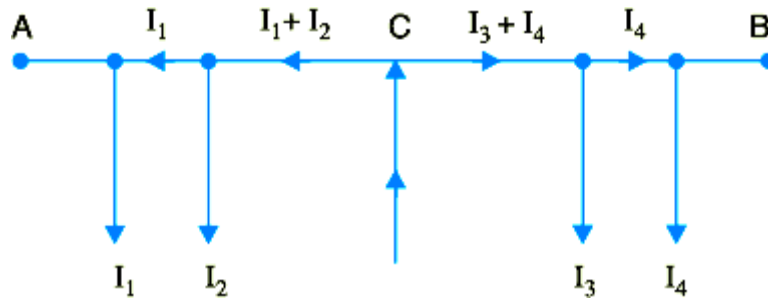
(a) If a fault occurs on any feeding point of the distributor, the continuity of supply is maintained from the other feeding point.

(b) In case of fault on any section of the distributor, the continuity of supply is maintained from the other feeding point.

(c) The area of X-section required for a doubly fed distributor is much less than that of a singly fed distributor.

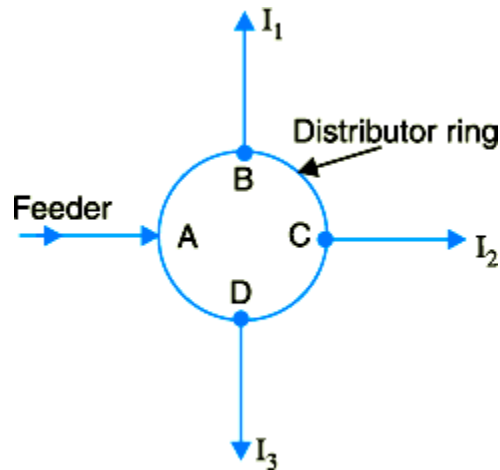
(iii) **Distributor fed at the centre.**

In this type of feeding, the centre of the distributor is connected to the supply mains as shown in Fig. It is equivalent to two singly fed distributors, each distributor having a common feeding point and length equal to half of the total length.



(iv) **Ring mains.**

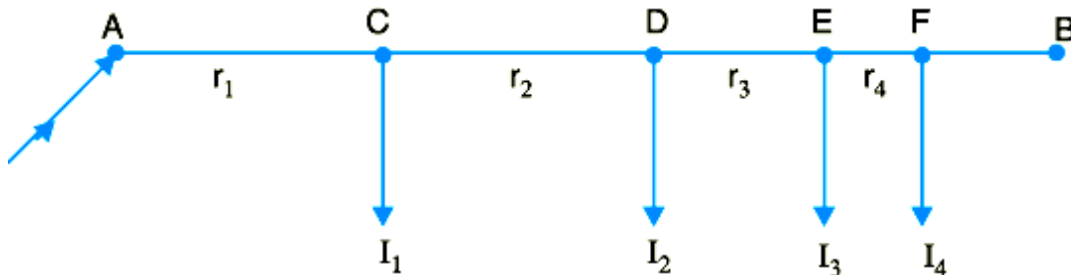
In this type, the distributor is in the form of a closed ring as shown in Fig. It is equivalent to a straight distributor fed at both ends with equal voltages, the two ends being brought together to form a closed ring. The distributor ring may be fed at one or more than one point.



1.12.1 D.C. DISTRIBUTOR FED AT ONE END — CONCENTRATED LOADING

Fig. shows the single line diagram of a 2-wire d.c. distributor AB fed at one end A and having concentrated loads I_1 , I_2 , I_3 and I_4 tapped off at points C, D, E and F respectively.

Let r_1 , r_2 , r_3 and r_4 be the resistances of both wires (go and return) of the sections AC, CD, DE and EF of the distributor respectively

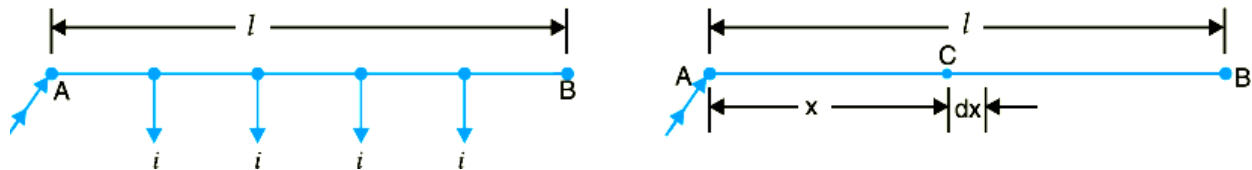


Current fed from point A	$= I_1 + I_2 + I_3 + I_4$
Current in section AC	$= I_1 + I_2 + I_3 + I_4$
Current in section CD	$= I_2 + I_3 + I_4$
Current in section DE	$= I_3 + I_4$
Current in section EF	$= I_4$
Voltage drop in section AC	$= r_1 (I_1 + I_2 + I_3 + I_4)$
Voltage drop in section CD	$= r_2 (I_2 + I_3 + I_4)$
Voltage drop in section DE	$= r_3 (I_3 + I_4)$
Voltage drop in section EF	$= r_4 I_4$
\therefore Total voltage drop in the distributor	$= r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$

It is easy to see that the minimum potential will occur at point F which is farthest from the feeding point A .

1.12.2 UNIFORMLY LOADED DISTRIBUTOR FED AT ONE END

Fig shows the single line diagram of a 2-wire d.c. distributor AB fed at one end A and loaded uniformly with i amperes per metre length. It means that at every 1 m length of the distributor, the load tapped is i amperes. Let l metres be the length of the distributor and r ohm be the resistance per metre run.



Consider a point C on the distributor at a distance x metres from the feeding point A as shown in Fig. Then current at point C is

$$= i l - i x \text{ amperes} = i (l - x) \text{ amperes}$$

Now, consider a small length dx near point C . Its resistance is $r dx$ and the voltage drop over length dx is $d v = i (l - x) r dx = i r (l - x) dx$ Total voltage drop in the distributor upto point C is

The voltage drop upto point B (i.e. over the whole distributor) can be obtained by putting $x = l$

$$v = \int_0^l i r (l - x) dx = i r \left(l x - \frac{x^2}{2} \right)$$

in the above expression.

\therefore Voltage drop over the distributor AB

$$\begin{aligned}
 &= i r \left(l \times l - \frac{l^2}{2} \right) \\
 &= \frac{1}{2} i r l^2 = \frac{1}{2} (i l) (r l) \\
 &= \frac{1}{2} I R
 \end{aligned}$$

where

$i l = I$, the total current entering at point A

$r l = R$, the total resistance of the distributor

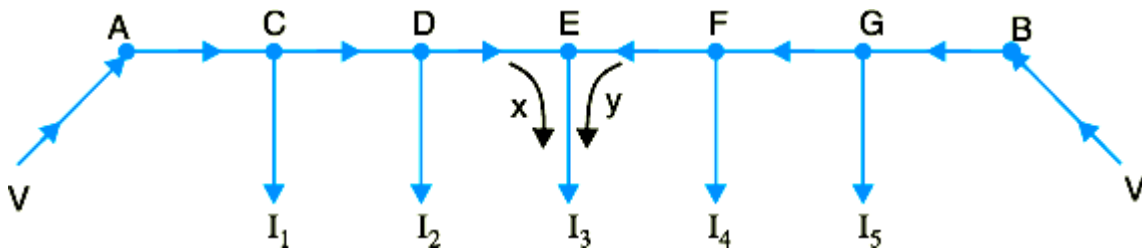
Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.

1.12.3 DISTRIBUTOR FED AT BOTH ENDS — CONCENTRATED LOADING

Whenever possible, it is desirable that a long distributor should be fed at both ends instead of at one end only, since total voltage drop can be considerably reduced without increasing the cross-section of the conductor. The two ends of the distributor may be supplied with (i) equal voltages (ii) unequal voltages.

(i) **Two ends fed with equal voltages.** Consider a distributor A B fed at both ends with equal voltages V volts and having concentrated loads I_1, I_2, I_3, I_4 and I_5 at points C, D, E, F and G respectively as shown in Fig. As we move away from one of the feeding points, say A, p.d. goes on decreasing till it reaches the minimum value at some load point, say E, and then again starts rising and becomes V volts as we reach the other feeding point B.

All the currents tapped off between points A and E (minimum p.d. point) will be supplied from the feeding point A while those tapped off between B and E will be supplied from the feeding point B.



The current tapped off at point E itself will be partly supplied from A and partly from B. If these currents are x and y respectively, then,

$$I_3 = x + y$$

Therefore, we arrive at a very important conclusion that at the point of minimum potential, current comes from both ends of the distributor.

Point of minimum potential.

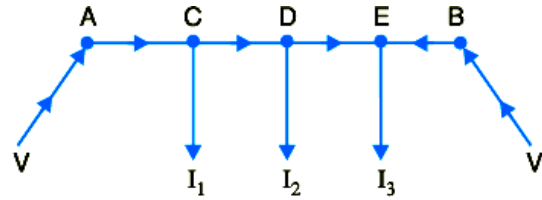
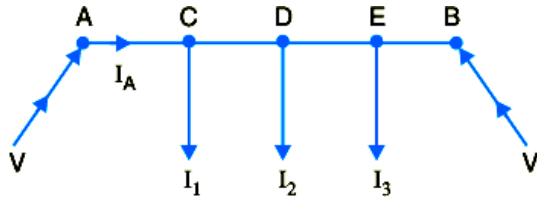
It is generally desired to locate the point of minimum potential. There is a simple method for it. Consider a distributor A B having three concentrated loads I_1, I_2 and I_3 at points C, D and E respectively. Suppose that current supplied by feeding end A is I_a . Then current distribution in the various sections of the distributor can be worked out as shown in Fig.

$$I_{AC} = I_A;$$

$$I_{DE} = I_A - I_1 - I_2;$$

$$I_{CD} = I_A - I_1$$

$$I_{EB} = I_A - I_1 - I_2 - I_3$$



Voltage drop between A and B = Voltage drop over A B

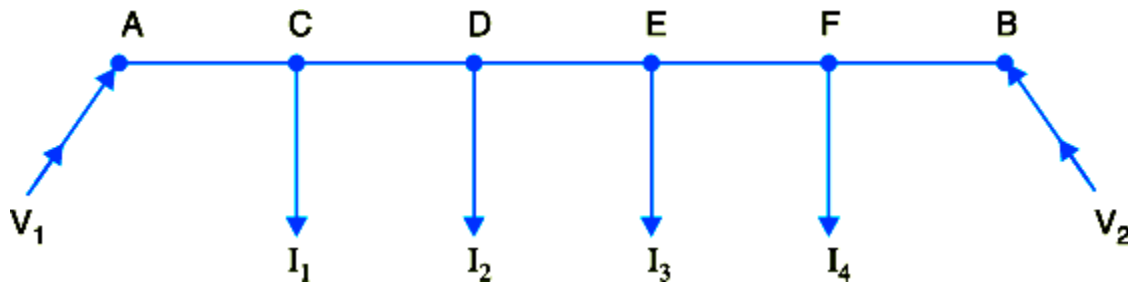
$$\text{or } V - V = I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EB}$$

From this equation, the unknown I_A can be calculated as the values of other quantities are generally given. Suppose actual directions of currents in the various sections of the distributor are indicated as shown in Fig. The load point where the currents are coming from both sides of the distributor is the point of minimum potential i.e. point E in this case

(ii) **Two ends fed with unequal voltages.**

Fig. shows the distributor A B fed with unequal voltages end A being fed at V_1 volts and end B at V_2 volts. The point of minimum potential can be found by following the same procedure as discussed above. Thus in this case, Voltage drop between A and B = Voltage drop over A B

$$V_1 - V_2 = \text{Voltage drop over A B}$$



1.12.4 UNIFORMLY LOADED DISTRIBUTOR FED AT BOTH ENDS

We shall now determine the voltage drop in a uniformly loaded distributor fed at both ends. There can be two cases *viz.* the distributor fed at both ends with (i) equal voltages (ii) unequal voltages. The two cases shall be discussed separately.

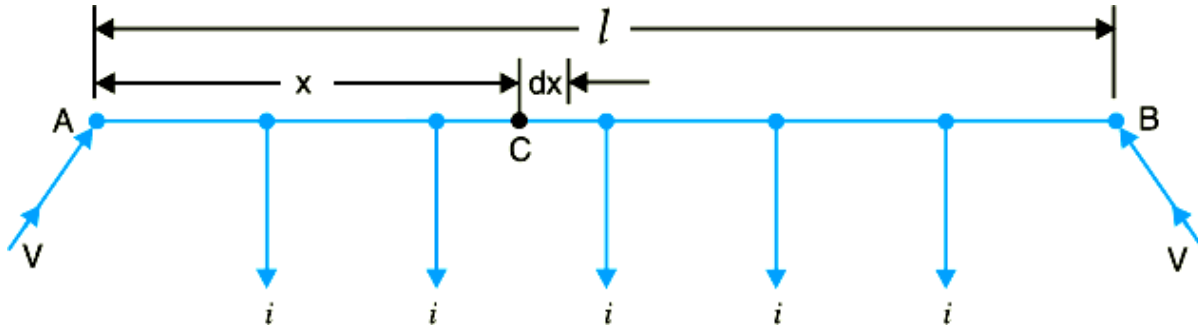
(i) Distributor fed at both ends with equal voltages.

Consider a distributor A B of length l metres, having resistance r ohms per metre run and

with uniform loading of i amperes per metre run as shown in Fig. Let the distributor be fed at the feeding points A and B at equal voltages, say V volts. The total current supplied to the distributor is $i l$. As the two end voltages are equal, therefore, current supplied from each feeding point is $i l/2$ i.e.

Current supplied from each feeding point

$$= \frac{i l}{2}$$



Consider a point C at a distance x metres from the feeding point A . Then current at point C is $i l$

$$= \frac{i l}{2} - i x = i \left(\frac{l}{2} - x \right)$$

Now, consider a small length dx near point C . Its resistance is $r dx$ and the voltage drop over length dx is

$$dv = i \left(\frac{l}{2} - x \right) r dx = i r \left(\frac{l}{2} - x \right) dx$$

$$\begin{aligned} \therefore \text{Voltage drop upto point } C &= \int_0^x i r \left(\frac{l}{2} - x \right) dx = i r \left(\frac{l x}{2} - \frac{x^2}{2} \right) \\ &= \frac{i r}{2} (l x - x^2) \end{aligned}$$

Obviously, the point of minimum potential will be the mid-point. Therefore, maximum voltage drop will occur at mid-point i.e. where $x = l/2$.

$$\begin{aligned} \therefore \text{Max. voltage drop} &= \frac{i r}{2} (l x - x^2) \\ &= \frac{i r}{2} \left(l \times \frac{l}{2} - \frac{l^2}{4} \right) && [\text{Putting } x = l/2] \\ &= \frac{1}{8} i r l^2 = \frac{1}{8} (i l) (r l) = \frac{1}{8} I R \end{aligned}$$

where

$i l = I$, the total current fed to the distributor from both ends

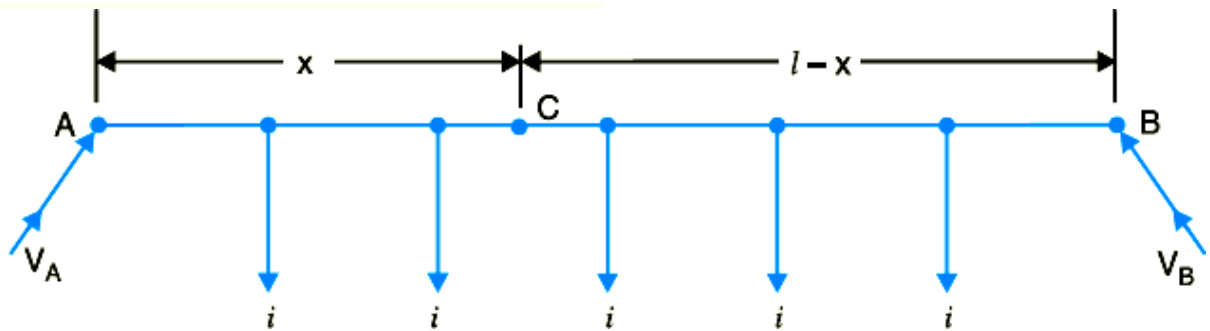
$r l = R$, the total resistance of the distributor

$$\text{Minimum voltage} = V - \frac{I R}{8} \text{ volts}$$

(ii) **Distributor fed at both ends with unequal voltages.**

Consider a distributor AB of length l metres having resistance r ohms per metre run and with a uniform loading of i amperes per metre run as shown in Fig. Let the distributor be fed from feeding points A and B at voltages V_A and V_B respectively. Suppose that the point of minimum potential C is situated at a distance x metres from the feeding point A. Then current supplied by the feeding point A will be $i x$.

$$\text{Voltage drop in section } AC = \frac{i r x^2}{2} \text{ volts}$$



As the distance of C from feeding point B is $(l - x)$, therefore, current fed from B is $i (l - x)$.

$$\therefore \text{Voltage drop in section } BC = \frac{i r (l - x)^2}{2} \text{ volts}$$

$$\text{Voltage at point C, } V_C = V_A - \text{Drop over } AC$$

$$= V_A - \frac{i r x^2}{2} \quad \dots(i)$$

$$\text{Also, voltage at point C, } V_C = V_B - \text{Drop over } BC$$

$$= V_B - \frac{i r (l - x)^2}{2} \quad \dots(ii)$$

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

$$V_A - \frac{i r x^2}{2} = V_B - \frac{i r (l - x)^2}{2}$$

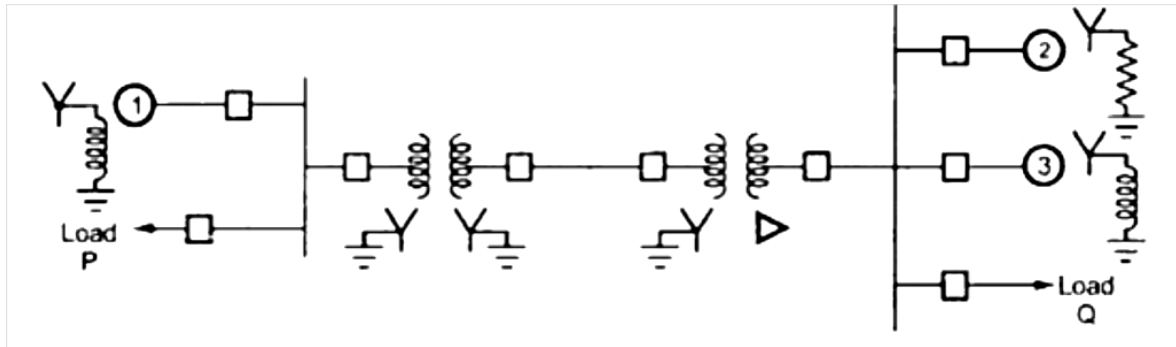
Solving the equation for x , we get,

$$x = \frac{V_A - V_B}{i r l} + \frac{l}{2}$$

As all the quantities on the right hand side of the equation are known, therefore, the point on the distributor where minimum potential occurs can be calculated.

1.13 COMPONENTS OF POWER SYSTEM

Components of the system are represented by standard symbols & the transmission lines are represented by straight lines. "Hence a single line diagram is diagrammatic of power system in which the components are represented by their symbols and the interconnection between them is shown by straight lines".



1.13.1 ELEMENTS OF POWER SYSTEM

Power transformers:

Power transformers are used generation and transmission network for stepping-up the voltage at generating station and stepping-down the voltage for distribution. Auxiliary transformers supply power to auxiliary equipments at the substations.

Current transformers (CT):

The lines in substations carry currents in the order of thousands of amperes. The measuring instruments are designed for low value of currents. Current transformers are connected in lines to supply measuring instruments and protective relays.

Potential transformers (PT):

The lines in substations operate at high voltages. The measuring instruments are designed for low value of voltages. Potential transformers are connected in lines to supply measuring instruments and protective relays. These transformers make the low voltage instruments suitable for measurement of high voltages. For example a 11kV/110V PT is connected to a power line and the line voltage is 11kV then the secondary voltage will be 110V.

Circuit breaker (CB):

Circuit breakers are used for opening or closing a circuit under normal as well as abnormal (faulty) conditions. Different types of CBs which are generally used are oil circuit breaker, air-blast circuit breaker, and vacuum circuit breaker and SF6 circuit breaker.

Isolators or Isolating switches:

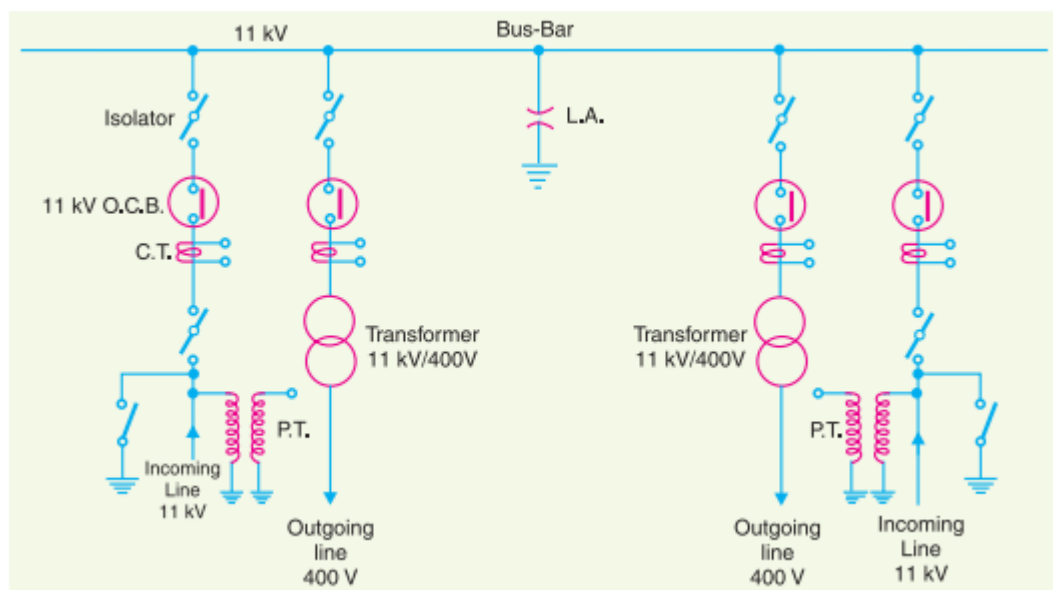
Isolators are employed in substations to isolate a part of the system for general maintenance. Isolator switches are operated only under no load condition. They are provided on each side of every circuit breaker Bus-bar: When number of lines operating at

the same voltage levels needs to be connected electrically, bus-bars are used. Bus-bars are conductors made of copper or aluminum, with very low impedance and high current carrying capacity. Different types of bus-bar arrangements are single bus bar arrangements, single bus-bar with sectionalisation, double bus-bar arrangements, sectionalized double bus-bar arrangement, double main and auxiliary bus-bar arrangement, breaker and a half scheme/1.5 Breaker scheme, and ring bus-bar scheme.

1.13 Bus-Bar Arrangements in Sub-Stations

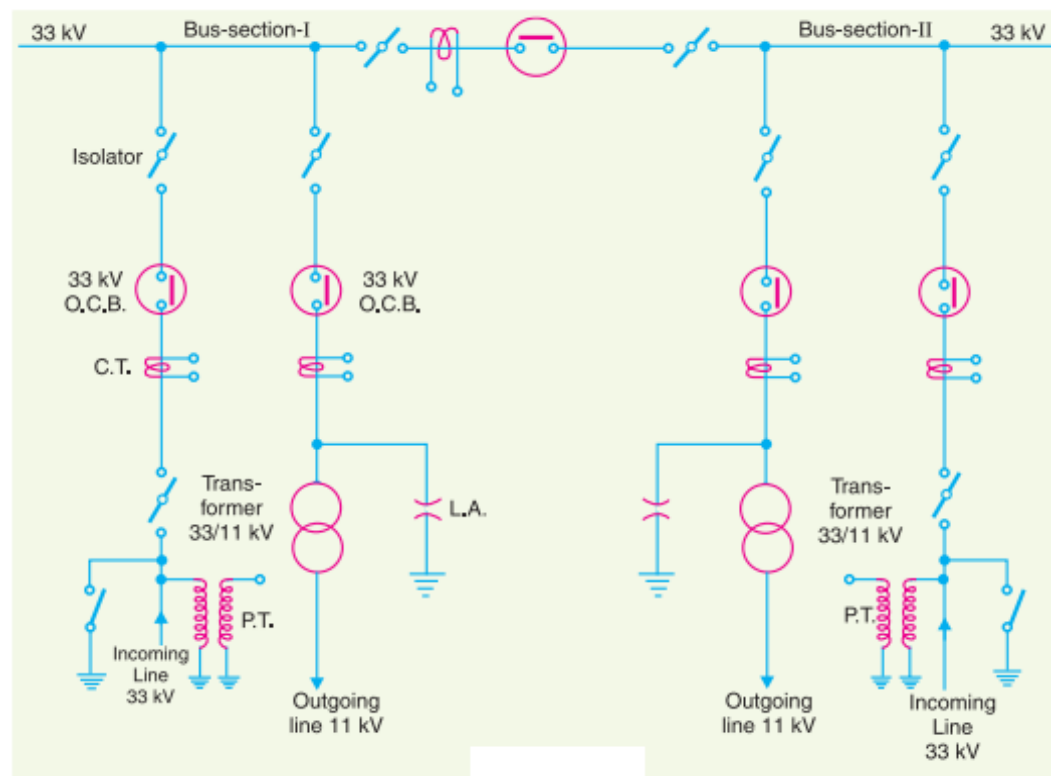
Bus-bars are the important components in a sub-station. There are several bus-bar arrangements that can be used in a sub-station. The choice of a particular arrangement depends upon various factors such as system voltage, position of sub-station, degree of reliability, cost etc. The following are the important bus-bar arrangements used in sub-stations :

- (i) **Single bus-bar system.** As the name suggests, it consists of a single bus-bar and all the incoming and outgoing lines are connected to it. The chief advantages of this type of arrangement are low initial cost, less maintenance and simple operation. However, the principal disadvantage of single bus-bar system is that if repair is to be done on the bus-bar or a fault occurs on the bus, there is a complete interruption of the supply. This arrangement is not used for voltages exceeding 33kV. The indoor 11kV sub-stations often use single bus-bar arrangement. Fig. shows single bus-bar arrangement in a sub-station. There are two 11 kV incoming lines connected to the bus-bar through circuit breakers and isolators. The two 400V outgoing lines are connected to the bus bars through transformers (11kV/400 V) and circuit breakers



(ii) Single bus-bar system with sectionalisation.

In this arrangement, the single bus-bar is divided into sections and load is equally distributed on all the sections. Any two sections of the busbar are connected by a circuit breaker and isolators. Two principal advantages are claimed for this arrangement. Firstly, if a fault occurs on any section of the bus, that section can be isolated without affecting the supply from other sections. Secondly, repairs and maintenance of any section of the busbar can be carried out by de-energising that section only, eliminating the possibility of complete shut down. This arrangement is used for voltages upto 33 kV. Fig.shows bus-bar with sectionalisation where the bus has been divided into two sections. There are two 33 kV incoming lines connected to sections I and II as shown through circuit breaker and isolators. Each 11 kV outgoing line is connected to one section through transformer (33/11 kV) and circuit breaker. It is easy to see that each bus-section behaves as a separate bus-bar.



(iii) Duplicate bus-bar system.

This system consists of two bus-bars, a “main” bus-bar and a “spare” bus-bar. Each bus-bar has the capacity to take up the entire sub-station load. The incoming and outgoing lines can be connected to either bus-bar with the help of a bus-bar coupler which consists of a circuit breaker and isolators. Ordinarily, the incoming

and outgoing lines remain connected to the main bus-bar. However, in case of repair of main bus-bar or fault occurring on it, the continuity of supply to the circuit can be maintained by transferring it to the spare bus-bar. For voltages exceeding 33kV, duplicate bus-bar system is frequently used.

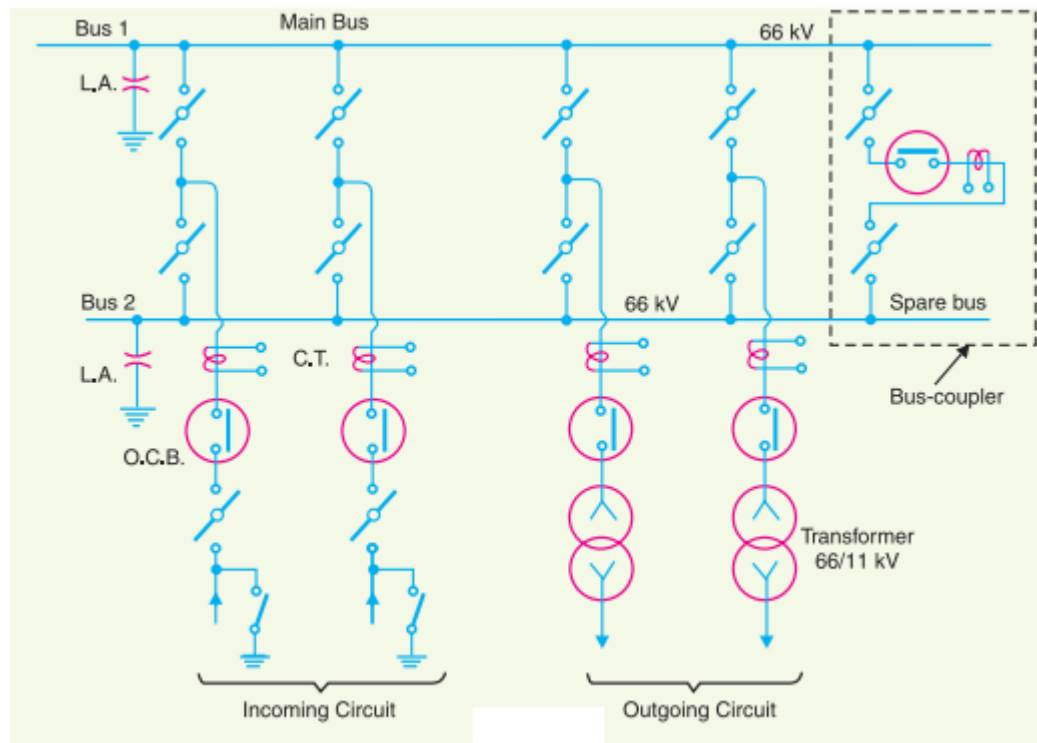


Fig. shows the arrangement of duplicate bus-bar system in a typical sub-station. The two 66kV incoming lines can be connected to either bus-bar by a bus-bar coupler. The two 11 kV outgoing lines are connected to the bus-bars through transformers (66/11 kV) and circuit breakers.

1.14 Economics of Power Transmission

While designing any scheme of power transmission, the engineer must have before him the commercial aspect of the work entrusted to him. He must design the various parts of transmission scheme in a way that maximum economy is achieved. The economic design and layout of a complete power transmission scheme is outside the scope of this book. However, the following two fundamental economic principles which closely influence the electrical design of a transmission line will be discussed :

- (i) Economic choice of conductor size
- (ii) Economic choice of transmission voltage

- (i) Annual charge on capital outlay. This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead system, it will be the annual interest and depreciation on the capital cost of conductors, supports and insulators and the cost of their erection. Now, for an overhead line, insulator cost is constant, the conductor cost is proportional to the area of X-section and the cost of supports and their erection is partly constant and partly proportional to area of X-section of the conductor. Therefore, annual charge on an overhead† transmission line can be expressed as :

$$\text{Annual charge} = P_1 + P_2 a$$

where P_1 and P_2 are constants and a is the area of X-section of the conductor.

- (ii) Annual cost of energy wasted. This is on account of energy lost mainly‡ in the conductor due to $I^2 R$ losses. Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance. As resistance is inversely proportional to the area of X section of the conductor, therefore, the energy lost in the conductor is inversely proportional to area of X-section. Thus, the annual cost of energy wasted in an overhead transmission line can be expressed as :

$$\text{Annual cost of energy wasted} = P_3/a \quad \dots(ii)$$

where P_3 is a constant.

$$\begin{aligned} \text{Total annual cost, } C &= \text{exp. (i)} + \text{exp. (ii)} \\ &= (P_1 + P_2 a) + P_3/a \end{aligned}$$

$$\therefore C = P_1 + P_2 a + P_3/a \quad \dots(iii)$$

In exp. (iii), only area of X-section a is variable. Therefore, the total annual cost of transmission line will be minimum if differentiation of C w.r.t. a is zero i.e.

$$\frac{d}{da} (C) = 0$$

$$\text{or } \frac{d}{da} (P_1 + P_2 a + P_3/a) = 0$$

$$\text{or } P_2 - \frac{P_3}{a^2} = 0$$

$$\text{or } P_2 = \frac{P_3}{a^2}$$

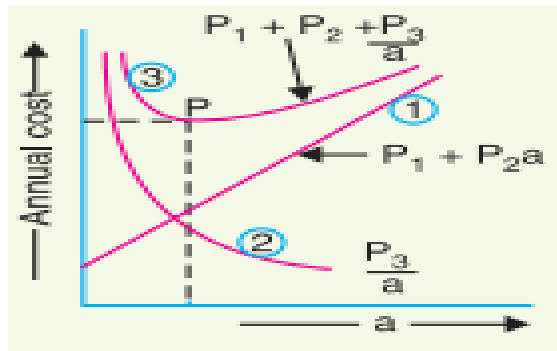
$$\text{or } P_2 a = \frac{P_3}{a}$$

i.e. Variable part of annual charge = Annual cost of energy wasted

Therefore Kelvin's Law can also be stated in an another way i.e. the most economical area of conductor is that for which the variable part* of annual charge is equal to the cost of energy losses per year

Graphical illustration of Kelvin's law. Kelvin's law can also be illustrated graphically by plotting annual cost against X-sectional area 'a' of the conductor . In the diagram, the straight line (1) shows the relation between the annual charge (i.e., $P_1 + P_2 a$) and the area of X-section a of the conductor. Similarly, the rectangular hyperbola (2) gives the relation between annual

cost of energy wasted and X-sectional area. By adding the ordinates of curves (1) and (2), the curve (3) is obtained. This latter curve shows the relation between total annual cost ($P_1 + P_2a + P_3/a$) of transmission line and area of X-section a . The lowest point on the curve (i.e., point P) represents the most economical area of X-section.



Limitations of Kelvin's law. Although theoretically Kelvin's law holds good, there is often considerable difficulty in applying it to a proposed scheme of power transmission. In practice, the limitations of this law are :

- (i) It is not easy to estimate the energy loss in the line without actual load curves, which are not available at the time of estimation.
- (ii) The assumption that annual cost on account of interest and depreciation on the capital outlay is in the form $P_1 + P_2a$ is strictly speaking not true. For instance, in cables neither the cost of cable dielectric and sheath nor the cost of laying vary in this manner
- (iii) This law does not take into account several physical factors like safe current density, mechanical strength, corona loss etc.
- (iv) The conductor size determined by this law may not always be practicable one because it may be too small for the safe carrying of necessary current.
- (v) Interest and depreciation on the capital outlay cannot be determined accurately.

QUESTIONS:

Q.No	Question
1	Draw a model one line diagram of a power system showing generation, transmission and distribution.
2	Compare feeder and distributor.
3	List the components of a power system?
4	State Kelvin's law.
5	State the limitations of kelvins law.
6	Discuss the need for DC power.
7	Why the transmission voltages are in terms of kV?
8	Explain ring main system
9	What are the transmission level voltages available in India?
10	Distinguish between 3 phase 3 wire and 3 phase 4 wire distribution systems?
11	List two main requirements of a good distribution system.

Q.No	Question
1	A dc 2-wire distributor AB is 500m long and is fed at both ends at 240V. The loads of 100 A and 60 A are tapped from C and D which are at a distance of 100m and 250m from point A respectively. The last 200m. (Near end B) is loaded uniformly at the rate of 1 A/m. The resistance of (both go and return) the distributor is 0.001 ohm per metre. Estimate i) the point of minimum potential and its value.
2	The cost of a 3 phase overhead transmission line is Rs. $(25000a + 2500)$ per km where 'a' is the area of cross-section of each conductor in cm^2 . The line is supplying a load of 5 MW at 33 kV and 0.8 p.f. lagging assumed to be constant throughout the year. Energy costs 4P per kWh and interest and depreciation total 10% per annum. Estimate the most economical size of the conductor. Given that the specific resistance of conductor material is 10^{-6} ohm-cm.
3	A single phase distributor one km. long has resistance and reactance per conductor of 0.1ohm and 0.15 ohm respectively. At the far end, the voltage is 200V and the

current is 100 A at a p.f. of 0.8 lagging. At the mid-point M of the distributor, a current of 100 A is tapped at a p.f of 0.6 lagging with reference to the voltage at the mid point. Determine :

- a. voltage at the midpoint
- b. sending end voltage
- c. phase angle between sending and receiving end voltages

- 4 An electric train runs between two two substations 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 ohm/km. Determine
 - a) the point of minimum potential along the track
 - b) currents supplied by the two substations when the train is at the point of minimum potential
- 5 A d.c ring main ABCDA is fed from point A at 250 V supply and the resistances of various sections are as follows :- AB = 0.02 Ω , BC = 0.018 Ω , CD = 0.025 Ω , DA = 0.02 Ω . The main supplies loads of 150 A at B, 300 A at C, 250 A at D. Determine the voltage at each point. If the points A & C are linked through an interconnector of resistance 0.02 Ω , determine the new voltage at each load point.
- 6 Explain Kelvin's law for economic selection of conductors and State its limitations
- 7
 - a. Draw the layout of a substation and explain the components in a substation.
 - b. Discuss the points and factors to be considered while planning a distribution system.

References :

1. C.L. Wadhwa, "Electrical Power Systems", 6th Edition, New Age International (P) Limited, New Delhi, 2010.
2. V.K. Metha & Rohit Metha, "Principles of Power System", S. Chand, 3rd Edition, 2006.



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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

TRANSMISSION AND DISTRIBUTION – SEEA1402
UNIT II- TRANSMISSION LINE PARAMETERS

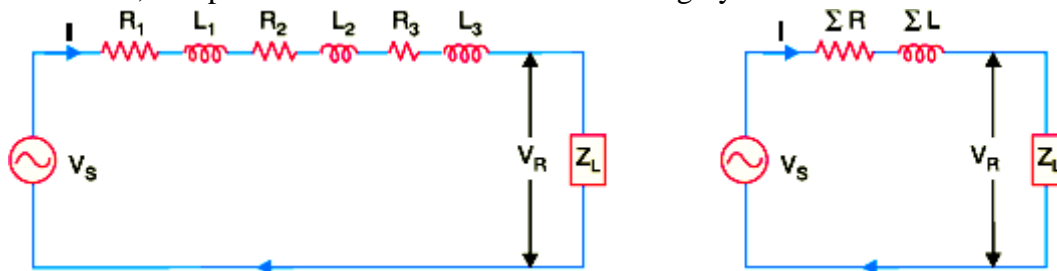
II. TRANSMISSION LINE PARAMETERS

Resistance, Inductance and Capacitance of Single Phase and Three Phase (Including Double Circuits) Transmission Lines - Stranded and Bundled Conductors - Symmetrical and Unsymmetrical Spacing - Transposition - Application of Self and Mutual GMD - Skin and Proximity Effect - Inductive Interference with Neighboring Circuits - Corona - Factors Affecting Corona - Advantages and Disadvantages of Corona - Methods of Reducing Corona Effect.

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

2.1.1 CONSTANTS OF A TRANSMISSION LINE

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



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

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

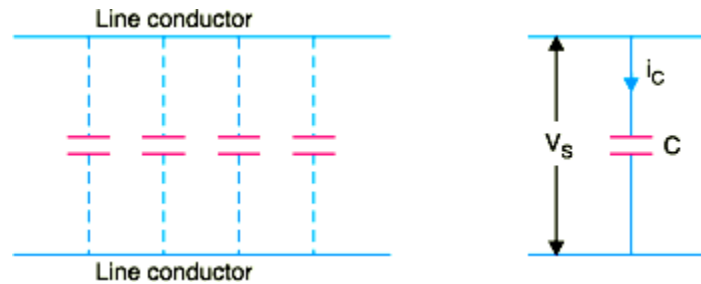
$$\text{Inductance, } L = \frac{\Psi}{I} \text{ henry}$$

where Ψ = flux linkages in weber-turns
 I = current in amperes

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

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

Capacitance, $C = \frac{q}{v}$ farad



where

q = charge on the line in coulomb

v = p.d. between the conductors in volts

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

Resistance of a Transmission Line

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

$$R = \rho l/a$$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation. Suppose R_1 and R_2 are the resistances of a conductor at t_1 °C and t_2 °C ($t_2 > t_1$) respectively. If α_1 is the temperature coefficient at t_1 °C, then,

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

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

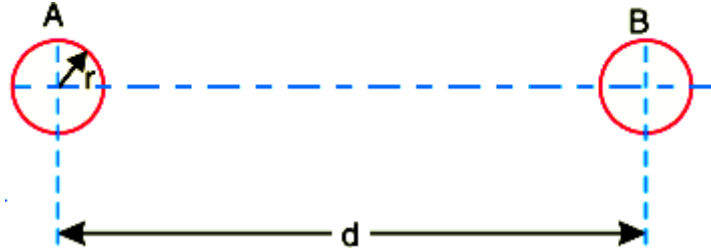
$$\alpha_0 = \text{temperature coefficient at } 0^\circ \text{C}$$

2.2 INDUCTANCE OF A SINGLE PHASE TWO-WIRE LINE

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

When an alternating current flows through such a loop, a changing magnetic flux is set up. The changing flux links the loop and hence the loop (or single phase line) possesses inductance. It may appear that inductance of a single phase line is negligible because it consists of a loop of one turn and the flux path is through air of high reluctance. But as the X-sectional

area of the loop is very **large, even for a small flux density, the total flux linking the loop is quite large and hence the line has appreciable inductance.



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

$$I_A + I_B = 0$$

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

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

Flux linkages with conductor A due to current I_B

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

Total flux linkages with conductor A is

$$\begin{aligned} \Psi_A &= \text{exp. (i)} + \text{exp (ii)} \\ &= \frac{\mu_0 I_A}{2\pi} \left(\frac{1}{4} + \int_r^\infty \frac{dx}{x} \right) + \frac{\mu_0 I_B}{2\pi} \int_d^\infty \frac{dx}{x} \\ &= \frac{\mu_0}{2\pi} \left[\left(\frac{1}{4} + \int_r^\infty \frac{dx}{x} \right) I_A + I_B \int_d^\infty \frac{dx}{x} \right] \\ &= \frac{\mu_0}{2\pi} \left[\left(\frac{1}{4} + \log_e \infty - \log_e r \right) I_A + (\log_e \infty - \log_e d) I_B \right] \\ &= \frac{\mu_0}{2\pi} \left[\left(\frac{I_A}{4} + \log_e \infty (I_A + I_B) - I_A \log_e r - I_B \log_e d \right) \right] \\ &= \frac{\mu_0}{2\pi} \left[\frac{I_A}{4} - I_A \log_e r - I_B \log_e d \right] \quad (\because I_A + I_B = 0) \end{aligned}$$

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

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

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

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

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

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

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

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

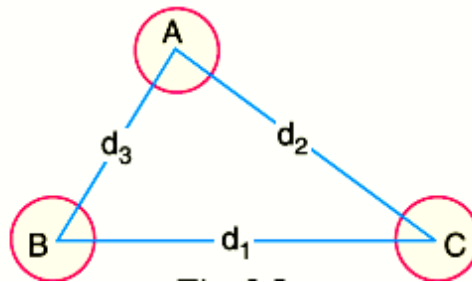
Loop inductance $= 2 L_A \text{ H/m} = 10^{-7} \left[1 + 4 \log_e \frac{d}{r} \right] \text{ H/m}$

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

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

2.2.1 INDUCTANCE OF A 3-PHASE OVERHEAD LINE

Fig. 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 .



Flux linkages with conductor A due to its own current

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

Flux linkages with conductor A due to current I_B

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

Flux linkages with conductor A due to current I_C

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

Total flux linkages with conductor A is

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

As $I_A + I_B + I_C = 0$,

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

2.2.2 SYMMETRICAL SPACING

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d , then, $d_1 = d_2 = d_3 = d$. Under such conditions, the flux Derived in a similar way, the expressions for inductance are the same for conductors B and C.

$$\begin{aligned}
\Psi_A &= \frac{\mu_0}{2\pi} \left[\left(\frac{1}{4} - \log_e r \right) I_A - I_B \log_e d - I_C \log_e d \right] \\
&= \frac{\mu_0}{2\pi} \left[\left(\frac{1}{4} - \log_e r \right) I_A - (I_B + I_C) \log_e d \right] \\
&= \frac{\mu_0}{2\pi} \left[\left(\frac{1}{4} - \log_e r \right) I_A + I_A \log_e d \right] \quad (\because I_B + I_C = -I_A) \\
&= \frac{\mu_0 I_A}{2\pi} \left[\frac{1}{4} + \log_e \frac{d}{r} \right] \text{ weber-turns/m} \\
L_A &= \frac{\Psi_A}{I_A} \text{ H/m} = \frac{\mu_0}{2\pi} \left[\frac{1}{4} + \log_e \frac{d}{r} \right] \text{ H/m} \\
&= \frac{4\pi \times 10^{-7}}{2\pi} \left[\frac{1}{4} + \log_e \frac{d}{r} \right] \text{ H/m} \\
L_A &= 10^{-7} \left[0.5 + 2 \log_e \frac{d}{r} \right] \text{ H/m}
\end{aligned}$$

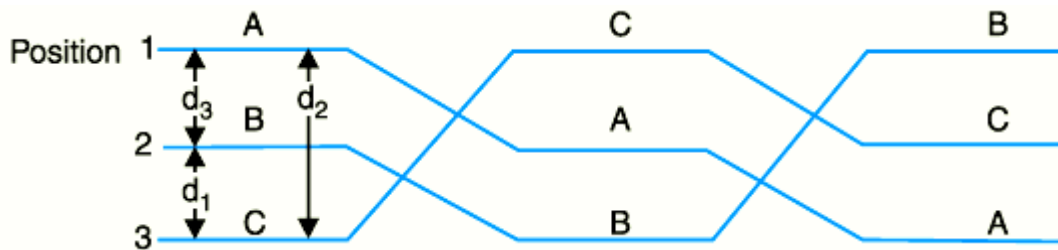
2.2.3 UNSYMMETRICAL SPACING

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



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

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

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

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,

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

\therefore Inductance of conductor A is

$$\begin{aligned} L_A &= \frac{\Psi_A}{I_A} = \frac{\Psi_A}{I} \\ &= \frac{\mu_0}{2\pi} \left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j0.866 \log_e \frac{d_3}{d_2} \right] \\ &= \frac{4\pi \times 10^{-7}}{2\pi} \left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j0.866 \log_e \frac{d_3}{d_2} \right] \text{ H/m} \\ &= 10^{-7} \left[\frac{1}{2} + 2 \log_e \frac{\sqrt{d_2 d_3}}{r} + j1.732 \log_e \frac{d_3}{d_2} \right] \text{ H/m} \end{aligned}$$

Similarly inductance of conductors B and C will be :

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

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

Inductance of each line conductor

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

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

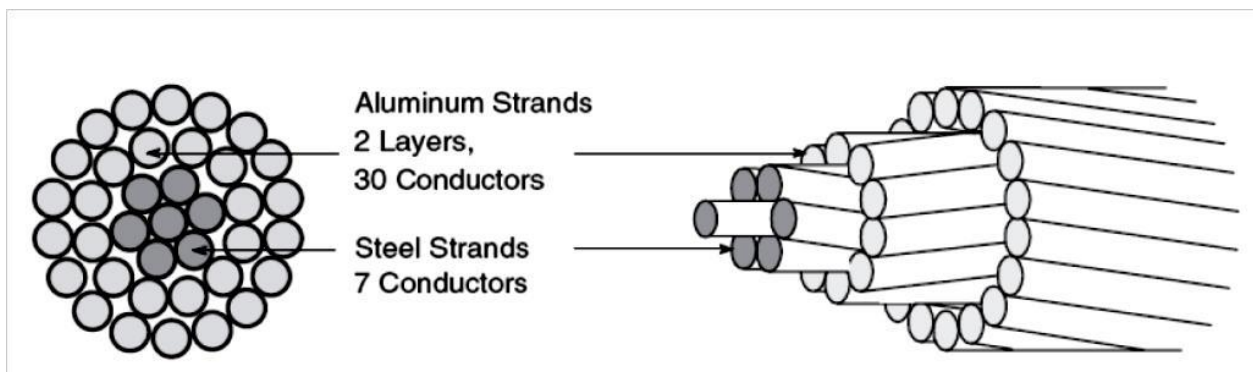
$$= \left[0.5 + 2 \log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r} \right] \times 10^{-7} \text{ H/m}$$

If we compare the formula of inductance of an un symmetrically spaced transposed line with that of symmetrically spaced line, we find that inductance of each line conductor in the two cases will

be equal if $d = \sqrt[3]{d_1 d_2 d_3}$. The distance d is known as equivalent equilateral spacing for un symmetrically transposed line

2.3 SPIRALING AND BUNDLE CONDUCTOR EFFECT

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



ACSR is one of the most used conductors in transmission lines. It consists of alternate layers of stranded conductors, spiraled in opposite directions to hold the strands together,

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

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

2.4 CONCEPT OF SELF-GMD AND MUTUAL-GMD

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

(i) Self-GMD (Ds)

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

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

In this expression, the term $2 \times 10^{-7} \times (1/4)$ is the inductance due to flux within the solid conductor. For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR. If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero. Consequently, inductance due to internal flux would be zero and the term $2 \times 10^{-7} \times (1/4)$ shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage. It can be proved mathematically that for a solid round conductor of radius r , the self-GMD or $GMR = 0.7788 r$. Using self-GMD, the eq. (i) becomes :

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

Where

$$D_s = GMR \text{ or self-GMD} = 0.7788 r$$

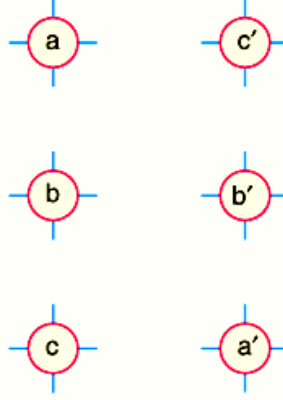
It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(ii) Mutual-GMD

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

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

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



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

Self-GMD of conductor = $0.7788 r$

Self-GMD of combination aa' is

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

Self-GMD of combination bb' is

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

Self-GMD of combination cc' is

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

Equivalent self-GMD of one phase

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

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

Mutual-GMD between phases A and B is

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

Mutual-GMD between phases B and C is

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

Mutual-GMD between phases C and A is

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

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

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

Inductance Formulas in Terms of GMD

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

(i) Single phase line

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

where $D_s = 0.7788 r$ and $D_m = \text{Spacing between conductors} = d$

(ii) Single circuit 3- ϕ line

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

where $D_s = 0.7788 r$ and $D_m = (d_1 d_2 d_3)^{1/3}$

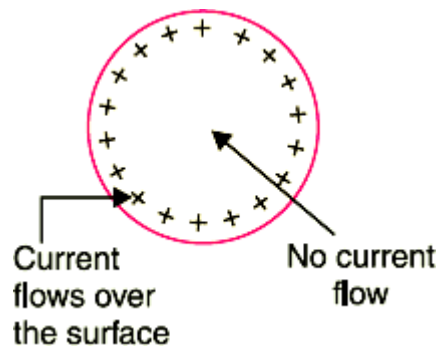
(iii) Double circuit 3- ϕ line

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

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

2.5 SKIN EFFECT

The phenomena arising due to unequal distribution of electric current over the entire cross section of the conductor being used for long distance power transmission is referred as the **skin effect in transmission lines**. Such a phenomena does not have much role to play in case of a very short line, but with increase in the effective length of the conductors, **skin effect** increases considerably. So the modifications in line calculation needs to be done accordingly. The distribution of electric current over the entire cross section of the conductor is quite uniform in case of a DC system. But what we are using in the present era of power system engineering is predominantly an alternating electric current system, where the electric current tends to flow with higher density through the surface of the conductors (i.e skin of the conductor), leaving the core deprived of necessary number of electrons.



In fact there even arises a condition when absolutely no electric current flows through the core, and concentrating the entire amount on the surface region, thus resulting in an increase in the effective electrical resistance of the conductor. This particular trend of an AC transmission system to take the surface path for the flow of electric current depriving the core is referred to as the **skin effect in transmission lines**.

2.6 PROXIMITY EFFECT

Proximity means nearness in space or time, so as the name suggests, **proximity effect in transmission lines** indicates the effect in one conductor for other neighboring conductors. When the alternating current is flowing through a conductor, alternating magnetic flux is generated

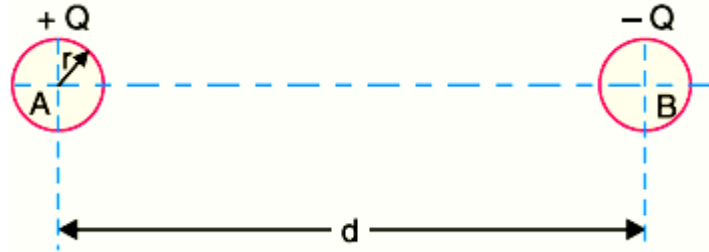
surrounding the conductor. This magnetic flux associates with the neighboring wires and generates a circulating current (it can be termed as ‘eddy current’ also). This circulating current increases the resistance of the conductor and push away the flowing current through the conductor, which causes the crowding effect.

2.7 CAPACITANCE OF A SINGLE PHASE TWO-WIRE LINE

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

$$V_A = \int_r^{\infty} \frac{Q}{2\pi x \epsilon_0} dx + \int_d^{\infty} \frac{-Q}{2\pi x \epsilon_0} dx$$

$$= \frac{Q}{2\pi \epsilon_0} \left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d} \right] \text{volts} = \frac{Q}{2\pi \epsilon_0} \log_e \frac{d}{r} \text{volts}$$



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

$$V_B = \int_r^{\infty} \frac{-Q}{2\pi x \epsilon_0} dx + \int_d^{\infty} \frac{Q}{2\pi x \epsilon_0} dx$$

$$= \frac{-Q}{2\pi \epsilon_0} \left[\log_e \frac{\infty}{r} - \log_e \frac{\infty}{d} \right] = \frac{-Q}{2\pi \epsilon_0} \log_e \frac{d}{r} \text{volts}$$

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

$$V_{AB} = 2V_A = \frac{2Q}{2\pi \epsilon_0} \log_e \frac{d}{r} \text{volts}$$

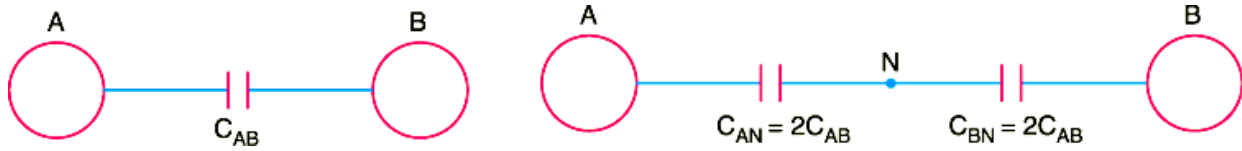
Capacitance, $C_{AB} = Q/V_{AB} = \frac{Q}{\frac{2Q}{2\pi \epsilon_0} \log_e \frac{d}{r}} \text{ F/m}$

$$C_{AB} = \frac{\pi \epsilon_0}{\log_e \frac{d}{r}} \text{ F / m}$$

Capacitance to neutral

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

between each conductor and the ground or neutral is half the potential difference between the conductors. Thus the capacitance to ground or capacitance to neutral for the two-wire line is twice the line-to-line capacitance



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

$$C_N = \frac{2 \pi \epsilon_0}{\log_e \frac{d}{r}} \text{ F / m}$$

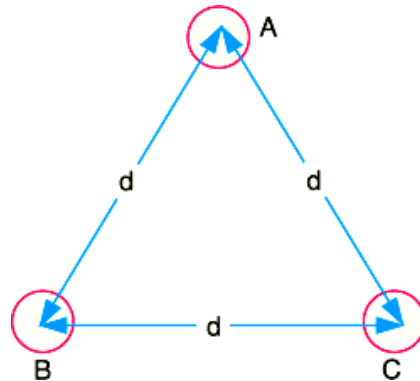
The reader may compare eq. (ii) to the one for inductance. One difference between the equations for capacitance and inductance should be noted carefully. The radius in the equation for capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula.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

2.7.1 CAPACITANCE OF A 3-PHASE OVERHEAD LINE

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

(i) Symmetrical Spacing

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



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

$$\begin{aligned}
V_A &= \int_r^\infty \frac{Q_A}{2\pi x \epsilon_0} dx + \int_d^\infty \frac{Q_B}{2\pi x \epsilon_0} dx + \int_d^\infty \frac{Q_C}{2\pi x \epsilon_0} dx \\
&= \frac{1}{2\pi \epsilon_0} \left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d} + Q_C \log_e \frac{1}{d} \right] \\
&= \frac{1}{2\pi \epsilon_0} \left[Q_A \log_e \frac{1}{r} + (Q_B + Q_C) \log_e \frac{1}{d} \right]
\end{aligned}$$

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

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

$$\therefore V_A = \frac{1}{2\pi \epsilon_0} \left[Q_A \log_e \frac{1}{r} - Q_A \log_e \frac{1}{d} \right] = \frac{Q_A}{2\pi \epsilon_0} \log_e \frac{d}{r} \text{ volts}$$

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

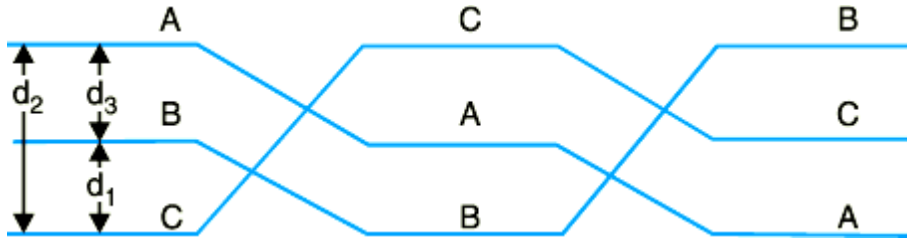
$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi \epsilon_0} \log_e \frac{d}{r}} \text{ F/m} = \frac{2\pi \epsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

$$C_A = \frac{2\pi \epsilon_0}{\log_e \frac{d}{r}} \text{ F/m}$$

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

(ii) Unsymmetrical spacing.

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



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

$$\text{Potential of 1st position, } V_1 = \frac{1}{2\pi \epsilon_0} \left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2} \right)$$

$$\text{Potential of 2nd position, } V_2 = \frac{1}{2\pi \epsilon_0} \left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_3} \right)$$

$$\text{Potential of 3rd position, } V_3 = \frac{1}{2\pi \epsilon_0} \left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_C \log_e \frac{1}{d_1} \right)$$

Average voltage on conductor A is

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

$$= \frac{1}{3 \times 2\pi\epsilon_0} * \left[Q_A \log_e \frac{1}{r^3} + (Q_B + Q_C) \log_e \frac{1}{d_1 d_2 d_3} \right]$$

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

$$\therefore V_A = \frac{1}{6\pi\epsilon_0} \left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3} \right]$$

$$= \frac{Q_A}{6\pi\epsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{1}{3} \times \frac{Q_A}{2\pi\epsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3}$$

$$= \frac{Q_A}{2\pi\epsilon_0} \log_e \left(\frac{d_1 d_2 d_3}{r^3} \right)^{1/3}$$

$$= \frac{Q_A}{2\pi\epsilon_0} \log_e \frac{(d_1 d_2 d_3)^{1/3}}{r}$$

Capacitance from conductor to neutral is

$$C_A = \frac{Q_A}{V_A} = \frac{2 \pi \epsilon_0}{\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}} F/m$$

2.8 INDUCTIVE INTERFERENCE WITH NEIGHBOURING COMMUNICATION CIRCUITS

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

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

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

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

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

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

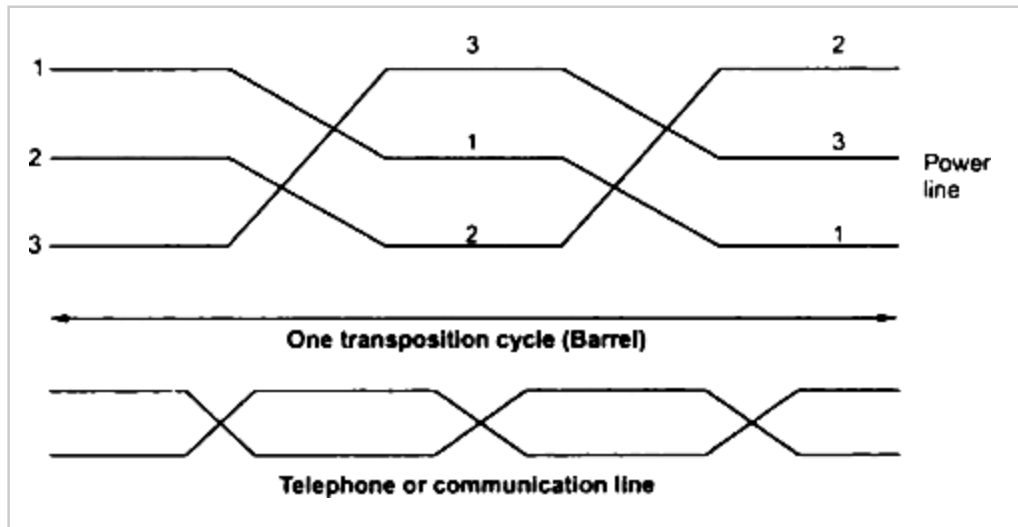
The electric coupling is in the form of capacitive coupling between power and telephone conductor whereas the magnetic coupling is through space and is generally expressed in terms of mutual inductance at harmonic frequencies.

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

Steps for Reducing Telephone Interference

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

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



2.9 CONDUCTORS

Commonly used conductor materials:

The most commonly used conductor materials for over head lines are copper, aluminium, steel cored aluminium, galvanised steel and cadmium copper. The choice of a particular material will depend upon the cost, the required electrical and mechanical properties and the local conditions. All conductors used for overhead lines are preferably stranded in order to increase the flexibility. In stranded conductors, there is generally one central wire and round this, successive layers of wires containing 6, 12, 18, 24 wires. Thus, if there are n layers, the total number of individual wires is $3n(n + 1) + 1$. In the manufacture of stranded conductors, the consecutive layers of wires are twisted or spiralled in opposite directions so that layers are bound together.

2.9.1 TYPES OF CONDUCTOR

1. Copper

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

2. Aluminium

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

(i) The conductivity of aluminium is 60% that of copper. The smaller conductivity of aluminium

means that for any particular transmission efficiency, the X-sectional area of conductor must be larger in aluminium than in copper. For the same resistance, the diameter of aluminium conductor is about 1.26 times the diameter of copper conductor. The increased X-section of aluminium exposes a greater surface to wind pressure and, therefore, supporting towers must be designed for greater transverse strength. This often requires the use of higher towers with consequence of greater sag.

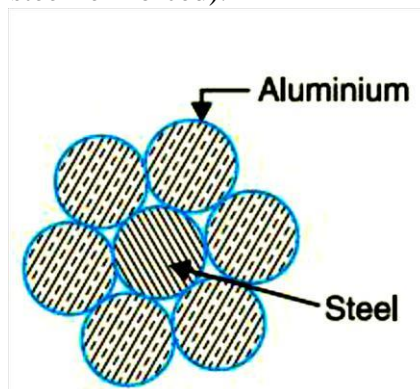
(ii) The specific gravity of aluminium (2.71 gm/cc) is lower than that of copper (8.9 gm/cc). Therefore, an aluminium conductor has almost one-half the weight of equivalent copper conductor. For this reason, the supporting structures for aluminium need not be made so strong as that of copper conductor.

(iii) Aluminium conductor being light, is liable to greater swings and hence larger cross-arms are required.

(iv) Due to lower tensile strength and higher co-efficient of linear expansion of aluminium, the sag is greater in aluminium conductors. Considering the combined properties of cost, conductivity, tensile strength, weight etc., aluminium has an edge over copper. Therefore, it is being widely used as a conductor material. It is particularly profitable to use aluminium for heavy-current transmission where the conductor size is large and its cost forms a major proportion of the total cost of complete installation.

3. Steel cored aluminium

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



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

Advantages:

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

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

4. Galvanised steel

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

5. Cadmium copper

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

2.10 CORONA

When an alternating potential difference is applied across two conductors whose spacing is large as compared to their diameters, there is no apparent change in the condition of atmospheric air surrounding the wires if the applied voltage is low. However, when the applied voltage exceeds a certain value, called critical disruptive voltage, the conductors are surrounded by a faint violet glow called corona.

The phenomenon of corona is accompanied by a hissing sound, production of ozone, power loss and radio interference. The higher the voltage is raised, the larger and higher the luminous envelope becomes, and greater are the sound, the power loss and the radio noise. If the applied voltage is increased to breakdown value, a flash-over will occur between the conductors due to the breakdown of air insulation. If the conductors are polished and smooth, the corona glow will be uniform throughout the length of the conductor, otherwise the rough points will appear brighter. With d.c. voltage, there is difference in the appearance of the two wires. The positive wire has uniform glow about it, while the negative conductor has spotty glow.

Theory of corona formation

Some 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 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 in turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cumulative. 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 ionisation of air surrounding the conductors, therefore, it is affected by the physical state of atmosphere. In the stormy weather, the number of ions is more than normal and as such corona occurs at much less voltage as compared with fair weather.

(ii) Conductor size.

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

(iii) Spacing between conductors.

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

(iv) Line voltage.

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

Important Terms

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

(i) Critical Disruptive Voltage

It is the minimum phase-neutral voltage at which corona occurs. Consider two conductors of radii r cm and spaced d cm apart. If V is the phase-neutral potential, then potential gradient at the conductor surface is given by:

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

In order that corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76 cm pressure and temperature of 25°C is 30 kV/cm (max) or 21.2 kV/cm (r.m.s.) and is denoted by g_0 . 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.*)

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

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

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

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

∴ 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 .

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

where

$$m_o = 1 \text{ for polished conductors} \\
= 0.98 \text{ to } 0.92 \text{ for dirty conductors} \\
= 0.87 \text{ to } 0.8 \text{ for stranded conductors}$$

(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 : where m_v is another irregularity factor having a value of 1.0 for polished conductors and 0.72 to 0.82 for rough conductors.

(iii) Power loss due to corona

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

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

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

Advantages and Disadvantages of Corona

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

Advantages

- (i) Due to corona formation, the air surrounding the conductor becomes conducting and hence virtual diameter of the conductor is increased. The increased diameter reduces the electrostatic stresses between the conductors.
- (ii) Corona reduces the effects of transients produced by surges.

Disadvantages

- (i) Corona is accompanied by a loss of energy. This affects the transmission efficiency of the line.
- (ii) Ozone is produced by corona and may cause corrosion of the conductor due to chemical action.
- (iii) The current drawn by the line due to corona is non-sinusoidal and hence no sinusoidal voltage drop occurs in the line. This may cause inductive interference with neighboring communication lines.

Methods of Reducing Corona Effect

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

(i) By increasing conductor size.

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

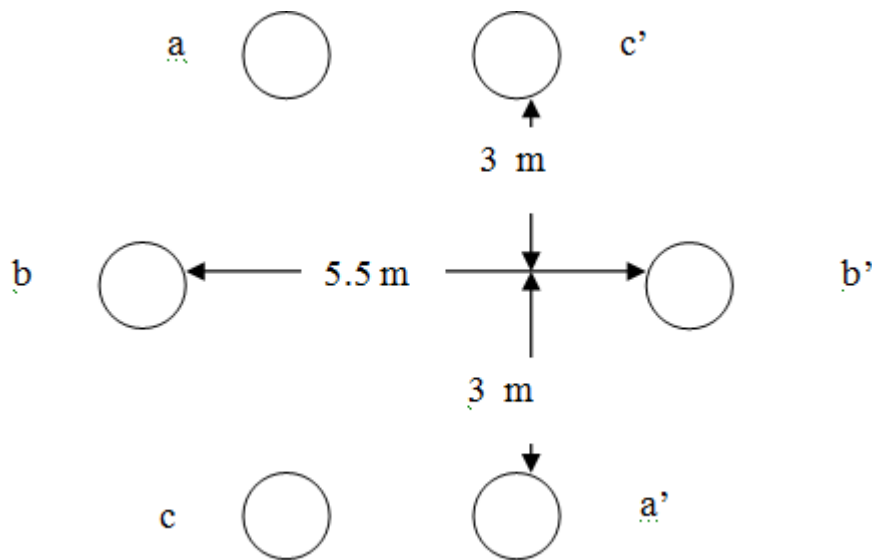
(ii) By increasing conductor spacing

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

QUESTIONS :

Q.No	Question
1	Define Skin effect.
2	Explain the term 'proximity effect' when referred to overhead lines.
3	Why transmission lines are transposed?
4	Deduce an expression for the capacitance of each conductor of single phase overhead line if there is effect of the earth.
5	What are the advantages of using bundled conductors?
6	What is critical disruptive voltage?
7	What do you understand by inductive interference?
8	What are the disadvantages of corona?
9	Determine the loop inductance per km of a single phase circuit comprising of two parallel conductors 1 m. apart and 1 cm. in diameter.
10	Distinguish between GMD and GMR

Q.No	Question
1	Deduce an expression for inductance of 3-phase transposed unsymmetrically spaced transmission line
2	Derive the formula for capacitance of 1-phase transmission line.
3	a. Derive an expression for critical disruptive voltage? b. A 3-phase line has conductors 2 cm. in diameter spaced equilaterally 1m. apart. If the dielectric strength of air is 30 kV (max) per cm., Evaluate the disruptive critical voltage for the line. Take air density factor $\delta = 0.952$ and irregularity factor $m_0 = 0.9$
4	Determine the inductance per phase per km. of double circuit 3-phase line shown in fig. The conductors are transposed and are of radius 0.75 cm. each. The phase sequence is ABC. The distance between a and c' is 4 m.



- 5 A 3 phase, 50 Hz,, 132 kV overhead line has regularly transposed conductors equilaterally spaced 3 m. apart. Conductor diameter is 2 cm. If the line length is 100 km., calculate the charging current per phase. Determine the capacitance of the same line taking into account the effect of ground.

- 6
 - a. Deduce an equation for the inductance of a single phase line by deriving the expression for calculating the internal and external flux linkages of a conductor carrying the current.
 - b. A 132 KV line with 1.96cm diameter conductors is built so that corona takes place if the line voltage exceeds 210 KV (r.m.s). if the value of potential gradient at which ionization occurs can be taken as 30 KV per cm, find the spacing between the conductors.

- 7 Elaborate the following
 - i. skin effect
 - ii. ACSR conductors
 - ii. Corona discharge

References :

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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

TRANSMISSION AND DISTRIBUTION – SEEA1402
UNIT III- PERFORMANCE OF TRANSMISSION LINES

III. PERFORMANCE OF TRANSMISSION LINES

Equivalent Circuits for Short, Medium (p and T circuits) and Long Lines - Efficiency and Regulation - Attenuation Constant, Phase Constant, Surge Impedance and Surge Impedance Loading - Real and Reactive Power Flows in Lines - Power Circle Diagrams for Receiving and Sending Ends - Ferranti Effect.

3.1 CLASSIFICATION OF LINES - INTRODUCTION

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

3.1.1 CLASSIFICATION OF OVERHEAD TRANSMISSION LINES

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

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

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

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

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

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

Important Terms

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

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

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

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

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

3.2 PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

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

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

Let

I = load current

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

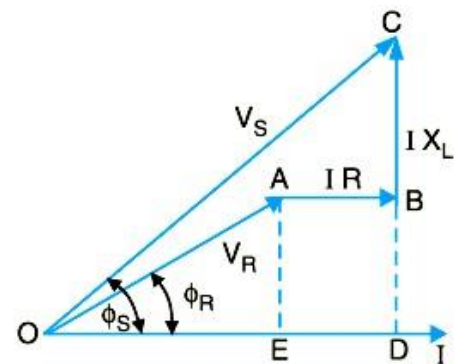
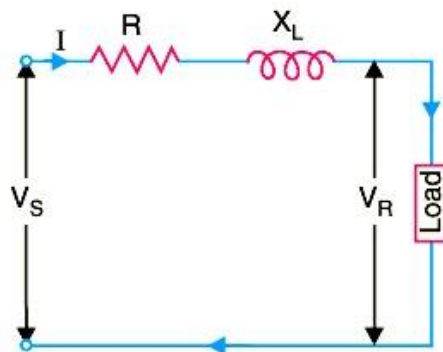
X_L = loop reactance

V_R = receiving end voltage

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

V_S = sending end voltage

$\cos \phi_S$ = sending end power factor



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

$$\begin{aligned}
 (OC)^2 &= (OD)^2 + (DC)^2 \\
 \text{or } V_S^2 &= (OE + ED)^2 + (DB + BC)^2 \\
 &= (V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2 \\
 \therefore V_S &= \sqrt{(V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2} \\
 \text{(i) \%age Voltage regulation} &= \frac{V_S - V_R}{V_R} \times 100 \\
 \text{(ii) Sending end } p.f., \cos \phi_S &= \frac{OD}{OC} = \frac{V_R \cos \phi_R + IR}{V_S} \\
 \text{(iii) Power delivered} &= V_R I_R \cos \phi_R \\
 \text{Line losses} &= I^2 R \\
 \text{Power sent out} &= V_R I_R \cos \phi_R + I^2 R \\
 \text{\%age Transmission efficiency} &= \frac{\text{Power delivered}}{\text{Power sent out}} \times 100 \\
 &= \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I^2 R} \times 100
 \end{aligned}$$

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

$$\begin{aligned}
 OC &= OF = OA + AF = OA + AG + GF \\
 &= OA + AG + BH
 \end{aligned}$$

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

3.2.1 THREE-PHASE SHORT TRANSMISSION LINES

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

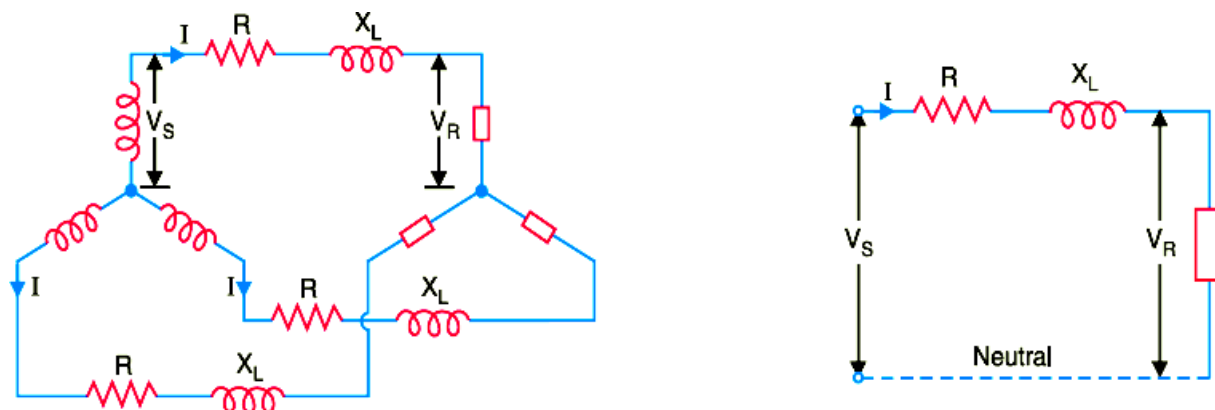


Fig (i) shows a Y-connected generator supplying a balanced Y-connected load through a transmission line. Each conductor has a resistance of $R \Omega$ and inductive reactance of $X \Omega$. Fig. (ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

3.2.2 Effect of Load p.f. On Regulation and Efficiency

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

1. Effect on regulation.

The expression for voltage regulation of a short transmission line is given by :

$$\% \text{age Voltage regulation} = \frac{IR \cos \phi_R + IX_L \sin \phi_R}{V_R} \times 100 \quad (\text{for lagging p.f.})$$

$$\% \text{age Voltage regulation} = \frac{IR \cos \phi_R - IX_L \sin \phi_R}{V_R} \times 100 \quad (\text{for leading p.f.})$$

The following conclusions can be drawn from the above expressions :

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

2. Effect on transmission efficiency.

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

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

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

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

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

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

3.3 SHORT TRANSMISSION LINES

As stated earlier, the effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in Fig. Here, the total line resistance and inductance are shown as concentrated or lumped instead of being distributed. The circuit is a simple a.c. series circuit. Let

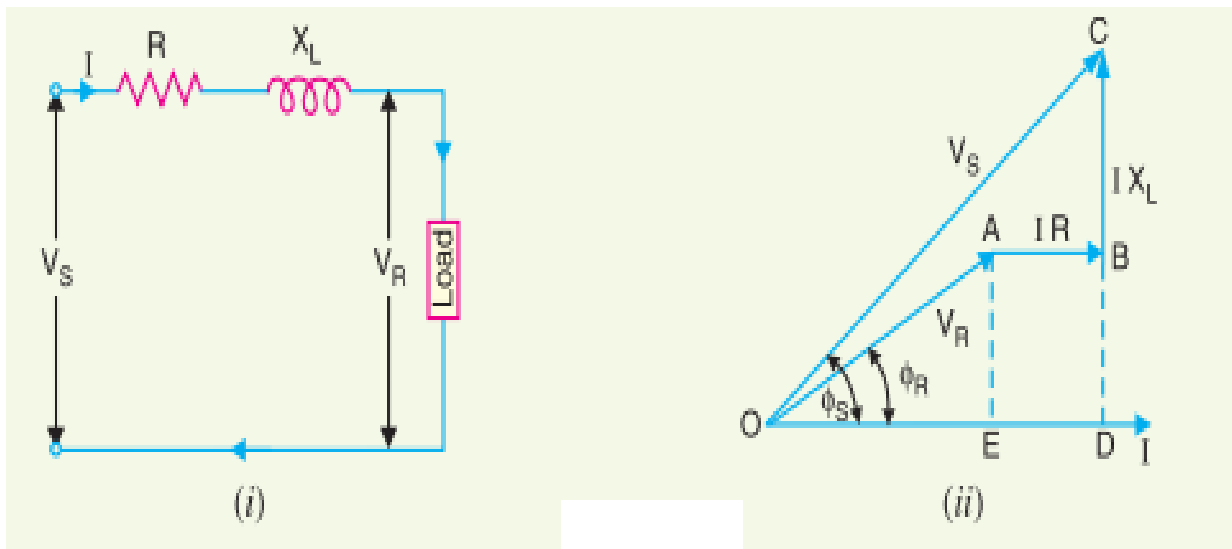
I = load current

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

X_L = loop reactance V_R = receiving end voltage

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

V_S = sending end voltage $\cos \phi_S$ = sending end power factor



$$\begin{aligned}
 (OC)^2 &= (OD)^2 + (DC)^2 \\
 \text{or } V_S^2 &= (OE + ED)^2 + (DB + BC)^2 \\
 &= (V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2 \\
 \therefore V_S &= \sqrt{(V_R \cos \phi_R + IR)^2 + (V_R \sin \phi_R + IX_L)^2} \\
 \text{(i) \%age Voltage regulation} &= \frac{V_S - V_R}{V_R} \times 100 \\
 \text{(ii) Sending end p.f., } \cos \phi_S &= \frac{OD}{OC} = \frac{V_R \cos \phi_R + IR}{V_S} \\
 \text{(iii) Power delivered} &= V_R I_R \cos \phi_R \\
 \text{Line losses} &= I^2 R \\
 \text{Power sent out} &= V_R I_R \cos \phi_R + I^2 R \\
 \text{\%age Transmission efficiency} &= \frac{\text{Power delivered}}{\text{Power sent out}} \times 100 \\
 &= \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I^2 R} \times 100
 \end{aligned}$$

3.4 MEDIUM TRANSMISSION LINES

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

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

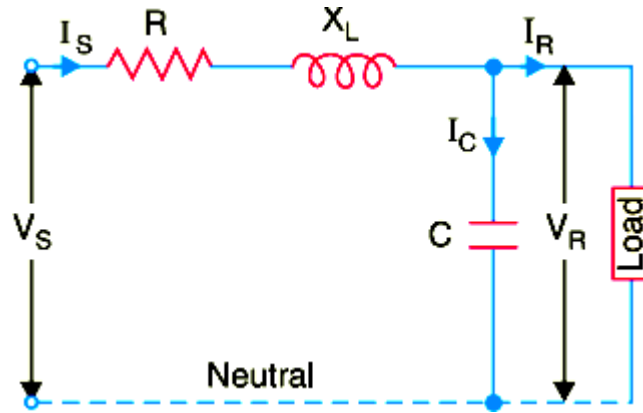
The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localising the line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

i) End Condenser Method

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



Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

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

V_S = sending end voltage per phase

The *phasor diagram for the circuit is shown in Fig Taking the receiving end voltage 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 I_S is the phasor sum of load current I_R and capacitive current I_C i.e. ,

$$\begin{aligned} \vec{I}_S &= \vec{I}_R + \vec{I}_C \\ &= I_R (\cos \phi_R - j \sin \phi_R) + j 2 \pi f C V_R \\ &= I_R \cos \phi_R + j (-I_R \sin \phi_R + 2 \pi f C V_R) \\ &= \vec{I}_S \vec{Z} = \vec{I}_S (R + j X_L) \end{aligned}$$

$$\vec{V}_S = \vec{V}_R + \vec{I}_S \vec{Z} = \vec{V}_R + \vec{I}_S (R + j X_L)$$

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

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

$$\begin{aligned} \% \text{ Voltage transmission efficiency} &= \frac{\text{Power delivered / phase}}{\text{Power delivered / phase} + \text{losses / phase}} \times 100 \\ &= \frac{V_R I_R \cos \phi_R}{V_R I_R \cos \phi_R + I_S^2 R} \times 100 \end{aligned}$$

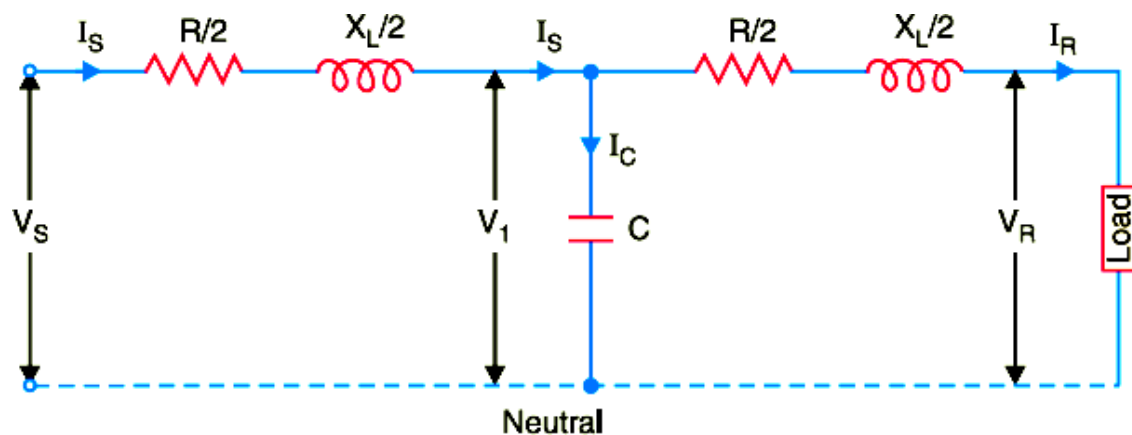
Limitations

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

- (i) There is a considerable error (about 10%) in calculations because the distributed capacitance has been assumed to be lumped or concentrated.
- (ii) This method overestimates the effects of line capacitance.

ii) Nominal T Method

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



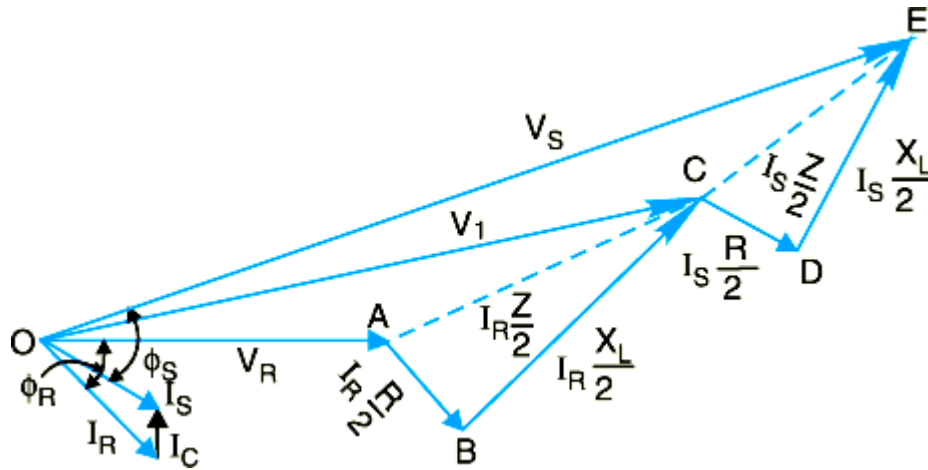
Let

- I_R = load current per phase ;
- R = resistance per phase
- X_L = inductive reactance per phase ;
- C = capacitance per phase
- $\cos \phi_R$ = receiving end power factor (lagging) ;
- V_s = sending end voltage/phase
- V_1 = voltage across capacitor C

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

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

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



Voltage across C, $\vec{V}_1 = \vec{V}_R + \vec{I}_R \vec{Z} / 2$

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

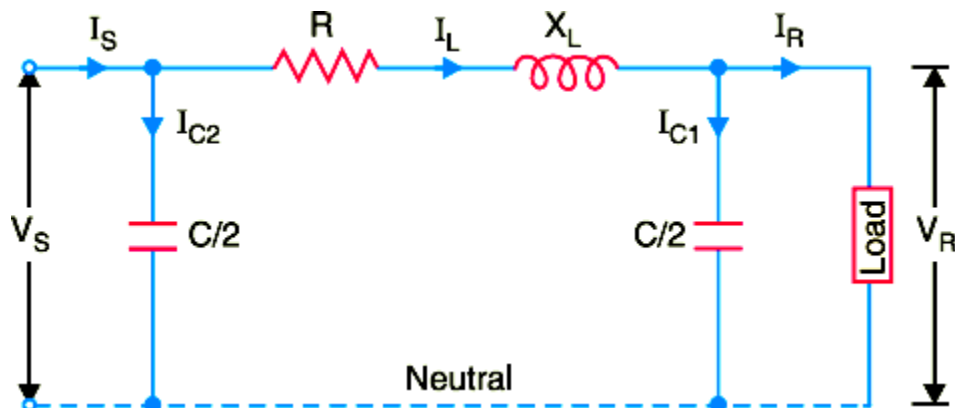
Capacitive current, $\vec{I}_C = j \omega C \vec{V}_1 = j 2\pi f C \vec{V}_1$

Sending end current, $\vec{I}_S = \vec{I}_R + \vec{I}_C$

Sending end voltage, $\vec{V}_S = \vec{V}_1 + \vec{I}_S \frac{\vec{Z}}{2} = \vec{V}_1 + \vec{I}_S \left(\frac{R}{2} + j \frac{X_L}{2} \right)$

iii) Nominal π Method

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



Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

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

V_S = sending end voltage per phase

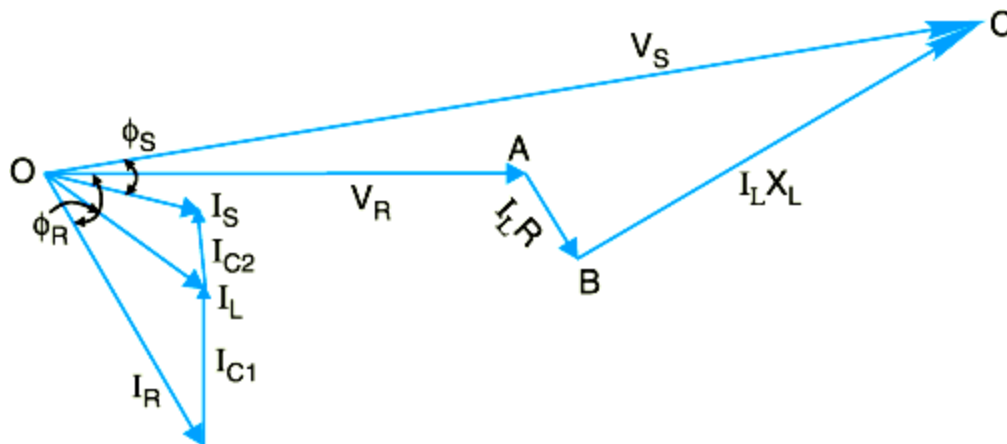
The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage as the reference phasor, we have,

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

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

$$\vec{I}_{C2} = j \omega (C/2) \vec{V}_S = j \pi f C \vec{V}_S$$

\therefore Sending end current,
$$\vec{I}_S = \vec{I}_L + \vec{I}_{C2}$$

3.5 LONG TRANSMISSION LINES

It is well known that line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped. If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are reconsidered as uniformly distributed throughout the length of the line. Rigorous mathematical

treatment is required for the solution of such lines. Fig shows the equivalent circuit of a 3-phase long transmission line on a phase-neutral basis. The whole line length is divided into n sections, each section having line constants 1/n th of those for the whole line. The following points may be noted :

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

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

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

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

insulators or due to corona effect between conductors. Admittance

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

3.5.1 ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD)

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

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

Let

z = series impedance of the line per unit length

y = shunt admittance of the line per unit length

V = voltage at the end of element towards receiving end

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

I + dI = current entering the element dx

I = current leaving the element dx

Then for the small element dx,

z dx = series impedance

y dx = shunt admittance

Obviously, $dV = I z dx$

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

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

dI = Current through shunt admittance of element = Vy dx

or
$$\frac{dI}{dx} = Vy \quad \dots(ii)$$

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

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

or
$$\frac{d^2V}{dx^2} = yzV \quad \dots(iii)$$

The solution of this differential equation is

$$V = k_1 \cosh(x\sqrt{yz}) + k_2 \sinh(x\sqrt{yz}) \quad \dots(iv)$$

or
$$\frac{dI}{dx} = Vy \quad \dots(ii)$$

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

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

or
$$\frac{d^2V}{dx^2} = yzV \quad \dots(iii)$$

The solution of this differential equation is

$$V = k_1 \cosh(x\sqrt{yz}) + k_2 \sinh(x\sqrt{yz}) \quad \dots(iv)$$

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

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

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

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

$$\therefore V_R = k_1$$

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

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

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

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

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

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

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 :

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

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

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

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

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

3.6 CIRCLE DIAGRAMS

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

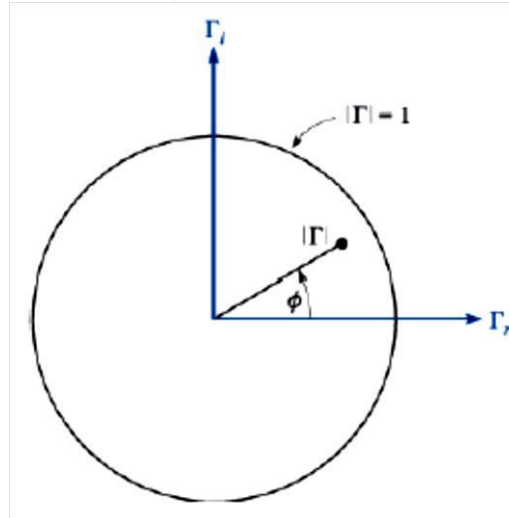
$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

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

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

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

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



3.7 SURGE IMPEDANCE LOADING

Surge impedance of a line, Z_o

$$= \sqrt{\frac{L}{C}}. \quad \text{SIL} = \frac{(kV_{LL})^2}{Z_o}, \quad (\text{MW})$$

A transmission line loaded to its surge impedance loading:

- (i) has no net reactive power flow into or out of the line, and
- (ii) will have approximately a flat voltage profile along its length.

For (i) to hold:

$$I^2 X_L = \frac{V^2}{X_c}, \quad \text{or,} \quad \frac{V^2}{I^2} = X_L X_c = \frac{\omega L}{\omega C}, \quad \text{or,} \quad \frac{V}{I} = \sqrt{\frac{L}{C}} = Z_o = \text{Load impedance}$$

This means that there will be no net reactive power flow at surge-impedance loading.

For (ii) to hold:

$$V_s = AV_r + BI_r; \quad I_s = CV_r + DI_r,$$

$$\text{where, } A = D = \cosh \sqrt{ZY}; \quad B = Z_o \sinh \sqrt{ZY}; \quad C = \frac{\sinh \sqrt{ZY}}{Z_o}; \quad Z = j\omega L \ell; \quad Y = j\omega C \ell$$

$$\sqrt{ZY} = j\omega \ell \sqrt{LC} = \frac{j\omega \ell}{v_c} = j \frac{2\pi f \ell}{\lambda} = j \frac{2\pi \ell}{\lambda}$$

$$\text{Then, } A = D = \cos \frac{2\pi\ell}{\lambda} ; B = jZ_o \sin \frac{2\pi\ell}{\lambda} ; C = j \frac{\sin \frac{2\pi\ell}{\lambda}}{Z_o}$$

At surge-impedance loading, $\frac{V_r}{I_r} = Z_o$.

$$\text{And, } V_s = \left(A + \frac{B}{Z_o}\right) V_r = \left(\cos \frac{2\pi\ell}{\lambda} + j \sin \frac{2\pi\ell}{\lambda}\right) V_r = V_r \angle \tan^{-1} \frac{2\pi\ell}{\lambda},$$

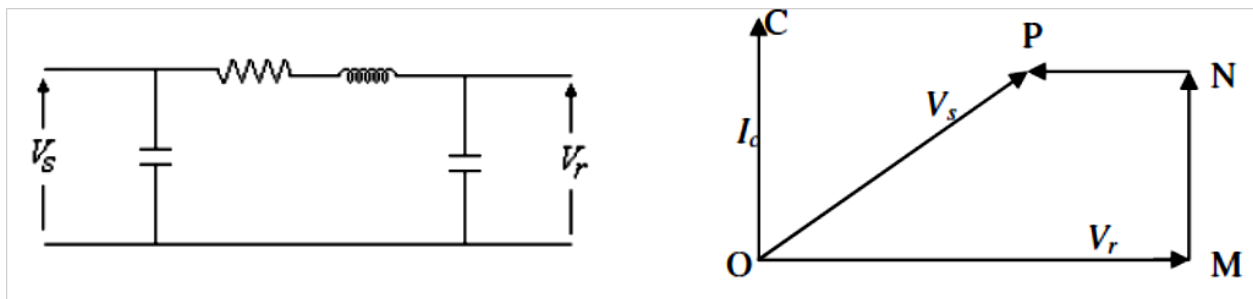
$$I_s = (C Z_o + D) I_r = \left(j \sin \frac{2\pi\ell}{\lambda} + \cos \frac{2\pi\ell}{\lambda}\right) I_r = I_r \angle \tan^{-1} \frac{2\pi\ell}{\lambda}$$

This means that the line will have a flat voltage profile, i.e., no voltage drop.

3.8 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.



Line capacitance is assumed to be concentrated at the receiving end.

OM = receiving end voltage V_r

OC = Current drawn by capacitance = I_c

MN = Resistance drop

NP = Inductive reactance drop

Therefore;

OP = Sending end voltage at no load and is less than receiving end voltage (V_r)

Since, resistance is small compared to reactance; resistance can be neglected in calculating Ferranti effect.

From π model,

$$V_s = \left(1 + \frac{YZ}{2}\right) V_r + Z I_r$$

For open circuit line; $I_r = 0$

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

$$\text{or; } V_s - V_r = \left(1 + \frac{YZ}{2}\right) V_r - V_r = V_r \left(1 + \frac{YZ}{2} - 1\right)$$

$$\text{or; } V_s - V_r = \left(\frac{YZ}{2}\right) V_r = \frac{(j\omega Cl)(r + j\omega L)l}{2} V_r$$

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;

$$\left[1 - \frac{\omega^2 l^2 \times 10^{-10}}{18} \right] < 1$$

$$V_s < V_r \quad \text{or; } V_r > V_s$$

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.

QUESTIONS :

Q.No	Question
1	Define regulation of a transmission line
2	What is surge impedance?
3	Outline about tuned power lines
4	What is the use of power circle diagram?
5	Model the T-equivalent circuit of a medium transmission line
6	How the capacitance effects infer in a long transmission line?
7	What are voltage regulating equipments used in transmission system?
8	What are the units of ABCD constants and give the relation between those constants?
9	Classify the transmission line based on length
10	Identify suitable methods to control the voltage

Q.No	Question
1	A 3 phase, 50 Hz, 150 km line has a resistance, inductive reactance and capacitive shunt admittance of 0.1 ohm, 0.5 ohm and 3×10^{-6} S per km per phase. If the line delivers 50 MW at 110 kV and 0.8 p.f. lagging, determine the sending end voltage and current. Assume Nominal π method.
2	A 3-phase, 50 Hz overhead transmission line 100km. long has the following constants: Resistance/km/phase = 0.1 ohm Inductive reactance/km/phase = 0.2 ohm Capacitive susceptance/km/ phase = 0.04×10^{-4} siemen Determine i) sending end current ii) sending end voltage iii) sending end power factor and iv) transmission efficiency when supplying a balanced load of 10000 kW at 66 kV, p.f. 0.8 lagging. Use Nominal T method
3	Explain the power circle diagram for sending end.
4	Explain briefly the voltage control of transmission line by i) Tap-changing transformers ii) Synchronous condenser iii) Induction regulators
5	A balanced 3-phase load of 30 MW is supplied at 132 kV, 50 Hz and 0.85 p.f. lagging by means of a transmission line. The series impedance of a single conductor is $(20 + j52)$ ohms and the total phase-neutral admittance is 315×10^{-6} siemen. Using Nominal T method, determine i) A,B,C and D constants of the line ii) sending end voltage iii) regulation of the line
6	A 3-phase transmission line 200 km long has the following constants: Resistance/phase/km = 0.16 ohm Reactance/phase/km = 0.25 ohm

Shunt admittance/phase/km = $1.5 \times 10^{-6} \text{ S}$

Solve by rigorous method, the sending end voltage and current when the line is delivering a load of 20 MW at 0.8 p.f. lagging. The receiving end voltage is kept constant at 110 kV.

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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

TRANSMISSION AND DISTRIBUTION – SEEA1402
UNIT IV- INSULATORS, CABLES AND MECHANICAL DESIGN
OF OH LINES

IV. INSULATORS, CABLES AND MECHANICAL DESIGN OF OH LINES

Insulators - Types and Construction - Voltage Distribution in String Insulator - string Efficiency - Methods of Improving String Efficiency - Cables - types - Capacitance of Cables - Insulation Resistance - Dielectric Stress and Grading - Dielectric Loss - Thermal Characteristics - capacitance of Three Core Cables - Stress and Sag Calculations - Effect of Wind and Ice - Supports at Different Levels - stringing Chart.

4.1 INSULATOR - INTRODUCTION

Electrical Insulator must be used in electrical system to prevent unwanted flow of current to the earth from its supporting points. The **insulator** plays a vital role in electrical system. **Electrical Insulator** is a very high resistive path through which practically no current can flow. In transmission and distribution system, the overhead conductors are generally supported by supporting towers or poles. The towers and poles both are properly grounded. So there must be **insulator** between tower or pole body and current carrying conductors to prevent the flow of current from conductor to earth through the grounded supporting towers or poles.

4.1.1 INSULATING MATERIAL

The main cause of failure of overhead line insulator, is flash over, occurs in between line and earth during abnormal over voltage in the system. During this flash over, the huge heat produced by arcing, causes puncture in insulator body. Viewing this phenomenon the materials used for electrical insulator, has to possess some specific properties.

Properties of insulating material

The materials generally used for insulating purpose is called **insulating material**. For successful utilization, this material should have some specific properties as listed below-

1. It must be mechanically strong enough to carry tension and weight of conductors.

2. It must have very high dielectric strength to withstand the voltage stresses in High Voltage system.

3. It must possess high Insulation Resistance to prevent leakage current to the earth.

4. Their physical as well as electrical properties must be less affected by changing temperature

Porcelain

Porcelain is most commonly used material for overhead insulator in present days. The porcelain is aluminium silicate. The aluminium silicate is mixed with plastic kaolin, feldspar and quartz to obtain final hard and glazed **porcelain insulator** material. The surface of the insulator should be glazed enough so that water should not be traced on it. Porcelain also should be free from porosity since porosity is the main cause of deterioration of its dielectric property. It must also be free from any impurity and air bubble inside the material which may affect the insulator properties.



Glass Insulator

Now days **glass insulator** has become popular in transmission and distribution system. Annealed tough glass is used for insulating purpose. Glass insulator has numbers of advantages over conventional porcelain insulator



Glass Insulator (Disc)

Advantage

1. It has very high dielectric strength compared to porcelain.
2. Its resistivity is also very high.
3. It has low coefficient of thermal expansion.
4. It has higher tensile strength compared to porcelain insulator.
5. As it is transparent in nature is not heated up in sunlight as porcelain.
6. The impurities and air bubble can be easily detected inside the glass insulator body because of its transparency.
7. Glass has very long service life as because mechanical and electrical properties of glass do not be affected by ageing.
8. After all, glass is cheaper than porcelain.

Disadvantage

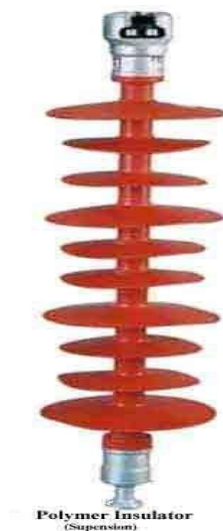
1. Moisture can easily condensed on glass surface and hence air dust will be deposited on the wet glass surface which will provide path to the leakage current of the system.
2. For higher voltage glass cannot be cast in irregular shapes since due to irregular cooling internal cooling internal strains are caused.

Polymer Insulator

In a **polymer insulator** has two parts, one is glass fiber reinforced epoxy resin rod shaped core and other is silicone rubber or EPDM (Ethylene Propylene Diene Monomer) made weather sheds. Rod shaped core is covered by weather sheds. Weather sheds protect the insulator core from outside environment. As it is made of two parts, core and weather sheds, **polymer insulator** is also called **composite insulator**. The rod shaped core is fixed with Hot dip galvanized cast steel made end fittings in both sides.

Advantage

1. It is very light weight compared to porcelain and glass insulator.
2. As the **composite insulator** is flexible the chance of breakage becomes minimum.
3. Because of lighter in weight and smaller in size, this insulator has lower installation cost.
4. It has higher tensile strength compared to porcelain insulator.
5. Its performance is better particularly in polluted areas.
6. Due to lighter weight polymer insulator imposes less load to the supporting structure.
7. Less cleaning is required due to hydrophobic nature of the insulator.



Disadvantage

1. Moisture may enter in the core if there is any unwanted gap between core and weather sheds. This may cause electrical failure of the insulator.
2. Over crimping in end fittings may result to cracks in the core which leads to mechanical failure of polymer insulator.

In addition to these, some other disadvantages might be experienced. Let us give a practical example where many difficulties are faced in maintaining a distribution network in Victoria Australia due to polymeric insulator.

There are many Cockatoos, Galahs & Parrots in that area of Australia, which love to chew on polymeric strain insulators. Here, the 22KV network has many of polymeric strain insulators installed and now after a few years of installing polymeric strain insulators, the authority is now replacing many of them back with Glass disc insulators.

Another disadvantage is that they have had post type polymeric insulators melt and bend in bushfire areas. They have a concrete pole and a steel cross arm that survives a bushfire, however the polymers in some cases fail. This would not be the case with glass or porcelain insulators.

They have also had polymeric insulators fail in areas close to the ocean coastline where there are high salt levels in the air.

1. Subject to bird attack by Parrots, Cockatoos & Galahs.
2. Not resilient to bushfire temperatures.
3. Not recommended for location near surf beaches due to salt spray.

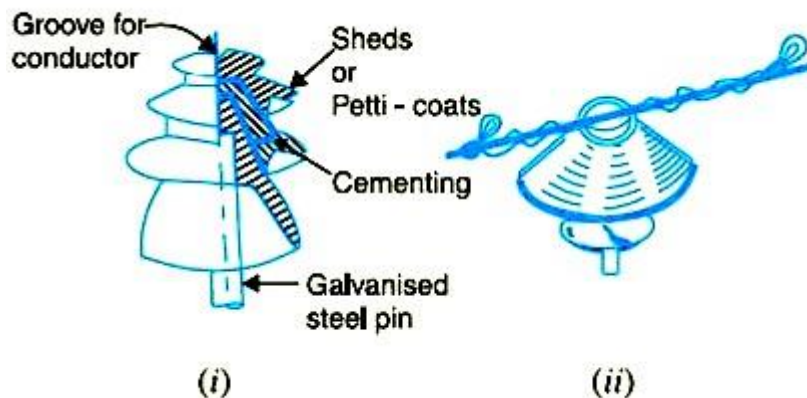
4.2 TYPES OF INSULATOR

There are mainly three types of insulator likewise

1. Pin Insulator
2. Suspension Insulator
3. Stray Insulator

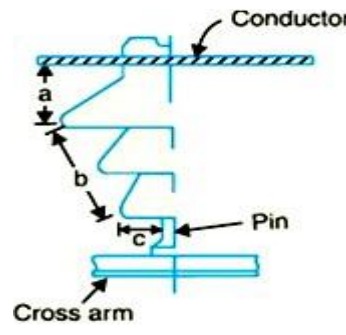
In addition to that there are other two types of electrical insulator available mainly for low voltage application, e.i. stay insulator and shackle insulator.

1. Pin Type Insulators



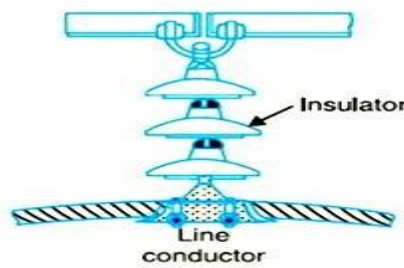
As the name suggests, the pin type insulator is secured to the cross-arm on the pole. There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor. Pin type insulators are used for transmission and distribution of electric power at voltages up to 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.

Causes of Insulator Failures:



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 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 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.

2. Suspension Type



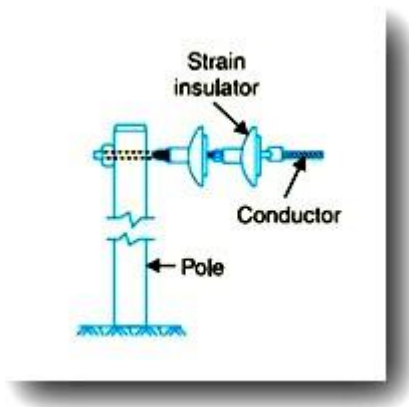
For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Figure. Consist of a number of porcelain discs connected in series by metal links in the form

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.

Advantages of suspension type:

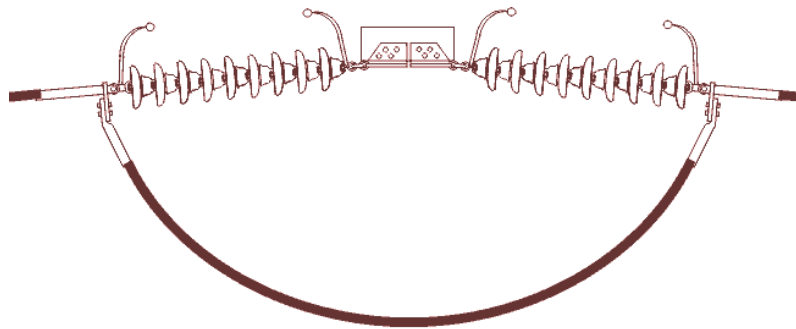
- Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
- Each unit or disc of suspension type insulator is designed for low voltage, usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.
- If anyone disc is damaged, 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

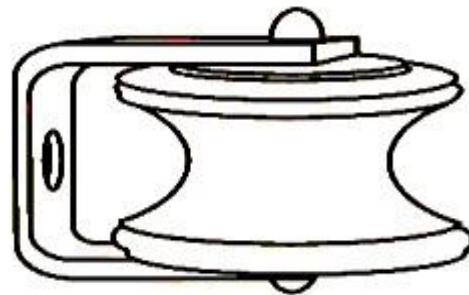
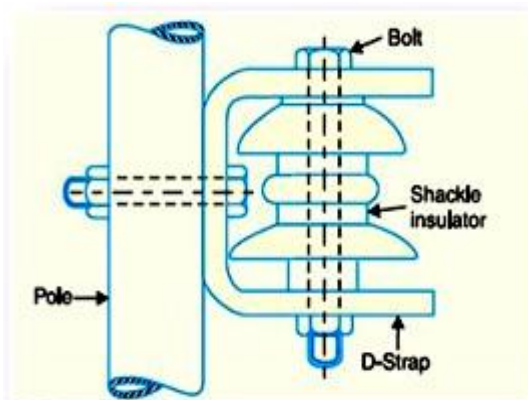
shown in Figure. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, at long river spans, two or more strings are used in parallel.



STRAIN INSULATOR

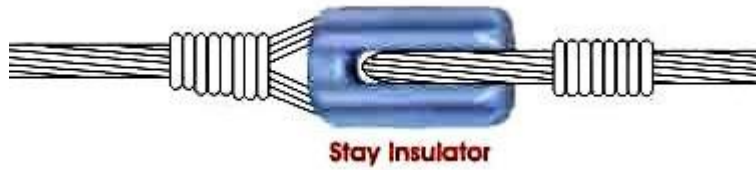
4. Shackle Insulators

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.



5. Stay Insulator

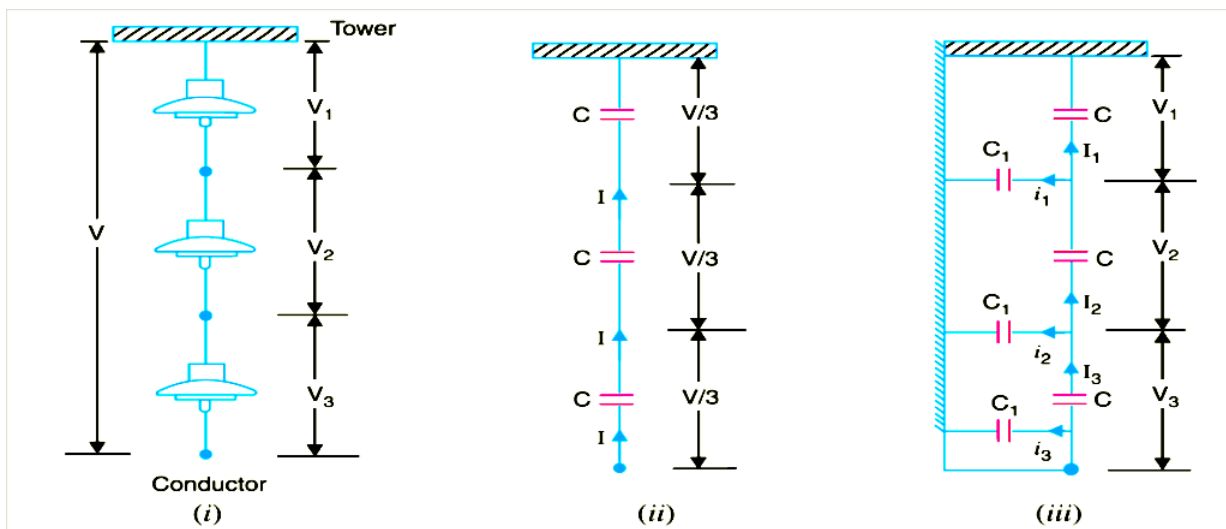
For low voltage lines, the stays are to be insulated from ground at a height. The insulator used in the stay wire is called as the **stay insulator** and is usually of porcelain and is so designed that in case of breakage of the insulator the guy-wire will not fall to the ground. There are several methods of increasing the string efficiency or improving voltage distribution across different units of a string.



4.3 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. 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. 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. However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance C_1 . 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 V_2 or V_1 . 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.



4.4 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 $n = \text{number of discs in the string.}$

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.

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 C_1 is some fraction K of self capacitance i.e., $C_1 = KC$. Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.

Applying Kirchhoff's current law to node A , we get,

$$\begin{aligned} I_2 &= I_1 + i_1 \\ \text{or } V_2 \omega C^* &= V_1 \omega C + V_1 \omega C_1 \\ \text{or } V_2 \omega C &= V_1 \omega C + V_1 \omega K C \\ \therefore V_2 &= V_1 (1 + K) \quad \dots(i) \end{aligned}$$

Applying Kirchhoff's current law to node B , we get,

$$\begin{aligned} I_3 &= I_2 + i_2 \\ \text{or } V_3 \omega C &= V_2 \omega C + (V_1 + V_2) \omega C_1 \\ \text{or } V_3 \omega C &= V_2 \omega C + (V_1 + V_2) \omega K C \end{aligned}$$

$$\begin{aligned} \text{or } V_3 &= V_2 + (V_1 + V_2)K \\ &= KV_1 + V_2 (1 + K) \end{aligned}$$

$$\begin{aligned}
 &= KV_1 + V_1 (1 + K)^2 && [\because V_2 = V_1 (1 + K)] \\
 &= V_1 [K + (1 + K)^2] \\
 \therefore V_3 &= V_1 [1 + 3K + K^2] && \dots(ii) \\
 \text{Voltage between conductor and earth (i.e., tower) is} \\
 V &= V_1 + V_2 + V_3 \\
 &= V_1 + V_1(1 + K) + V_1 (1 + 3K + K^2) \\
 &= V_1 (3 + 4K + K^2) \\
 \therefore V &= V_1(1 + K) (3 + K) && \dots(iii) \\
 \text{From expressions (i), (ii) and (iii), we get,} \\
 \frac{V_1}{1} &= \frac{V_2}{1 + K} = \frac{V_3}{1 + 3K + K^2} = \frac{V}{(1 + K)(3 + K)} && \dots(iv)
 \end{aligned}$$

$$\therefore \text{Voltage across top unit, } V_1 = \frac{V}{(1 + K)(3 + K)}$$

$$\begin{aligned}
 \text{Voltage across second unit from top, } V_2 &= V_1 (1 + K) \\
 \text{Voltage across third unit from top, } V_3 &= V_1 (1 + 3K + K^2) \\
 \text{\%age String efficiency} &= \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100 \\
 &= \frac{V}{3 \times V_3} \times 100
 \end{aligned}$$

The Following Points May Be Noted From The Above Mathematical Analysis

- (i) If $K = 0.2$ (Say), then from exp. (iv), we get, $V_2 = 1.2 V_1$ and $V_3 = 1.64 V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm is approached.
- (ii) The greater the value of $K (= C_1/C)$, the more non-uniform is the potential across the discs and lesser is the string efficiency.
- (iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one

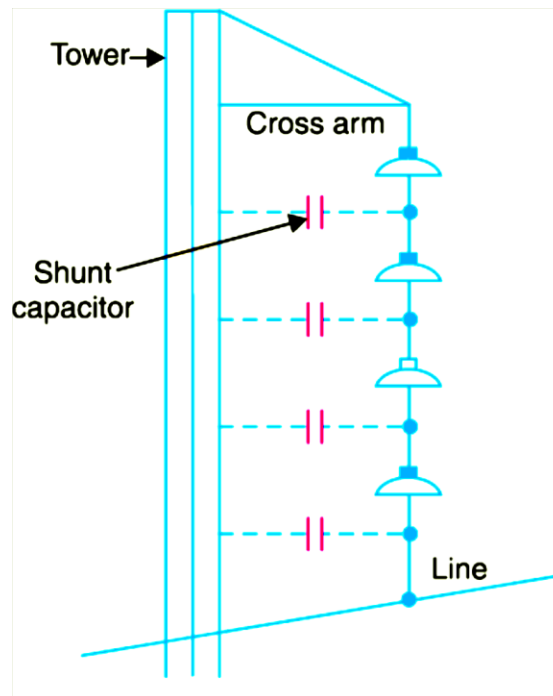
4.5 METHODS OF IMPROVING STRING EFFICIENCY

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:

(I) By Using Longer Cross-Arms

The value of string efficiency depends upon the value of K *i.e.*, ratio of shunt capacitance to mutual capacitance. The lesser the value of K , the greater is the string efficiency

and more uniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased i.e., longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, $K = 0.1$ is the limit that can be achieved by this method.

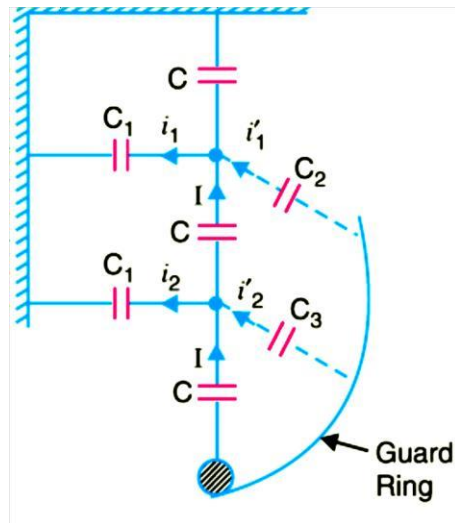


(II) By Grading The Insulators

In this method, insulators of different dimensions are so chosen that each has a different capacitance. The insulators are capacitance graded i.e. they are assembled in the string in such a way that the top unit has the minimum capacitance, increasing progressively as the bottom unit (i.e., nearest to conductor) is reached. Since voltage is inversely proportional to capacitance, this method tends to equalize the potential distribution across the units in the string. This method has the disadvantage that a large number of different-sized insulators are required. However, good results can be obtained by using standard insulators for most of the string and larger units for that near to the line conductor.

(III) By Using A Guard Ring

The potential across each unit in a string can be 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 i_1, i_2 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.



4.6 TESTING OF INSULATOR

To ensure the desired performance of an electrical insulator, that is for avoiding unwanted **insulator failure**, each insulator has to undergo numbers of **insulator test**. Before going through **testing of insulator** we will try to understand different causes of **insulator failure**. Because insulator testing ensures the quality of electrical insulator and chances for **failure of insulation** depend upon the quality of insulator.

Causes

There are different causes due to which **failure of insulation** in electrical power system may occur. Let's have a look on them one by one-

Cracking Of Insulator

The porcelain insulator mainly consists of three different materials. The main porcelain body, steel fitting arrangement and cement to fix the steel part with porcelain. Due to changing climate conditions, these different materials in the insulator expand and contract in different rate. These unequal expansion and contraction of porcelain, steel and cement are the chief cause of cracking of insulator.

Defective Insulation Material

If the insulation material used for insulator is defective anywhere, the insulator may have a high chance of being punched from that place.

Porosity In The Insulation Materials

If the porcelain insulator is manufactured at low temperatures, it will make it porous, and due to this reason it will absorb moisture from air thus its insulation will decrease and leakage current will start to flow through the insulator which will lead to **insulator failure**.

Improper Glazing on Insulator Surface

If the surface of porcelain insulator is not properly glazed, moisture can stick over it. This moisture along with deposited dust on the insulator surface, produces a conducting path. As a

result the flash over distance of the insulator is reduced. As the flash over distance is reduced, the chance of failure of insulator due to flash over becomes more.

Flash Over Across Insulator

If flash over occurs, the insulator may be over heated which may ultimately results into shuttering of it.

Mechanical Stresses on Insulator

If an insulator has any weak portion due to manufacturing defect, it may break from that weak portion when mechanical stress is applied on it by its conductor. These are the main causes of insulator failure. Now we will discuss the different **insulator test** procedures to ensure minimum chance of failure of insulation.

4.7 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

Let's have a discussion one by one

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.

Power Frequency Wet Flashover Test or Rain Test of Insulator

- 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 45° 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

Now we will discuss performance test of insulator one by one

Temperature Cycle Test of Insulator

- The insulator is first heated in water at 70°C for one hour.
- Then this insulator immediately cooled in water at 7°C 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/cm^2 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 $2\frac{1}{2}$ 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.

Corrosion Test of 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.

4.8 INSULATED CABLE - INTRODUCTION

Electric power can be transmitted or distributed either by overhead system or by underground cables. The underground cables have several advantages such as less liable to damage through storms or lightning, low maintenance cost, less chance of faults, smaller voltage drop and better general appearance. However, their major drawback is that they have greater installation cost and introduce insulation problems at high voltages compared with the equivalent overhead system. For this reason, underground cables are employed where it is impracticable to use overhead lines. Such locations may be thickly populated areas where municipal authorities prohibit overhead lines for reasons of safety, or around plants and substations or where maintenance conditions do not permit the use of overhead construction. The chief use of underground cables for many years

has been for distribution of electric power in congested urban areas at comparatively low or moderate voltages. However, recent improvements in the design and manufacture have led to the development of cables suitable for use at high voltages. This has made it possible to employ underground cables for transmission of electric power for short or moderate distances. In this chapter, we shall focus our attention on the various aspects of underground cables and their increasing use in power system.

4.8.1 UNDERGROUND CABLES

An underground cable essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover. Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfill the following necessary requirements:

(i) The conductor used in cables should be tinned stranded copper or aluminum of high conductivity. Stranding is done so that conductor may become flexible and carry more current.

(ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.

(iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.

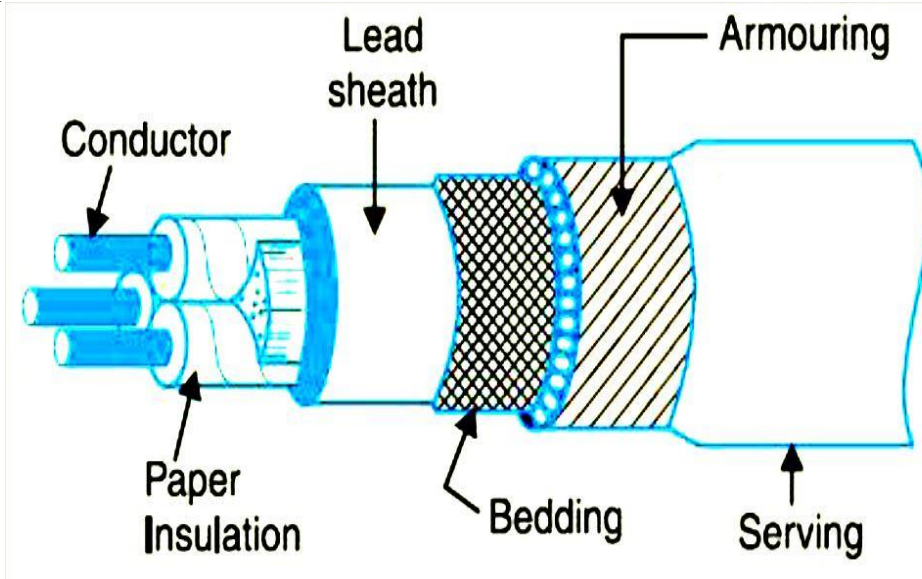
(iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.

(v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

4.9 CONSTRUCTION OF CABLES

Fig shows the general construction of a 3-conductor cable.

The various parts are



a) Cores or Conductors

A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3- conductor cable shown in Fig. is used for 3- phase service. The conductors are made of tinned copper or aluminum and are usually stranded in order to provide flexibility to the cable.

b) Insulation

Each core or conductor is provided with a suitable thickness of insulation, the thickness of layer depending upon the voltage to be withstood by the cable. The commonly used materials for insulation are impregnated paper, varnished cambric or rubber mineral compound.

c) Metallic sheath.

In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminum is provided over the insulation as shown in Fig.

d) Bedding.

Over the metallic sheath is applied a layer of bedding which consists of a fibrous material like jute or hessian tape. The purpose of bedding is to protect the metallic sheath against corrosion and from mechanical injury due to armoring.

e) Armouring.

Over the bedding, armouring is provided which consists of one or two layers of galvanized steel wire or steel tape. Its purpose is to protect the cable from mechanical injury while laying it and during the course of handling. Armouring may not be done in the case of some cables.

f) Serving.

In order to protect armouring from atmospheric conditions, a layer of fibrous material (like jute) similar to bedding is provided over the armouring. This is known as serving.

It may not be out of place to mention here that bedding, armouring and serving are only applied to the cables for the protection of conductor insulation and to protect the metallic sheath from Mechanical injury.

4.9.1 INSULATING MATERIALS FOR CABLES

The satisfactory operation of a cable depends to a great extent upon the characteristics of insulation used. Therefore, the proper choice of insulating material for cables is of considerable importance. In general, the insulating materials used in cables should have the following **Properties**

- (i) High insulation resistance to avoid leakage current.
- (ii) High dielectric strength to avoid electrical breakdown of the cable.
- (iii) High mechanical strength to withstand the mechanical handling of cables.
- (iv) Non-hygroscopic i.e., it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.
- (v) Non-inflammable.
- (vi) Low cost so as to make the underground system a viable proposition.
- (vii) Unaffected by acids and alkalies to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of

insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal insulating materials used in cables are rubber, vulcanized India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

Rubber

Rubber may be obtained from milky sap of tropical trees or it may be produced from oil products. It has relative permittivity varying between 2 and 3, dielectric strength is about 30 kV/mm and resistivity of insulation is 1017 cm. Although pure rubber has reasonably high insulating properties, it suffers from some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38°C), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

Vulcanised India Rubber (V.I.R.)

It is prepared by mixing pure rubber with mineral matter such as zinc oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150°C. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

Impregnated paper

It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or naphthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar. Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lengths are small and joints are required at a number of places, VIR cables will be cheaper and durable than paper insulated cables.

Varnished cambric

It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as empire tape. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4

kV/mm and permittivity is 2.5 to 3.8.

Polyvinyl chloride (PVC)

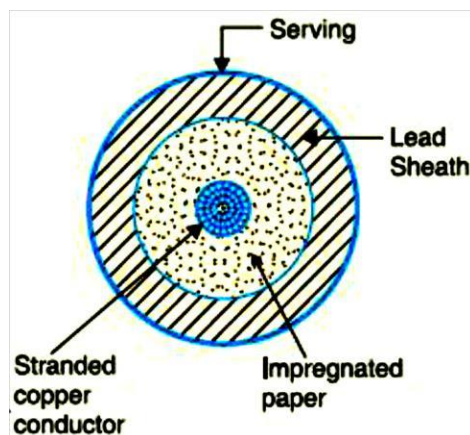
This insulating material is a synthetic compound. It is obtained from the polymerization of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gel and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over VIR in extreme environmental conditions such as in cement factory or chemical factory. As the mechanical properties (i.e., elasticity etc.) of PVC are not so good as those of rubber, therefore, PVC insulated cables are generally used for low and medium domestic lights and power installations.

4.10 CLASSIFICATION OF CABLES

Cables for underground service may be classified in two ways according to

- (i) the type of insulating material used in their manufacture
- (ii) the voltage for

which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups:



Low-tension (L.T.) cables — upto

- 1000 V High-tension (H.T.) cables
- — upto 11,000 V
- Super-tension (S.T.) cables — from 22 kV to 33 kV
- Extra high-tension (E.H.T.) cables — from 33 kV
- to 66 kV Extra super voltage cables — beyond 132 kV

A cable may have one or more than one core depending upon the type of service for which it is intended. It may be

- (i) single-core

- (ii) (ii) two-core
- (iii) (iii) three-core
- (iv) (iv) four-core etc.

For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. shows the constructional details of a single- core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (up to 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

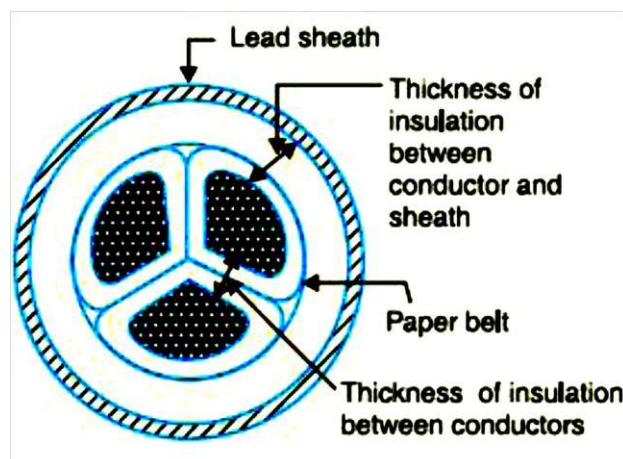
Cable For 3-Phase

In practice, underground cables are generally required to deliver 3-phase power. For the purpose, either three-core cable or three single core cables may be used. For voltages upto 66 kV, 3-core cable (i.e., multi-core construction) is preferred due to economic reasons. However, for voltages beyond 66 kV, 3-core-cables become too large and unwieldy and, therefore, single- core cables are used. The following types of cables are generally used for 3-phase service :

1. Belted cables — upto 11 kV
2. Screened cables — from 22 kV to 66 kV
3. Pressure cables — beyond 66 kV.

1. Belted Cables

These cables are used for voltages upto 11 kV but in extraordinary cases, their use may be extended upto 22 kV. Fig.3 shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layers of impregnated paper.



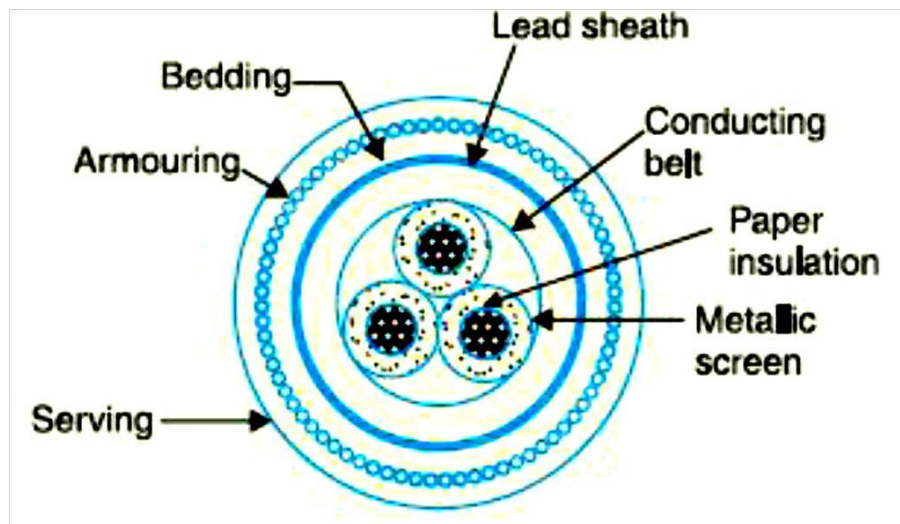
Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of non circular 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. 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

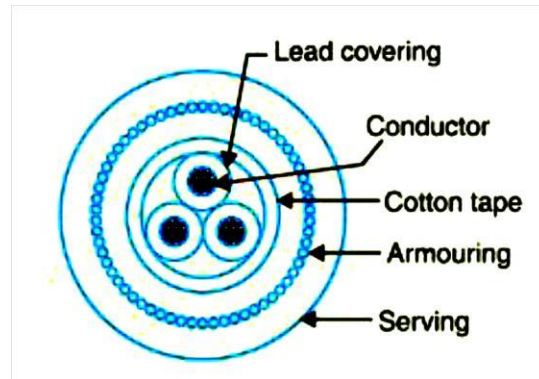


Fig. shows the constructional details of a 3-core S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over H-type cables. 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. Oilfilled cables are of three types viz., single-core conductor channel, single-core sheath channel and three-core filler- space channels.

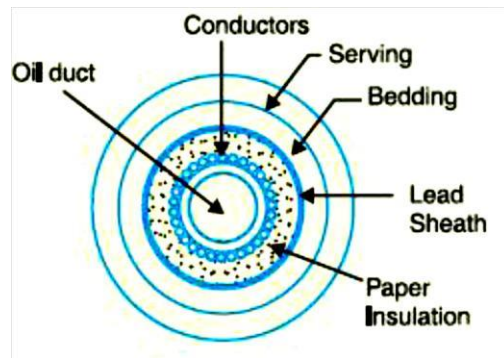
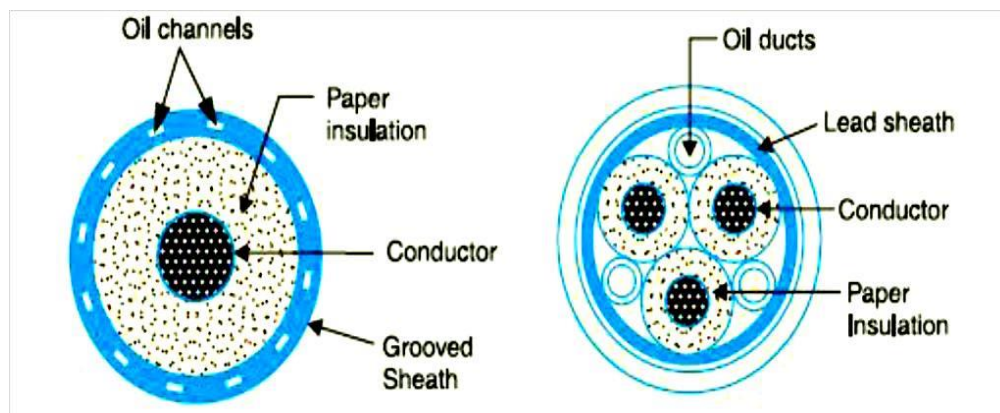


Fig. shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the center by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage *w.r.t.* earth, so that a very complicated system of joints is necessary. Fig. shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown. In the 3-core oil-filled cable shown in Fig. the oil ducts are located in the filler spaces. These channels are composed of perforated metal ribbon tubing and are at earth potential.



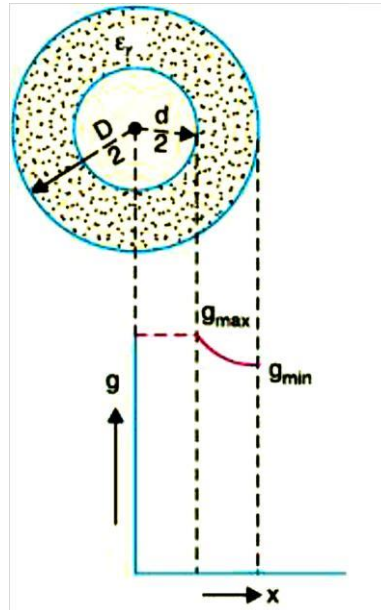
(ii) Gas Pressure Cable

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.



Fig 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. 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.

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

$$E_x = \frac{Q}{2\pi\epsilon_o\epsilon_r x} \text{ volts/m}$$

By definition, electric intensity is equal to potential gradient. Therefore, potential gradient g at a point x meters from the Centre of cable is

$$\begin{aligned} g &= E_x \\ \text{or } g &= \frac{Q}{2\pi\epsilon_o\epsilon_r x} \text{ volts/m} \quad \dots(i) \end{aligned}$$

As proved, potential difference V between conductor and sheath is

$$\begin{aligned} V &= \frac{Q}{2\pi\epsilon_o\epsilon_r} \log_e \frac{D}{d} \text{ volts} \\ \text{or } Q &= \frac{2\pi\epsilon_o\epsilon_r V}{\log_e \frac{D}{d}} \quad \dots(ii) \end{aligned}$$

Substituting the value of Q from exp. (ii) in exp. (i), we get,

$$g = \frac{2\pi\epsilon_o\epsilon_r V}{\log_e D/d} = \frac{V}{x \log_e \frac{D}{d}} \text{ volts/m} \quad \dots(iii)$$

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

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} \text{ volts/m} \quad [\text{Putting } x = D/2 \text{ in exp. (iii)}]$$

$$\therefore \frac{g_{max}}{g_{min}} = \frac{\frac{2V}{d \log_e D/d}}{\frac{2V}{D \log_e D/d}} = \frac{D}{d}$$

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 maximum stress. Rewriting the expression for maximum stress, we get,

$$g_{max} = \frac{2V}{d \log_e \frac{D}{d}} \text{ volts/m}$$

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.

$$\begin{aligned} \frac{d}{dd} \left[d \log_e \frac{D}{d} \right] &= 0 \\ \text{or} \quad \log_e \frac{D}{d} + d \cdot \frac{d}{D} \cdot \frac{-D}{d^2} &= 0 \\ \text{or} \quad \log_e (D/d) - 1 &= 0 \\ \text{or} \quad \log_e (D/d) &= 1 \\ \text{or} \quad (D/d) &= e = 2.718 \end{aligned}$$

Most economical conductor diameter is

$$d = \frac{D}{2.718}$$

and the value of gmax under this condition is

$$g_{max} = \frac{2V}{d} \text{ volts/m} \quad \text{[Putting } \log_e D/d = 1 \text{ in exp. (i)]}$$

4.11 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.

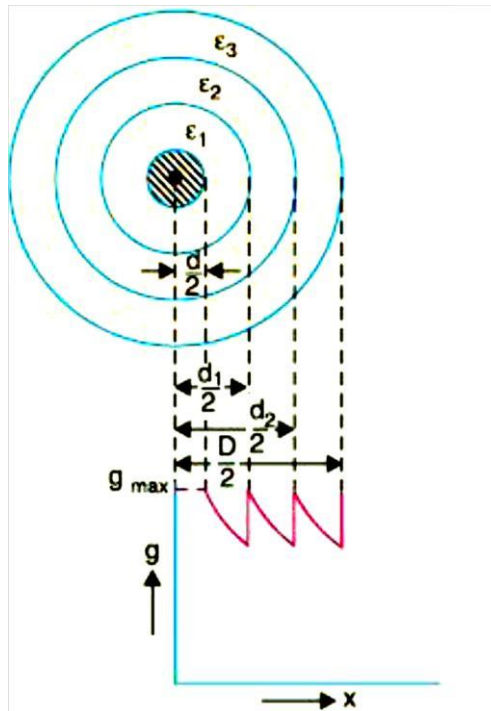
The maximum voltage that can be safely applied to a cable depends upon g_{\max} i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than g_{\max} . If a dielectric of high strength is used for a cable, 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 break down 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. There are three dielectrics of outer diameter d_1 , d_2 and D and of relative permittivity 1, 2 and 3 respectively. If the permittivity are such that $1 > 2 > 3$ and the three dielectrics are worked at the same maximum stress, then,

$$\text{or} \quad \frac{1}{\epsilon_1 d} = \frac{1}{\epsilon_2 d_1} = \frac{1}{\epsilon_3 d_2}$$

$$\epsilon_1 d = \epsilon_2 d_1 = \epsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g \, dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi \epsilon_0 \epsilon_1 x} dx$$

$$= \frac{Q}{2\pi \epsilon_0 \epsilon_1} \log_e \frac{d_1}{d} = \frac{g_{\max}}{2} d \log_e \frac{d_1}{d} \left[\because \frac{Q}{2\pi \epsilon_0 \epsilon_1} = \frac{g_{\max}}{2} d \right]$$

Similarly, potential across second layer (V_2) and third layer (V_3) is given by

$$V_2 = \frac{g_{\max}}{2} d_1 \log_e \frac{d_2}{d_1}$$

$$V_3 = \frac{g_{\max}}{2} d_2 \log_e \frac{D}{d_2}$$

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

$$= \frac{g_{\max}}{2} \left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2} \right]$$

$$V' = \frac{g_{\max}}{2} d \log_e \frac{D}{d}$$

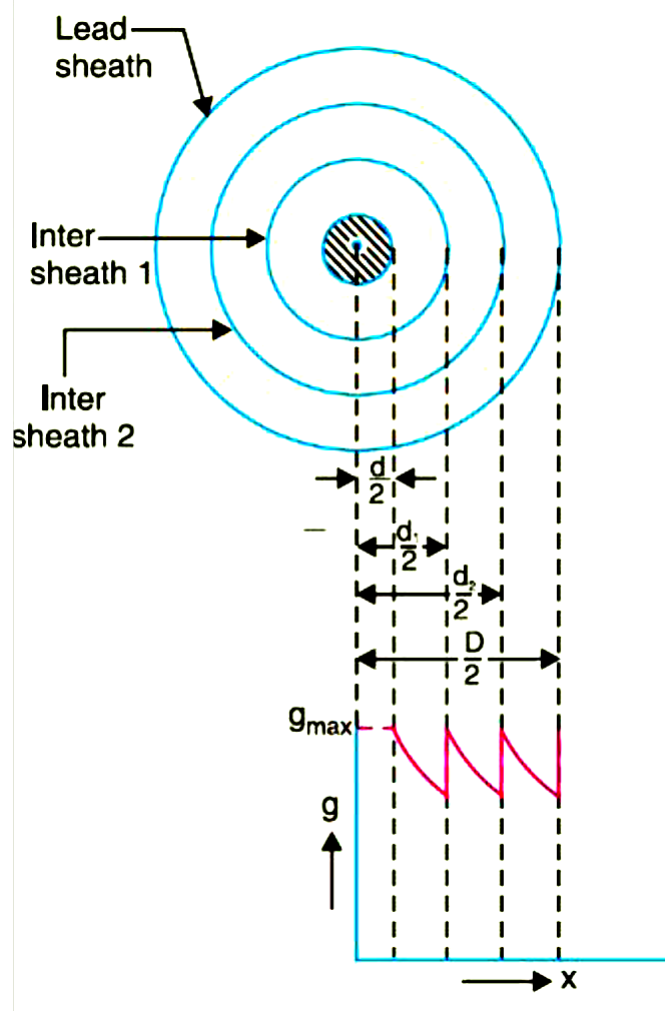
$$V = \frac{g_{1\max}}{2} d \log_e \frac{d_1}{d} + \frac{g_{2\max}}{2} d_1 \log_e \frac{d_2}{d_1} + \frac{g_{3\max}}{2} d_2 \log_e \frac{D}{d_2}$$

If the cable had homogeneous dielectric, then, for the same values of d , D and g_{max} , the permissible potential difference between core and earthed sheath would have been

$$V' = \frac{g_{max}}{2} d \log_e \frac{D}{d}$$

(ii) Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at 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 intersheaths of diameters d_1 and d_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials. Let V_1, V_2 and V_3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each intersheath,

therefore, each sheath can be treated like a homogeneous single core cable Maximum stress between core and inter sheath 1 is

$$\begin{aligned} g_{1max} &= \frac{V_1}{\frac{d}{2} \log_e \frac{d_1}{d}} \\ \text{Similarly, } g_{2max} &= \frac{V_2}{\frac{d_1}{2} \log_e \frac{d_2}{d_1}} \\ g_{3max} &= \frac{V_3}{\frac{d_2}{2} \log_e \frac{D}{d_2}} \end{aligned}$$

Since the dielectric is homogeneous, the maximum stress in each layer is the same i.e.,

$$\begin{aligned} \therefore \quad g_{1max} &= g_{2max} = g_{3max} = g_{max} \text{ (say)} \\ \frac{V_1}{\frac{d}{2} \log_e \frac{d_1}{d}} &= \frac{V_2}{\frac{d_1}{2} \log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2} \log_e \frac{D}{d_2}} \end{aligned}$$

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

$$V = V_1 + V_2 + V_3$$

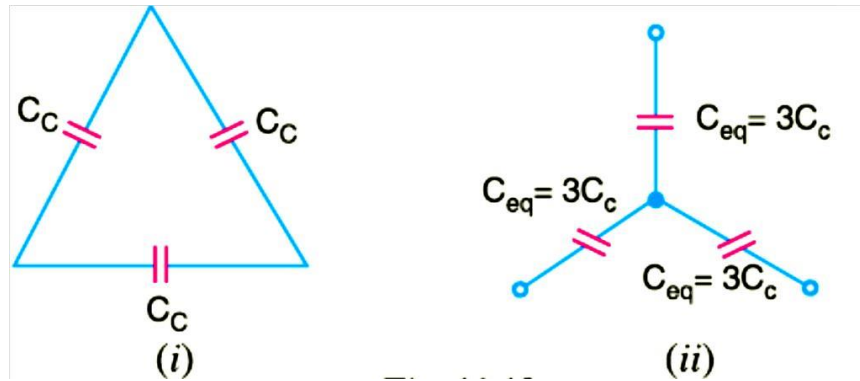
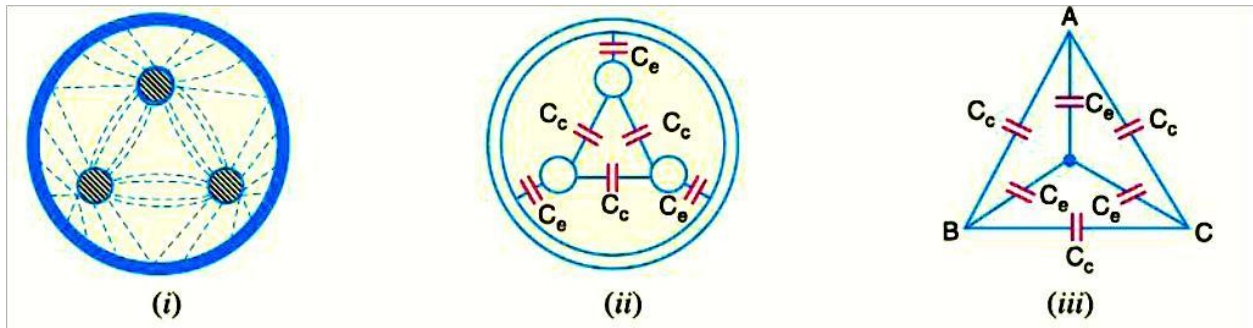
Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the inter sheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable losses in the inter sheaths due to charging currents. For these reasons, inter sheath grading is rarely used.

Capacitance of 3-core Cable

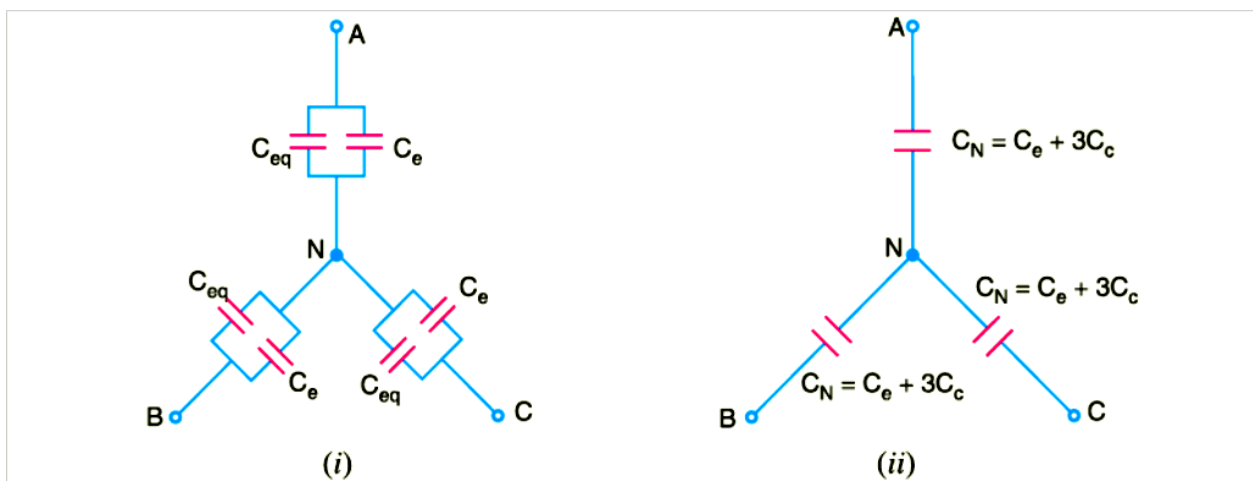
The capacitance of a cable system is much more important than that of overhead line because in cables

- (i) conductors are nearer to each other and to the earthed sheath
- (ii) they are separated by a dielectric of permittivity much greater than that of air.

Fig. shows a system of capacitances in a 3-core belted cable used for 3-phase system. Since potential difference exists between pairs of conductors and between each conductor and the sheath, electrostatic fields are set up in the cable as shown in Fig (i). These electrostatic fields give rise to core-core capacitances C_c and conductor-earth capacitances C_{ce} shown in Fig.(ii). The three C_c are delta connected whereas the three C_{ce} are star connected, the sheath forming the star point



They lay of a belted cable makes it reasonable to assume equality of each C_c and each C_e . The three delta connected capacitances C_c (i) can be converted into equivalent star connected capacitances as shown in Fig. It can be easily *shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c i.e. $C_{eq} = 3C_c$. The system of capacitances shown in Fig.(iii) reduces to the equivalent circuit shown in Fig. Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance See Fig.



$$C_N = C_e + C_{eq}$$

$$= C_e + 3C_c$$

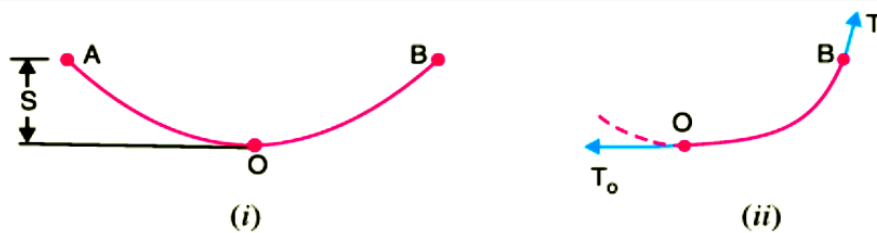
If V_{ph} is the phase voltage, then charging current I_C is given by ;

$$\begin{aligned}
 I_C &= \frac{V_{ph}}{\text{Capacitive reactance per phase}} \\
 &= 2 \pi f V_{ph} C_N \\
 &= 2 \pi f V_{ph} (C_e + 3C_c)
 \end{aligned}$$

4.12 MECHANICAL DESIGN OF TRANSMISSION LINE

4.12.1 SAG IN OVERHEAD LINES

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag. The difference in level between points of supports and the lowest point on the conductor is called sag. Following Fig. shows a conductor suspended between two equal level supports A and B. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is O and the sag is S. The following points may be noted



- (i) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.
- (ii) The tension at any point on the conductor acts tangentially. Thus tension T_0 at the lowest Point O acts horizontally as shown in Fig. (ii).
- (iii) The horizontal component of tension is constant throughout the length of the wire.
- (iv) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if T is the tension at the support B, then $T = T_0$

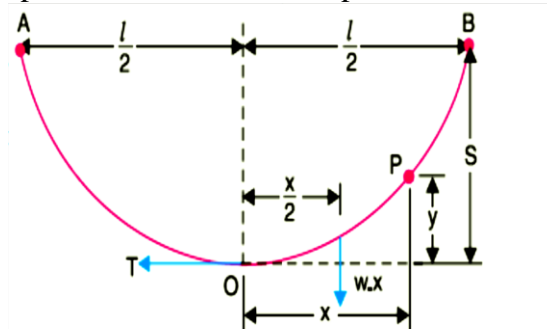
Conductor Sag And Tension

This is an important consideration in the mechanical design of overhead lines. The conductor sag should be kept to a minimum in order to reduce the conductor material required and to avoid extra pole height for sufficient clearance above ground level. It is also desirable that tension in the conductor should be low to avoid the mechanical failure of conductor and to permit the use of less strong supports. However, low conductor tension and minimum sag are not possible. It is because low sag means a tight wire and high tension, whereas a low tension means a loose wire and increased sag. Therefore, in actual practice, a compromise is made between the two.

4.12.2 CALCULATION OF SAG

In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations. It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be 2. We shall now calculate sag and tension of a conductor when (i) supports are at equal levels and (ii) supports are at unequal levels.

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.8.2. 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

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 w_x of conductor acting at a distance $x/2$ from O.
- (b) The tension T acting at O .

Equating the moments of above two forces about point O, we get,

$$Ty = wx \times \frac{x}{2}$$

or
$$y = \frac{wx^2}{2T}$$

The maximum dip (sag) is represented by the value of y at either of the supports A and B.

At support A, $x = l/2$ and $y = S$

\therefore
$$\text{Sag } S = \frac{w(l/2)^2}{2T} = \frac{wl^2}{8T}$$

(ii) When supports are at unequal levels. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig.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

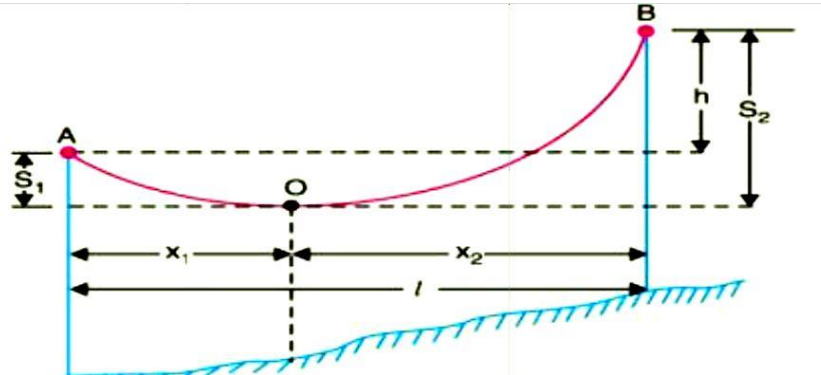
l = Span length

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



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

$$x_1 + x_2 = l$$

Now

$$S_2 - S_1 = \frac{w}{2T} [x_2^2 - x_1^2] = \frac{w}{2T} (x_2 + x_1) (x_2 - x_1)$$

\therefore

$$S_2 - S_1 = \frac{w l}{2T} (x_2 - x_1)$$

$$[\because x_1 + x_2 = l]$$

But

$$S_2 - S_1 = h$$

\therefore

$$h = \frac{w l}{2T} (x_2 - x_1)$$

or

$$x_2 - x_1 = \frac{2 T h}{w l}$$

...(ii)

Solving exps. (i) and (ii), we get,

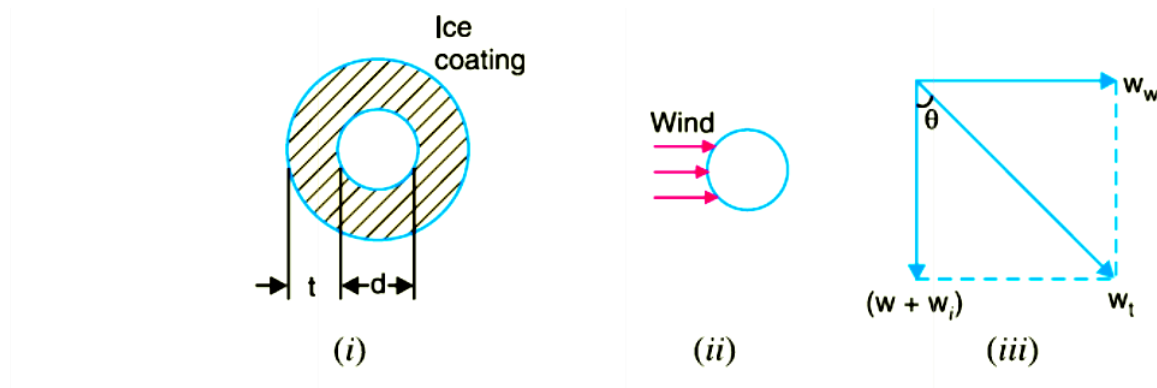
$$x_1 = \frac{l}{2} - \frac{T h}{w l}$$

$$x_2 = \frac{l}{2} + \frac{T h}{w l}$$

Having found x_1 and x_2 , values of S_1 and S_2 can be easily calculated.

4.12.3 EFFECT OF WIND AND ICE LOADING

The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards i.e., in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally i.e., at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in



Total weight of conductor per unit length is

$$w_t = \sqrt{(w + w_i)^2 + (w_w)^2}$$

Where w = weight of conductor per unit length

= conductor material density \cdot volume per unit length

w_i = weight of ice per unit length

= density of ice \cdot 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

$$= \text{wind pressure} \times [(d + 2t) \times 1]$$

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 sag is calculated by using the above formula.

iii) The vertical sag = $S \cos \theta$

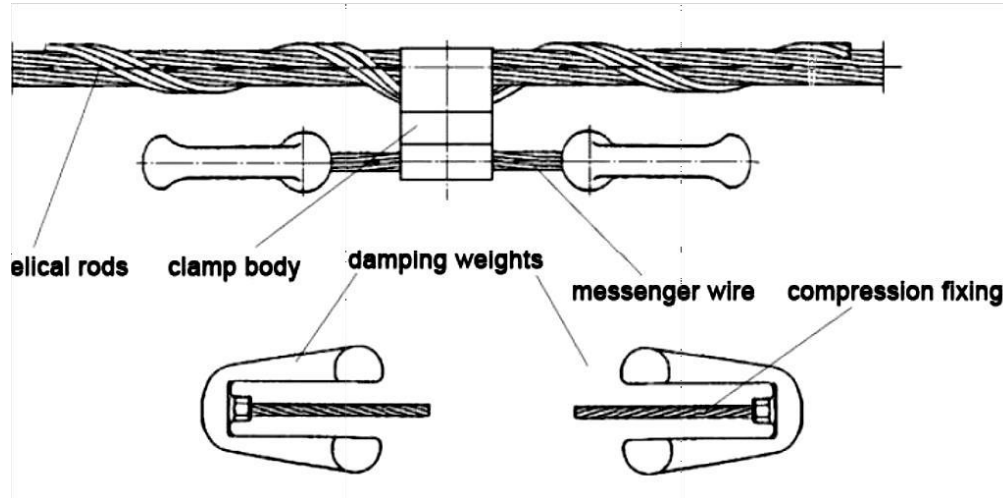
4.12.4 VIBRATION DAMPER

Aeolian vibrations mostly occur at steady wind velocities from 1 to 7 m/s. With increasing wind turbulences the wind power input to the conductor will decrease. The intensity to induce vibrations depends on several parameters such as type of conductors and clamps, tension, span length, topography in the surrounding, height and direction of the line as well as the frequency of occurrence of the vibration induced wind streams. In the wake of wind power plants (up to 3 x diameter of the rotor behind the plant) the wind velocity will be reduced up to 0,5 of the velocity of the free wind stream, so that lower wind velocities could be expected more frequently here. That's why the probability of a higher stresses for the conductors caused by wind-induced vibrations will be greater than without wind power plants. On the other hand the intensity of turbulences will increase which will hinder the arising of vibrations. The both important parameters for inducing vibrations, wind velocity and turbulence intensity, depends on the distance to the rotor and the height of it.

The investigations showed an increasing of damage probability on OHTL due to the wake of wind power plants of the factor 2,5 to 3,5 between one and three rotor diameters behind the plant which will cause an equivalent decreasing of lifetime of conductors and earth wires.

Vibration Damping

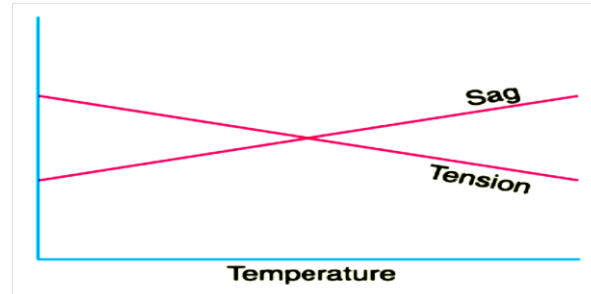
The knowledge of the mechanical self-damping of conductors is an important parameter for the energy balance calculation. The impedance and the efficiency of the vibration damper have been measured in relationship to frequency and used as input data for the energy balance.



The velocity of the damper clamp shall remain under the limit of 10 cm/s. The vibration dampers are tested at this vibrating velocity in an endurance test. They must stand at least 100 million vibrations without damages. If the velocity of the damper clamp remains beneath the value of 10 cm/s the bending stresses remain in the endurance range so that damages could not be expected.

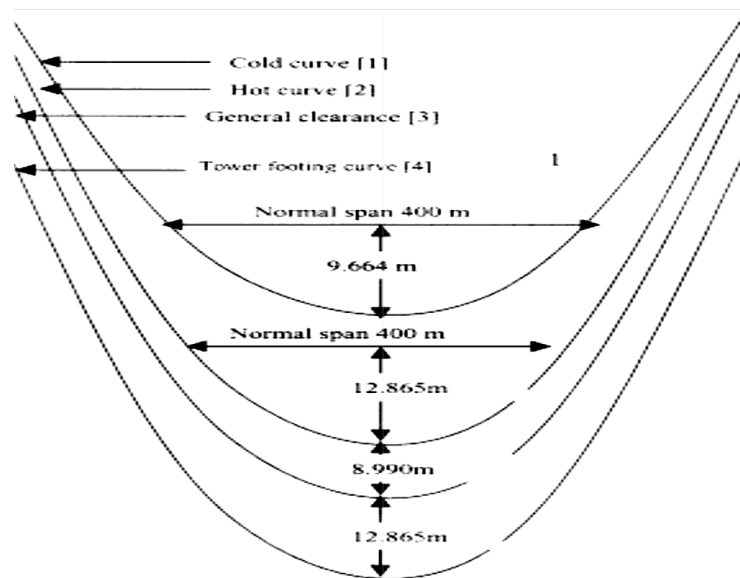
4.12.5 STRINGING CHART

For use in the field work of stringing the conductors, temperature-sag and temperature tension charts are plotted for the given conductor and loading conditions. Such curves are called stringing charts (see Fig). These charts are very helpful while stringing overhead lines.



4.12.6 SAG TEMPLATE

A Sag Template is a very important tool with the help of which the position of towers on the Profile is decided so that they conform to the limitations of vertical and wind loads on any particular tower, and minimum clearances, as per I.E. Rules, required to be maintained between the line conductor to ground, telephone lines, buildings, streets, navigable canals, power lines, or any other object coming under or near the line.



A Sag Template is specific for the particular line voltage, the conductor used and the applicable design conditions. Therefore, the correct applicable Sag Template should be used. A Sag Template consists of a set of parabolic curves drawn on a transparent celluloid or a crylic clear sheet duly cut in over the maximum conductor sag curve to allow the conductor curve to be drawn and the lowest points of the conductor sag to be marked on the profile when the profile is

placed underneath it.

The set of curves in the sag template consists of:

(i) Cold or Uplift Curve' showing sag of conductor at minimum temperature (minus 2.5°C) and still wind.

(ii) Hot or Maximum Sag Curve' showing maximum sag of conductor at maximum temperature and still wind including sag tolerances allowed (normally 4%), if any, and under maximum ice condition wherever applicable.

(iii) 'Ground Clearance Curve' which is drawn parallel to the 'Hot or Maximum Sag Curve' and at a distance equal to the specified minimum ground clearance for the relevant voltage.

(iv) 'Tower Footing Curve' which is drawn parallel to the 'Ground Clearance Curve' and separated by a minimum distance equal to the maximum sag at the basic design span.

QUESTIONS :

Q.No	Question
1	What is inter-sheath grading?
2	Identify the insulating materials used in cables?
3	Define insulation resistance?
4	List advantages of underground cables in distribution systems?
5	List out the methods of improving string efficiency
6	What are the requirements of insulators?
7	List the advantages of suspension type insulators over pin type insulators?
8	What is grading of cables?
9	Define string efficiency
10	Illustrate the types of cable based on voltage level
11	What is sag
12	What are the two types of supports used and when they are used?

Q.No	Question
1	Draw a neat sketch and explain the following <ol style="list-style-type: none">3-core belted cableH-type cableS.L. type cable
2	A single core 66 kV cable working on 3-phase system has a conductor diameter of 2 cm. and a sheath of inside diameter 5.3 cm. If two intersheaths are introduced in such a way that the stress varies between the same maximum and minimum in the three layers, Solve for: <ol style="list-style-type: none">positions of intersheaths

- ii. voltage on the intersheaths
 - ii. maximum and minimum stress
- 3 Each line of a 3-phase system is suspended by a string of 3 identical insulators of self-capacitance C farad. The shunt capacitance of connecting metal work of each insulator is $0.2 C$ to earth and $0.1 C$ to line. Determine the string efficiency of the system if a guard ring increases the capacitance to the line of metal work of the lowest insulator to $0.3 C$
 - 4 Discuss any two methods to increase the value of string efficiency, with suitable sketches.
 - 5 Explain any two methods of grading of cables with necessary diagrams
 - 6 With a neat sketch, explain the following:
 - a. pin type insulators
 - b. Suspension type insulators
 - c. Also list out the advantages of suspension type over pin type.
 - 7 Deduce an approximate expression for sag in overhead lines when supports are at equal levels
 - 8 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, Estimate the sag for a safety factor of 2. Weight of 1 c.c. of ice is 0.91 gm.

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TRANSMISSION AND DISTRIBUTION – SEEA1402
UNIT V- RECENT TRENDS IN TRANSMISSION

V. RECENT TRENDS IN TRANSMISSION

Extra High Voltage AC (EHVAC) Transmission - Need, Advantages, Limitations -High Voltage Direct current Transmission (HVDC) - Terminal Equipment for HVDC Systems - Classifications, Advantages, Limitations - Economic Distance for HVDC - Comparison of EHVAC and HVDC Transmission -Interconnection of HVDC & AC Systems - Voltage Control of Lines -Introduction to FACTS Technology -SVC,TCSC,STATCOM, UPFC.

5.1 EXTRA HIGH VOLTAGE ALTERNATING CURRENT(EHVAC)

The first 735 kV system was commissioned in Canada in 1965. Since then, voltage levels up to 765 kV have been introduced in Russia with neighboring countries, U.S.A, South Africa, Brazil, Venezuela and South Korea. The general trend of 800 kV investments is indicated in the diagram, which shows the total capacity of power transformers and generator step-up transformers for 800kV delivered by ABB. Since the 90's, However, plans are under way for future introduction of 800 kV in India and China.

5.1.1 Extra High Voltage (EHV)Transmission system

As per present terminology, voltages less than 300 kV are termed as High Voltages. The voltages in the range of 300 kV to 765 kV are known as Extra High Voltages (EHV). The voltages which are 765 kV are termed as Ultra High Voltage (UHV). In India, [transmission](#) voltage ranges from 66 kV to 400 kV ([RMS value](#) of line to line voltage in three phase system). There are several advantages of **extra high voltage transmission**. In EHV AC lines additional parallel three-phase line is always provided to ensure continuity of power supply and stability of line. A long EHV AC line is always double circuit line with intermediate substations at an interval of 250 km to 400 km for compensating reactive power. Electrical energy is generated at a voltage of about 11 kV. Then it is stepped up to 132, 220 or 400kV for transmission.

Electrical power [transmission](#) is preferred at high voltages because it has many advantages.

The advantages of extra high voltage transmission will be obvious from the following discussion.

Power transmitted is given by

$$P = \sqrt{3} V I \cos \phi$$

Where, V = transmission voltage, I = load current, $\cos \phi$ = load power factor.

$$\text{Or Load current, } I = P / (\sqrt{3} V \cos \phi)$$

From above expression, it is clear that for a constant power and power factor, the load current is inversely proportional to the transmission voltage. In simple words, as we increase the transmission voltage, the load [current](#) decreases.

Reasons for adoption of Extra High Voltage (EHV) Transmission system. This decrease in load current results in following advantages:

- As current gets reduced, size and volume of conductor required also reduces for transmitting the same amount of power.
- Voltage drop in line ($3IR$) reduces and hence [voltage regulation of the line](#) is improved.
- Line losses ($3I^2R$) gets reduced which results in the increase in [transmission line efficiency](#).
- Power handling capacity of the line increases as we increase the transmission voltage. It is proportional to the square of operating voltage.
- The cost related to tower, insulators and different types of equipment are proportional to voltage rather than the square of voltage.
- Thus the net capital cost of transmission line decreases as voltage increases. Therefore, a large power can be transmitted with high voltage transmission lines economically.
- The total line cost of per MW per km decreases considerably.
- The operation of EHV AC system is simple, reliable and can be adopted easily.
- The lines can be easily tapped and extended.

5.1.2 Problems involved in Extra High Voltage (EHV) Transmission system

The major problems in this system are as under.

- [Corona loss](#) is a big problem at higher voltages. This may further increase in bad weather conditions.
- It increases radio interference.
- The height of towers and insulation increases with increase in transmission voltage.
- The cost of different types of equipment and switchgear required for transmission increases with increase in transmission voltage.
- The high voltage lines produce electrostatic effects which are injurious to human beings and animals.

There are certain limitations in the transmission of power by EHV ac system. These limitations and design aspects are discussed below:

1. Stability Considerations:

Power transferred is expressed as:

$$P = \frac{V_S V_R}{X} \sin \delta \text{ watts per phase}$$

if resistance and shunt leakance of the transmission line are neglected.

For equal terminal voltages (i.e. $V_S = V_R = V$)

$P = \frac{V^2}{X} \sin \delta$ watts per phase or $\frac{(kV)^2}{X} \sin \delta$ MW for 3 phases where kV is the line voltage in kilovolts.

Maximum steady state transfer of power takes place theoretically for δ

$= 90^\circ$ but in actual practice δ is kept within limits of 20° to 30° at fullload. Taking $X = 0.3475 \Omega/\text{km}$ and $\delta = 30^\circ$, we have,

$$P = \frac{kV^2}{0.3475 l} \sin 30^\circ = 1.43 \frac{(kV)^2}{l} \text{ MW where } l \text{ is the length of line in km.}$$

If the line operates at natural load given by the expression:

$$P = VI = V \times \frac{V}{Z_C} \text{ watts or } \frac{(kV)^2}{Z_C} \text{ MW}$$

where Z_C is surge impedance and is equal to $\sqrt{\frac{L}{C}}$ ohms.

$$\text{then } \frac{1.43 \times (kV)^2}{l} = \frac{(kV)^2}{Z_C} \quad \text{or} \quad l = 1.43 Z_C \text{ kilometres}$$

- Thus we see that the theoretical length of a transmission line in km that can be operated on its natural load and load angle of 30° without loss of stability only is 1.43 times surge impedance (which comes out to be about 500 km).
- The transmission distance in EHV ac systems is, therefore, limited. This limitation is overcome by use of special equipment such as series capacitors or shunt reactors.

2. Current Carrying Capacity:

- The loading of overhead line conductors does not depend on the thermal considerations.
- However, for overhead transmission lines operating at voltage upto 220 kV, the conductor size is determined on the basis of its continuous and short-term current carrying capacity
- In case of underground cables, however, both thermal current limit and charging current are very important and that is why the underground cable is never operated beyond its natural load.

- Also the cost of cable is very high in comparison to that of an overhead line; therefore use of underground cables is limited in high voltage systems.

3. Ferranti Effect:

- We know that with the capacitive load on the line the receiving-end voltage is higher than sending-end voltage.
- This increase is of the order of 1.5 per cent for 160 km, 13 per cent for 500 km and 100 per cent for 960 km.
- Also there is a rise in sending- end voltage whenever the load on the generator is thrown off suddenly. Care is also to be taken from these aspects in case of ac transmission system.
- Voltage rise, due to Ferranti effect, is controlled by using shunt reactors at the load end.

4. Surge Impedance Loading:

- Surge impedance loading (SIL) of a transmission line is defined as the load at the receiving end which is equivalent to $\sqrt{L/C}$.
- The surge impedance loading for a transmission line is given as V^2/Z_0 watts per phase. SIL is also called the natural load.
- then the line carries natural load, the voltage along the entire length of line is the same.
- Other problems include Aeolian vibrations and galloping.
- The problem of galloping can, however, is controlled by applying weights at different locations of the line span.

6. Environment and Biological Aspects:

- EHV/UHV lines are designed such that maximum electrostatic field gradient does not exceed 9 kV/m at mid span under the line near the ground level.
- It has been found that very low frequency magnetic fields even of weak intensities can affect certain cellular processes.
- Induced current densities below 10 mA/m^2 have no significant biological effect. Currents $10\text{-}100 \text{ mA/m}^2$ cause minor biological effects. Current densities exceeding 100 mA/m^2 cause health hazards.
- Safe line to ground clearance of 20 m at mid span is recommended for 400 kV lines and 24 m for 1,100 kV lines. This permits movement of vehicles safely.

7. Route Clearance:

- EHV/UHV transmission lines are generally constructed over different terrain including dense forests, hilly areas and agricultural land, and clearance of minimum ROW is very important.

- Generally the trees are not taller than 10 m. Only dry trees need to be cleared from the ROW of transmission lines because a live tree is found to be well grounded through its sap, has small power loss and little chance of burning.
- It has also been found that the dry tree burning can occur if an induced voltage exceeding 100 kV occurs and potential of 100 kV can exist within a radius of 6 m from 765 kV line. So a minimum clearance of 6 m from 765 kV line conductors is essential.

8. Conductor Material:

- ACSR conductors are universally employed for overhead transmission lines.
- Necessary data about ACSR bundle conductors used for ac transmission lines is given below in tabular form:

Normal voltage in kV	Highest Voltage in kV	Phase Spacing in Metres	Sub-conductor Diameter in mm	Number of Sub-conductors Per Phase
230	245	6	25	1
345	365	8.3		2
500	550	11		3
765	800	15.3		4
1,100	1,200	20		8

9. Span, Number of Circuits, Conductor Configuration:

- For a high voltage line the economical value of span is 200-300 m, whereas for 400 kV line it is 350-400 m
- If two three-phase lines are on the same tower and are identical in construction and electrically in parallel then they have the same reactance X . The inductive reactance of the single equivalent circuit becomes $X/2$ and hence the power transfer capability is doubled. Double-circuit lines are in common use. They have additional advantage that continuity of supply is maintained over one line, though with reduced capability, while the other line is out of service for maintenance or repair.
- Each circuit of a double circuit line is usually designed for 75% of the line capacity. In India, both single and double circuit lines exist in the high voltage and extra high voltage class (66, 132, 220 and 400 kV). The number of circuits is determined from the SIL.
- Vertical configuration has been found the most economical for double circuit lines. For single circuit lines, horizontal or L type configurations are most suitable.

10. Insulation Coordination:

- Transmission lines and substations are subjected to overvoltages due to switching, lightning, faults, resonance and other causes.
- The surge arrestors are provided at strategic locations to protect the line insulation and substation equipment from transient and temporary overvoltages.

- In general there are three types of overvoltages viz. switching overvoltages, temporary overvoltages and overvoltages due to lightning. Switching overvoltages are caused due to energization of lines, reclosing, fault interruption, load throw, out of phase switching and sudden switch-off of a line.
- The temporary overvoltages at power frequency are due to sudden loss of load, disconnection of inductive loads, connections of capacitive loads, etc.
- For EHV and UHV transmission lines the switching overvoltages become the limiting factor in the design of insulation levels and arrester characteristics.
- Once the line is designed adequately against switching overvoltages, it is capable of encountering temporary overvoltages.
- It has also been found that overvoltages due to lightning are not very important for EHV/UHV transmission lines.

.11. Series Compensation:

- Series compensation is an important method of improving the performance of EHV transmission lines.
- It consists of capacitors connected in series with the line at suitable locations and thus opposes directly the effect of series inductive reactance of the line.
- It increases the power handling capacity and reduces the voltage regulation of a transmission line.

12. Shunt Compensation:

- In EHV transmission systems, shunt compensation is invariably essential.
- Shunt compensation with capacitive VARs is used to inject reactive power and control the receiving-end voltage whereas shunt reactor compensation is used to neutralize the Ferranti effect.
- For shunt compensation, static compensation employing capacitors and reactors or synchronous compensation using synchronous phase modifier may be employed.

5.2 HIGH VOLTAGE DIRECT CURRENT (HVDC)

- The first HVDC system for ± 500 kV and above was the Cabora Bassa project, commissioned in 1979.
- The major HVDC investments at these voltage levels were made in the late 80's and early 90's.
- However, an increasing interest in high-capacity HVDC links have been noted in recent years, as seen from the diagram, which shows all HVDC projects for ± 500 kV and above.
- The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long.
- From a technical point of view, there are no special obstacles against higher DC voltages.

Present solutions are extendable to e.g. ± 800 kV when the need arises.

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5.2.1 Advantages of HVDC Transmission

- The [HVDC system](#) needs only one or two conductors, therefore, cost of conductor reduces considerably. Hence it is very economical for bulk transmission of power over long distances. The cost of towers and insulators is also reduced.
- Due to [corona loss](#) considerations, when the AC system voltage exceeds 200 kV 'bundle conductors' are required. With [HVDC transmission](#) this limit is 400 kV.
- The radio interference is less and [corona loss](#) is low with HVDC system.
- The transmission losses are less with the DC system.
- In the HVDC system rectifier unit can be converted into inverter unit very easily and vice versa. Thus in this system, power flow can be reversed very easily.
- The charging current considerations at 400 kV for AC cables limits the 'critical length' to 40 km. HVDC cables do not need such charging current and there is no such limit for DC cables. Cables in the DC system do not suffer from the high [dielectric loss](#). The [skin effect](#) is also low in the DC system.
- DC power can be transmitted between two systems operating at different frequencies. This is not possible with AC transmission.
- Greater power transmission per conductor is possible with HVDC system.
- There are no serious problems of [voltage regulation](#) as there is no reactance drop in this system.
- AC cables require shunt inductors for compensation. DC can be compensated by capacitors which are cheaper and with little-associated losses. Further, these capacitors can be used as 'harmonic filter' also.
- In the development stage, a DC system can be worked with a single conductor and earth as the return. This is also an advantage under the emergency conditions.
- During fault with HVDC system, the grid control of the converter reduces the fault current significantly.
- Intermediate substations are not required in this system.
- Due to unidirectional stress, DC cable insulation has longer life.
- In case of insulation degradation, DC converter can be operated at a reduced voltage.

- Lightning has never struck two poles of a DC line together. However, in the case of AC, it is known to have struck two sections simultaneously. This increases the reliability of DC link and in many cases, shield wire can be dispensed with.

5.2.2 Disadvantages of HVDC Transmission

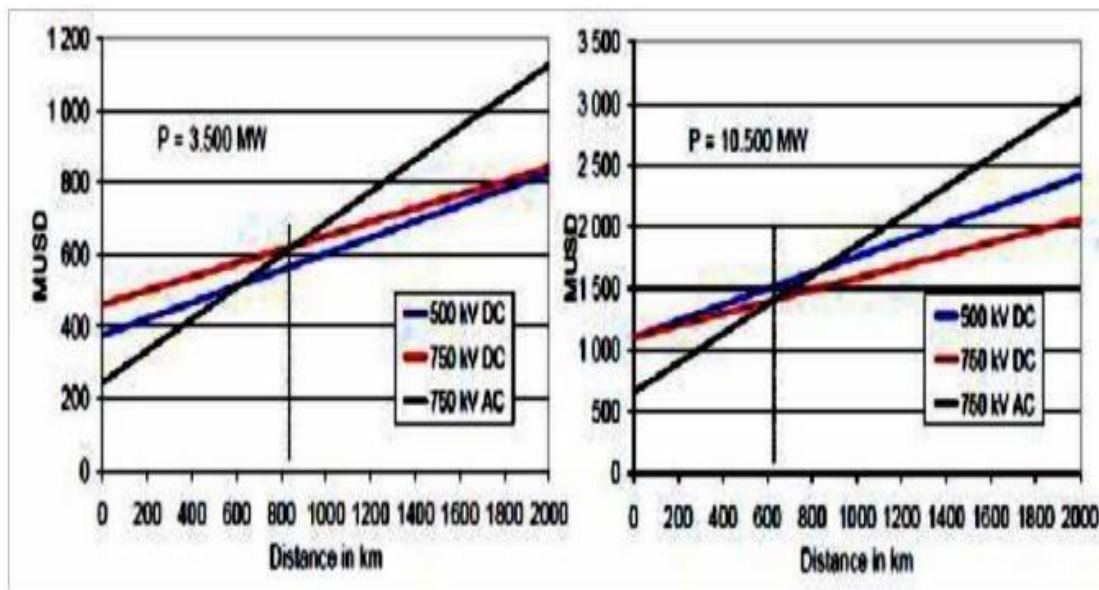
- This system is uneconomical if the length of the transmission line is less than 500 km as converters, inverters, and filters are required additionally in this system.
- DC circuit breaking is difficult and expensive.
- Filtration is very necessary for this system due to excessive generation of harmonics.
- Overload capacity of this system is low.
- As HVDC does not transmit reactive power, it has to supply locally if required.
- The maintenance of insulators in this system is more.
- There are additional losses in valves and converter transformers. These losses are continuous. Hence, a very efficient cooling system has to be provided.

5.3 ECONOMICAL COMPARISION and HVDC EHVAC

The trend of power electronic components, for use in the main circuit of an HVDC transmission, being developed means that the relative cost of HVDC transmissions is reduced as the components become cheaper as a result of continuing innovative technological developments. Thus a large converter station with a cost of 50 USD/kW is today cheaper in current dollars compared with the situation 20 years ago. The dc line is less costly compared with an 800 kV ac line. On the other hand, the converter station cost offsets the gain in reduced cost of the transmission line. Thus a short line is cheaper with ac transmission, while a longer line is cheaper with dc.

In a general comparison of HVDC vs. EHVAC power transmission, the design of the transmission lines and the related

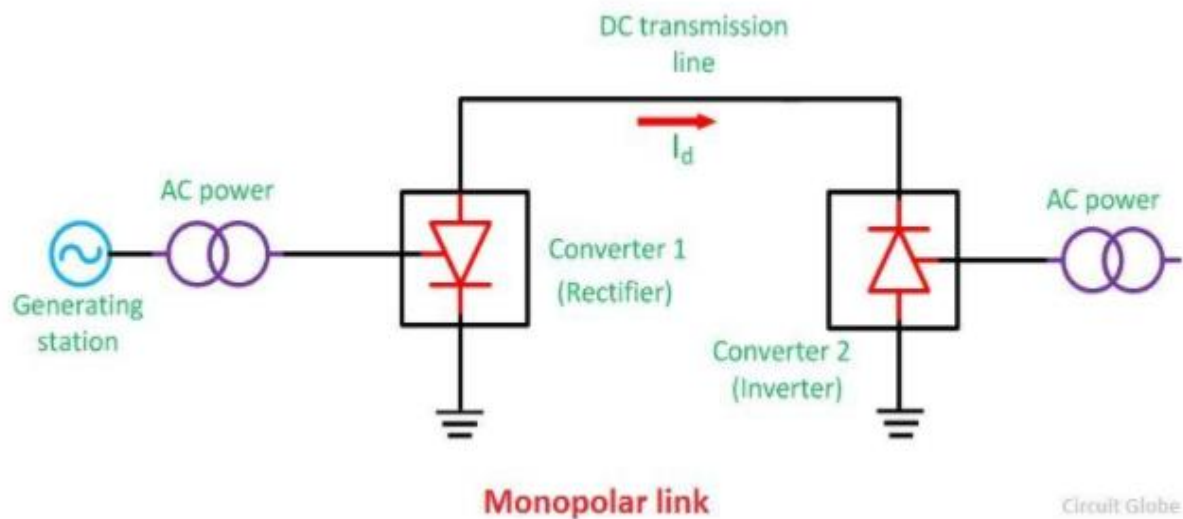
investment costs are of great importance. The aim of this paper has been to focus on the differences in the design of line insulation and conductor configuration, and its influence on the mechanical loads. For the line insulation, air clearance requirements are more critical with EHVAC due to the nonlinear behavior of the switching overvoltage withstand. The corona effects are more pronounced at AC voltage, therefore, larger conductor bundles are needed at higher system voltages. The altitude effects are more important to HVDC lines, since the lightning overvoltage withstand is the most sensitive insulation parameter with regard to air density. The mechanical load on the tower is considerably lower with HVDC due to less number of sub conductors required to fulfill the corona noise limits. The high transmission capacity of the HVDC lines, combined with lower requirements on conductor bundles and air clearances at the higher voltage levels, makes the HVDC lines very cost efficient compared to EHVAC lines. The cost advantage is even more pronounced at the highest voltage levels.



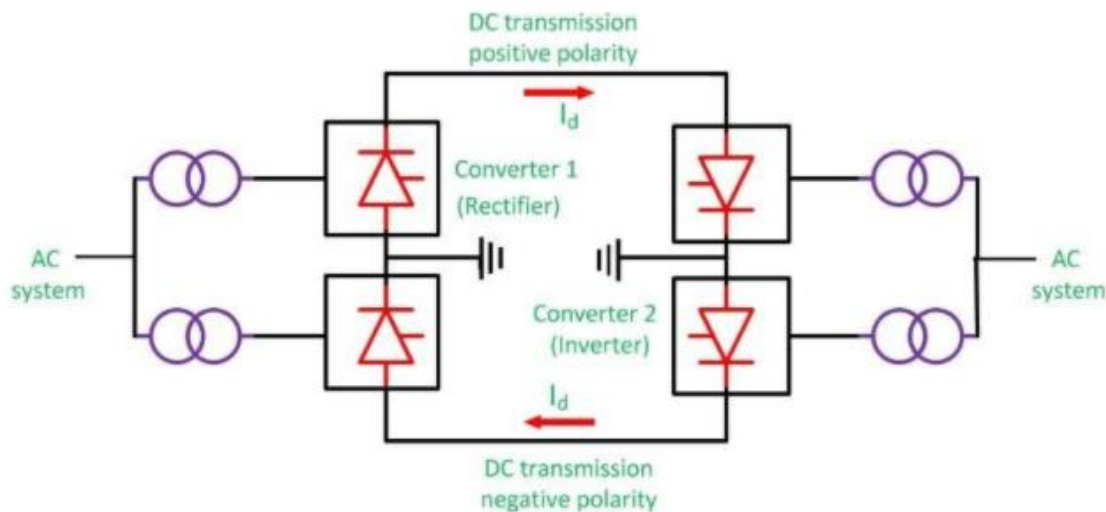
5.4 HVDC CLASSIFICATIONS

The HVDC transmission, which is economical for long distance power transmission, and for the interconnection of two or more networks that has different frequencies or voltages. For connecting two networks or system, various types of HVDC links are used. HVDC links are classified into three types. These links are explained below;

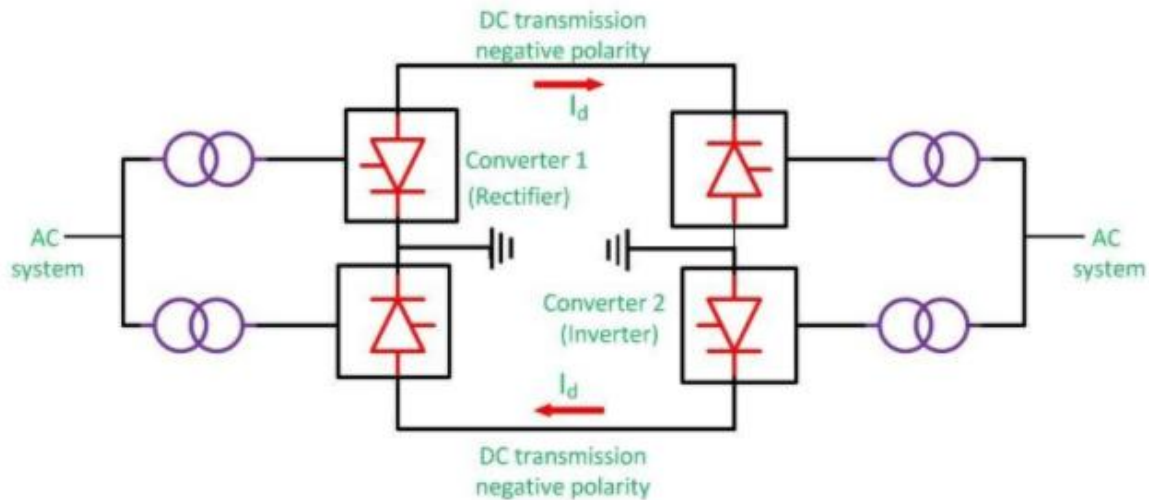
1. Monopolar link – It has a single conductor of negative polarity and uses earth or sea for the return path of current. Sometimes the metallic return is also used. In the Monopolar link, two converters are placed at the end of each pole. Earthing of poles is done by earth electrodes placed about 15 to 55 km away from the respective terminal stations. But this link has several disadvantages because it uses earth as a return path. The monopolar link is not much in use nowadays.



2. Bipolar Link– The Bipolar link has two conductors one is positive, and the other one is negative to the earth. The link has converter station at each end. The midpoints of the converter stations are earthed through electrodes. The voltage of the earthed electrodes is just half the **Bipolar link** voltage of the conductor used for transmission the HVDC.



3.Homopolar link– It has two conductors of the same polarity usually negative polarity, and always operates with earth or metallic return. In the homopolar link, poles are operated in parallel, which reduces the insulation cost.



5.5 COMPARISON OF HVDC AND EHVAC TRANSMISSION

S.No	HVDC Transmission Lines	HVAC Transmission Lines
1	For lines designed for same insulation It can carry as much power with level, it can carry more power with two conductors of the same size. conductors (positive and negative).	It can carry as much power with three number of conductors
2	For a given power level, it requires less right of way, cheaper towers, reduced conductor costs.	For given Power level, the cost of the towers and conductors are high
3	Cable insulation required is less	Cable Insulation strength is required more. Hence it consume high cost on the insulation factor.
4	The net power losses are reduced as the decreased the number of comductor usage	The power losses is very high as it has three number of conductors.

5	HVDC does not have skin effect hence the net operation cost get reduced.	Due to the skin effect, power losses increases, therefore the operation cost very increases as compared with HVDC transmission lines.
6	Dielectric losses is less	Dielectric losses is high
7	Corona loss and radio interference is less compared to that of A.C. This leads to the choice of economic size of conductors for D.C	Corona loss and radio interference is high and which causes high Operational cost
8	DC does not require shunt compensation. So In DC we do not want to install shunt compensation devices.	It is requires shunt compensation devices.
9	Terminal equipment such as converters inverters, filters cost is high	Terminal equipment cost is low
10	HVDC requires High maintenance cost. I.e failure of IGBTs leads to high cost. A 400 Volts FF300 model IGBTs are cost about \$2000, So think what about 500kV igt cost.	In AC No maintenance cost. Even We do not want to touch our system for a year.
11	DC Tranmission systems are more economical, if the transmitting distance is more than breake even point. The breaken even point will be 500 to 600 KM depending on the PU Units	For transferring power to Short distance, AC Tranmission power has more advantages.
S.No	HVDC	HVAC
1	Full Control on Power Transmitted: DC does not affect by the distance of the transmission line. In DC we can send constant power over long distance.	But In AC transmission, the tranmitting power is depending on the voltage ange. Hence power carrying capatity of the transmission line decreases after some

		distance. The power transfer is limited by the consideration of transient and steady state stability.
2	Voltage control: DC Converter station requires reactive power related to the line loading, the line itself does not require reactive power control	Voltage control is very complicated in AC transmission system due to line charging and inductive voltage drops. Voltage profile is flat due to surge impedance loading. AC transmission line needs reactive power control to maintain the same voltage at receiving end. The reactive power compensation is directly proportional to the length of the transmission line, hence the long distance transmission lines need high reactive power.
3	Fault current: DC line allows the fault current up to maximum rating of the line.	The fault current increases as the number of interconnection of AC system increases.
4	DC Does not require any line compensation devices because of the Inductor and capacitor characteristics on DC. Inductor acts as short circuit and capacitor acts as open circuit on DC	AC System Needs reactive power compensation components (shunt reactor) in long transmission lines to overcome line charging and stability limitations.
5	Interconnection problem: In DC Two systems are interconnected with different frequencies. Synchronization of DC tie lines, no need of co-ordinated control for inter connection.	Two systems can not be interconnected with different frequencies.
6	Ground Impedance: DC does not have any ground impedance, hence the ground can be taken as current return path.	But In AC system, the ground offers high magnitude of impedance, hence the ground

		current can not permitted for steady state operation.
7	Fast control to limit the fault current in DC: DC breakers in Two terminal DC links are avoided. At the same time the cost of DC circuit breakers are very high as compared with AC circuit breaker.	Circuit Breaker is compulsory.
8	Transformer can not be used to reduce the voltage level	Transformer is the heart of the AC power system. Which can be used to reduce the voltage level.

5.6 VOLTAGE CONTROL - INTRODUCTION

In a modern power system, electrical energy from the generating station is delivered to the ultimate consumers through a network of transmission and distribution. For satisfactory operation of motors, lamps and other loads, it is desirable that consumers are supplied with substantially constant voltage. Too wide variations of voltage may cause erratic operation or even malfunctioning of consumers' appliances. To safeguard the interest of the consumers, the government has enacted a law in this regard. The statutory limit of voltage variation is $\pm 6\%$ of declared voltage at consumers' terminals. The principal cause of voltage variation at consumer's premises is the change in load on the supply system. When the load on the system increases, the voltage at the consumer's terminals falls due to the increased voltage drop in

(i) alternator synchronous impedance

(ii) transmission line

(iii) transformer impedance

(iv) feeders and Condenser

(v) Distributors.

The reverse would happen should the load on the system decrease. These voltage variations are undesirable and must be kept within the prescribed limits (i.e. $\pm 6\%$ of the declared voltage). This is achieved by installing voltage regulating equipment at suitable places in the Voltage Control power system. The purpose of this chapter is to deal with important voltage control equipment and its increasing utility in this fast developing power system.

5.6.1 IMPORTANCE OF VOLTAGE CONTROL

When the load on the supply system changes, the voltage at the

consumer's terminals also changes.

The variations of voltage at the consumer's terminals are undesirable and must be kept within prescribed limits for the following reasons :

(i) In case of lighting load, the lamp characteristics are very sensitive to changes of voltage.

For instance, if the supply voltage to an incandescent lamp decreases by 6% of rated value, then illuminating power may decrease by 20%. On the other hand, if the supply voltage is 6% above the rated value, the life of the lamp may be reduced by 50% due to rapid deterioration of the filament.

(ii) In case of power load consisting of induction motors, the voltage variations may cause erratic operation. If the supply voltage is above the normal, the motor may operate with a saturated magnetic circuit, with consequent large magnetising current, heating and low power factor. On the other hand, if the voltage is too low, it will reduce the starting torque of the motor considerably.

(iii) Too wide variations of voltage cause excessive heating of distribution transformers.

This may reduce their ratings to a considerable extent.

It is clear from the above discussion that voltage variations in a power system must be kept to minimum level in order to deliver good service to the consumers. With the trend towards larger and larger interconnected system, it has become necessary to employ appropriate methods of voltage control.

5.6.2 LOCATION OF VOLTAGE CONTROL EQUIPMENT

In a modern power system, there are several elements between the generating station and the consumers. The voltage control equipment is used at more than one point in the system for two reasons.

Firstly, the power network is very extensive and there is a considerable voltage drop in transmission and distribution systems. Secondly, the various circuits of the power system have dissimilar load characteristics. For these reasons , it is necessary to provide individual means of voltage control for each circuit or group of circuits. In practice, voltage control equipment is used at :

(i) generating stations

(ii) transformer stations

(iii) the feeders if the drop exceeds the permissible limits

15.3 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.

1. 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.

(i) Tirril Regulator

(ii) 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.

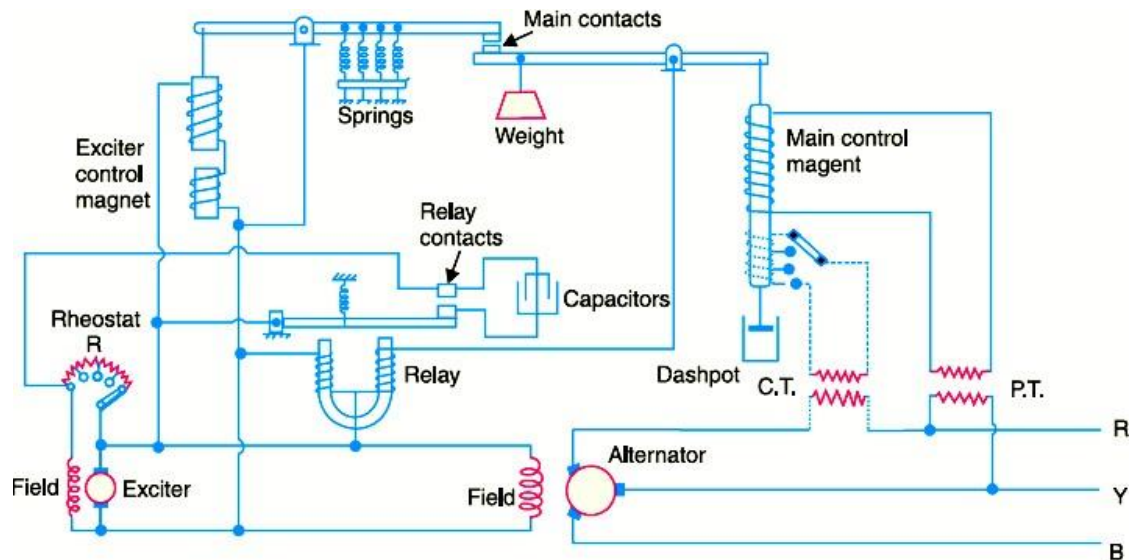
i) Tirril Regulator

In this type of regulator, a fixed resistance is cut in and cut out of the exciter field circuit of the alternator. This is achieved by rapidly opening and closing a shunt circuit across the exciter rheostat.

For this reason, it is also known as vibrating type voltage regulator.

Construction

Fig. shows the essential parts of a Tirril voltage regulator. A rheostat R is provided in the exciter circuit and its value is set to give the required excitation. This rheostat is put in and out of the exciter circuit by the regulator, thus varying the exciter voltage to maintain the desired voltage of the alternator.



(i) Main contact.

There are two levers at the top which carry the main contacts at the facing ends. The left- hand lever is controlled by the exciter magnet whereas the right hand lever is controlled by an a.c. magnet known as main control magnet.

(ii) Exciter magnet.

This magnet is of the ordinary solenoid type and is connected across the exciter mains. Its exciting current is, therefore, proportional to the exciter voltage. The counter balancing force for the exciter magnet is provided by four coil springs.

(iii) A. C. magnet.

It is also of solenoid type and is energised from a.c. bus-bars. It carries series as well as shunt excitation. This magnet is so adjusted that with normal load and voltage at the alternator, the pulls of the two coils are equal and opposite, thus keeping the right-hand lever in the horizontal position.

(iv) Differential relay.

It essentially consists of a U-shaped relay magnet which operates the relay contacts. The relay magnet has two identical windings wound differentially on both the limbs. These windings are connected across the exciter mains—the left hand one permanently while the right hand one has its circuit completed only when the main contacts are closed. The relay contacts are arranged to shunt the exciter-field rheostat R. A capacitor is provided across the relay contacts to reduce the sparking at the time the relay contacts are opened.

Operation

The two control magnets (i.e. exciter magnet and a.c. magnet) are so adjusted that with normal load and voltage at the alternator, their pulls are equal, thus keeping the main contacts open. In this position of main contacts, the relay magnet remains energised and pulls down the armature carrying one relay contact.

When the load on the alternator increases, its terminal voltage tends to fall. This causes the series excitation to predominate and the a.c. magnet pulls down the right-hand lever to close the main contacts. Consequently, the relay magnet is *de-energised and releases the armature carrying the relay contact. The relay contacts are closed and the rheostat R in the field circuit is short circuited.

It is worthwhile to mention here that exciter voltage is controlled by the rapid opening and closing of the relay contacts. As the regulator is worked on the overshooting the mark principle, therefore, the terminal voltage does not remain absolutely constant but oscillates between the maximum and minimum values. In fact, the regulator is so quick acting that voltage variations never exceed $\pm 1\%$.

In this type of regulator, exciter field rheostat is varied continuously or in small steps instead of being first completely cut in and then completely cut out as in Tirril regulator. For this purpose, a regulating resistance is connected in series with the field circuit of the exciter. Fluctuations in the alternator voltage are detected by a control device which actuates a motor. The motor drives the regulating rheostat and cuts out or cuts in some resistance from the rheostat, thus changing the exciter and hence the alternator voltage.

Fig. shows the schematic diagram of a Brown-Boveri voltage regulator. It also works on the “overshooting the mark principle” and has the following four important parts :

The control system is built on the principle of induction motor. It consists

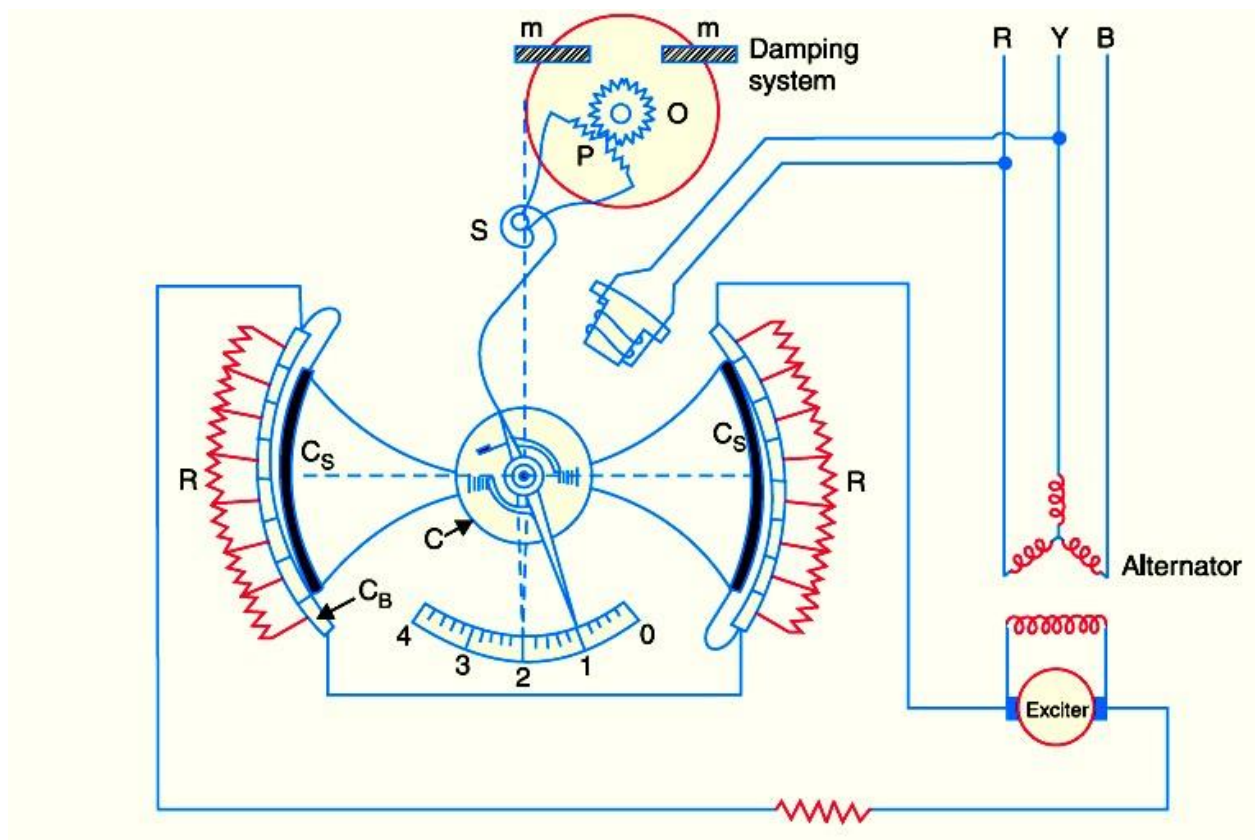


of two windings A and B on an annular core of laminated sheet steel. The winding A is excited from two of the generator terminals through resistances U and U' while a resistance R is inserted in the circuit of winding B. The ratio of resistance to reactance of the two windings are suitably adjusted so as to create a phase difference of currents in the two windings. Due to the phase difference of currents in the two windings, rotating magnetic field is set up. This produces electromagnetic torque on the thin aluminium drum C carried by steel spindle; the latter being supported at both ends by jewel bearings. The torque on drum C varies with the terminal voltage of the alternator. The variable resistance U' can also vary the torque on the drum.

If the resistance is increased, the torque is decreased and vice-versa. Therefore, the variable resistance U' provides a means by which the regulator may be set to operate at the desired voltage.

(ii) Mechanical control torque

The electric torque produced by the current in the split phase winding is opposed by a combination of two springs (main spring and auxiliary spring) which produce a constant mechanical torque irrespective of the position of the drum. Under steady deflected state, mechanical torque is equal and opposite to the electric torque.



(iii) Operating system

It consists of a field rheostat with contact device. The rheostat consists of a pair of resistance elements connected to the stationary contact blocks C_B . These two resistance sectors R are connected in series with each other and then in series with the field circuit of the exciter. On the inside surface of the contact blocks roll the contact sectors C_s .

When the terminal voltage of the alternator changes, the electric torque acts on the drum. This causes the contact sectors to roll over the contact blocks, cutting in or cutting out rheostat resistance in the exciter field circuit.

(iv) Damping torque

The regulator is made stable by damping mechanism which consists of an aluminium disc O rotating between two permanent magnets m . The disc is geared to the rack of an aluminium sector P and is fastened to the aluminium drum C by means of a flexible spring S acting as the recall spring. If there is a change in the alternator voltage, the eddy currents induced in the disc O produce the necessary damping torque to resist quick response of the moving system.

Operation

Suppose that resistances U and U' are so adjusted that terminal voltage of the alternator is normal at position 1. In this position, the electrical torque is counterbalanced by the mechanical torque and the moving system is in equilibrium. It is assumed that electrical torque rotates the shaft in a clockwise direction.

Now imagine that the terminal voltage of the alternator rises due to decrease in load on the supply system. The increase in the alternator voltage will cause an increase in electrical torque which becomes greater than the mechanical torque. This causes the drum to rotate in clockwise direction, say to position 3. As a result, more resistance is inserted in the exciter circuit, thereby decreasing the field current and hence the terminal voltage of the alternator. Meanwhile, the recall spring S is tightened and provides a counter torque forcing the contact roller back to position 2 which is the equilibrium position. The damping system prevents the oscillations of the system about the equilibrium position.

2. Tap-Changing Transformers

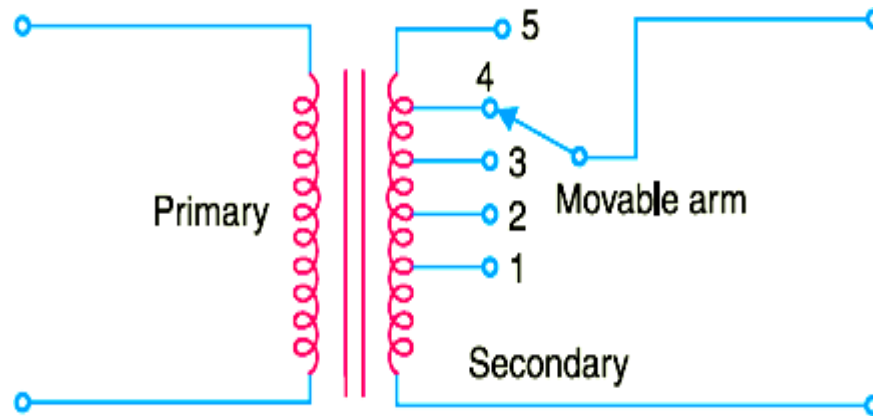
The excitation control method is satisfactory only for relatively short lines.

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.

(i) Off load tap-changing transformer.

Fig. shows the arrangement where a number of tapings 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

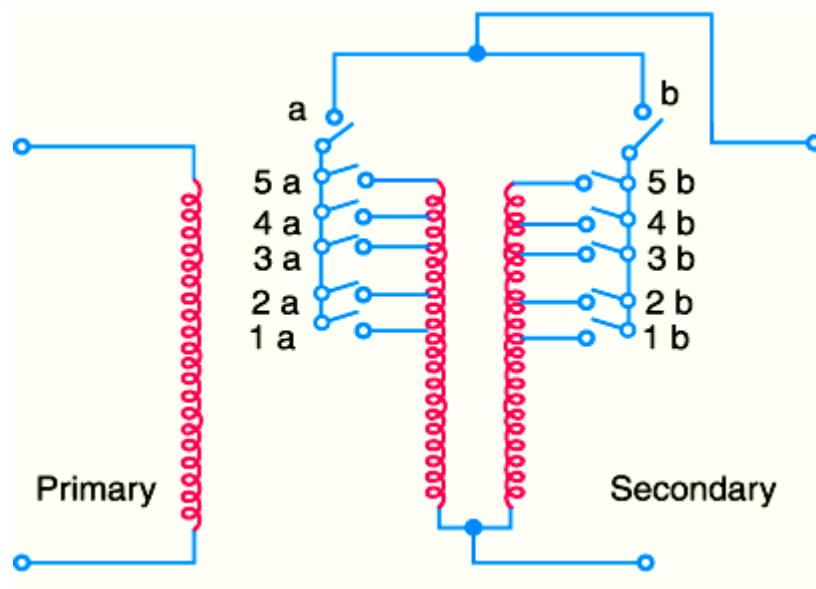


can be changed. Thus referring to Fig.

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. The principal disadvantage of the circuit arrangement shown in Fig. is that it cannot be used for tap-changing on load. Suppose for a moment that tapping is changed from position 1 to position 2 when the transformer is supplying load. If contact with stud 1 is broken before contact with stud 2 is made, there is break in the circuit and arcing results. On the other hand, if contact with stud 2 is made before contact with stud 1 is broken, the coils connected between these two tappings are short-circuited and carry damaging heavy currents. For this reason, the above circuit arrangement cannot be used for tap-changing on load.

(ii) 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 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.

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. 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.

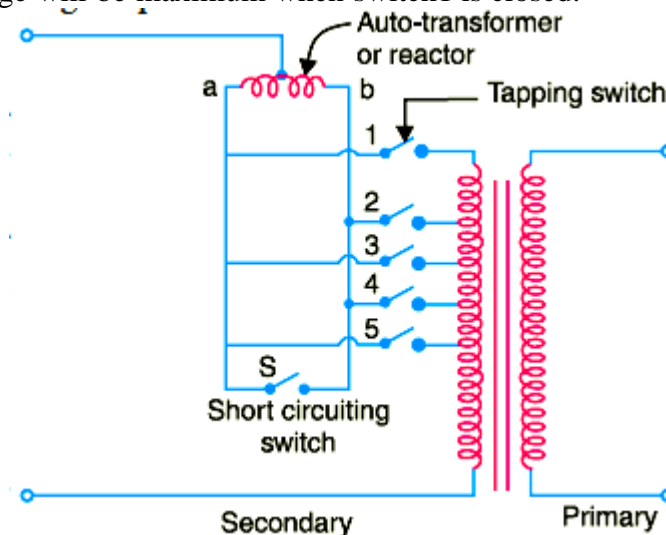
This method has the following disadvantages:

- (i) During switching, the impedance of transformer is increased and there will be a voltage surge.
- (ii) There are twice as many tappings as the voltage steps.

3. Auto-Transformer Tap-changing

Fig. 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 tapings and the other end bis connected to switches across even tapings. 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, 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.



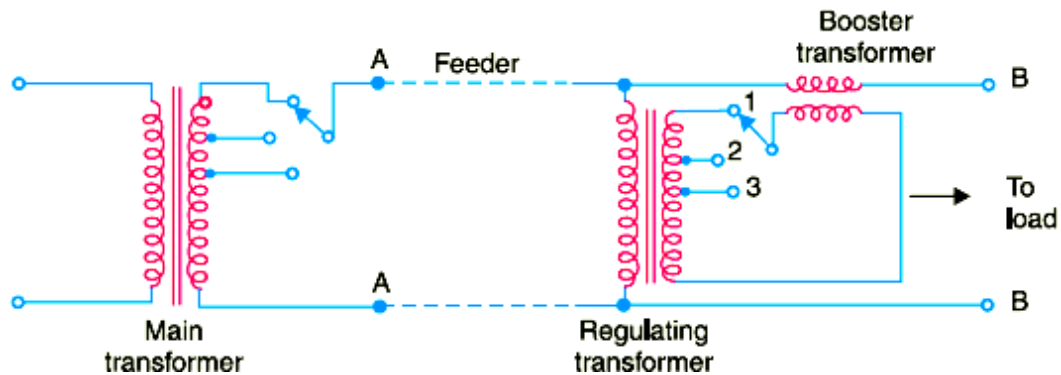
Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage. For this purpose, short-circuiting switch S is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed. In this way, tapping can be changed 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.

4. 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.

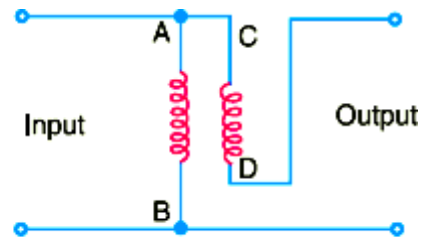
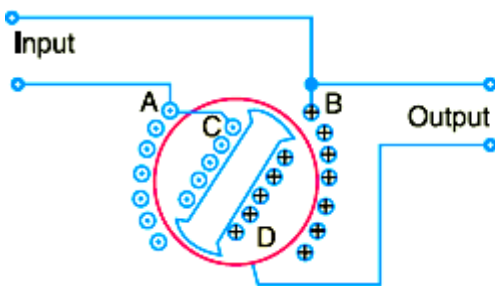
The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled. The primary of this transformer is supplied from a regulating transformer *fitted with on-load tap-changing gear. The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.



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 tapping 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. shows a three-phase booster transformer.

5. 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.



(i) Single-phase induction regulator.

A single phase induction regulator is illustrated in Fig. 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

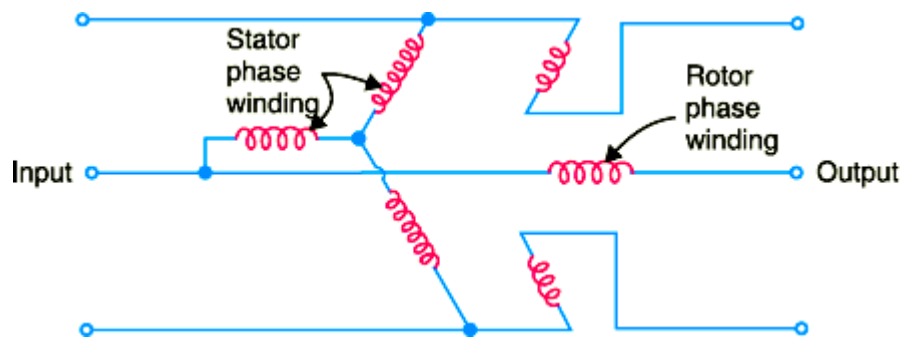
alternating voltage in the secondary winding CD. The magnitude of voltage induced in the secondary depends upon its position w.r.t. the primary winding. By adjusting the rotor to a suitable position, the secondary voltage can be varied from a maximum positive to a maximum negative value. In this way, 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.

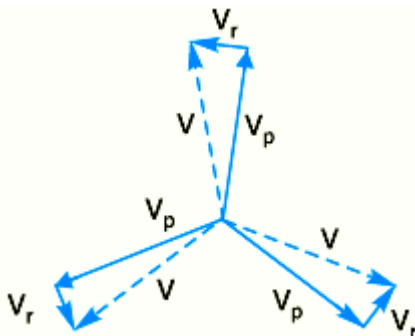
(ii) Three-phase induction regulator

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 poly phase currents flow through the primary windings, a rotating field is set up which induces an e.m.f. in each of the rotor windings. 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.



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 p induction regulators are used to regulate the voltage of feeders and in connection with high voltage oil testing transformers.

6. Voltage Control by Synchronous Condenser

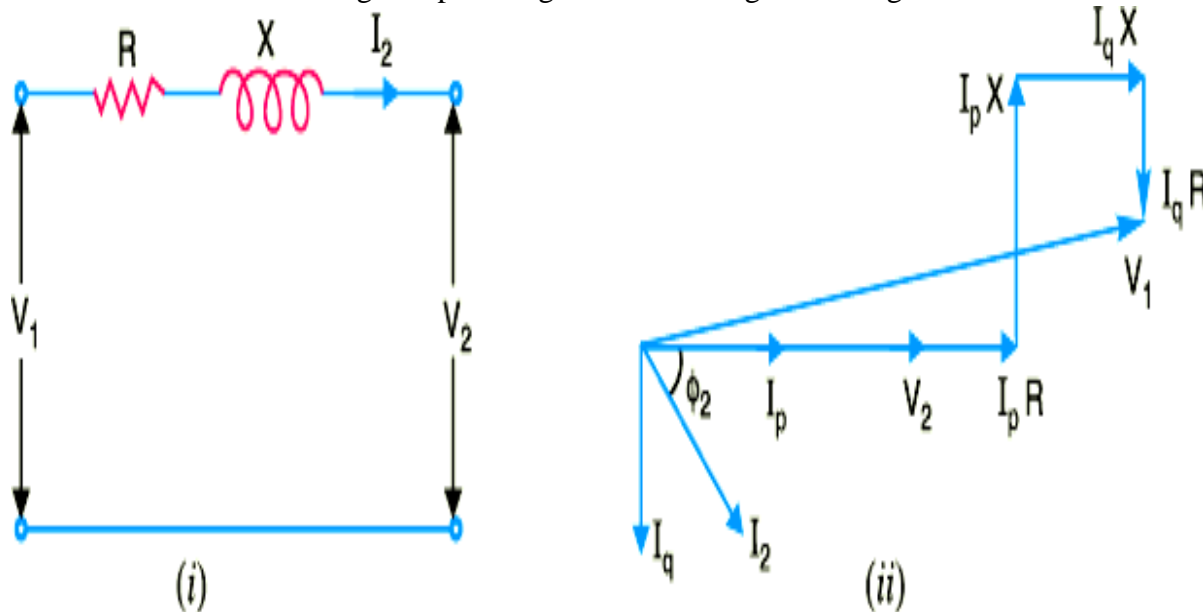
The voltage at the receiving end of a transmission line can be controlled by installing specially designed synchronous motors called *synchronous condensers at the receiving end of the line. The synchronous condenser supplies watt less leading kVA to the line depending upon the excitation of the motor. This watt less leading kVA partly or fully cancels the watt less 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 $\cos \phi_2$.

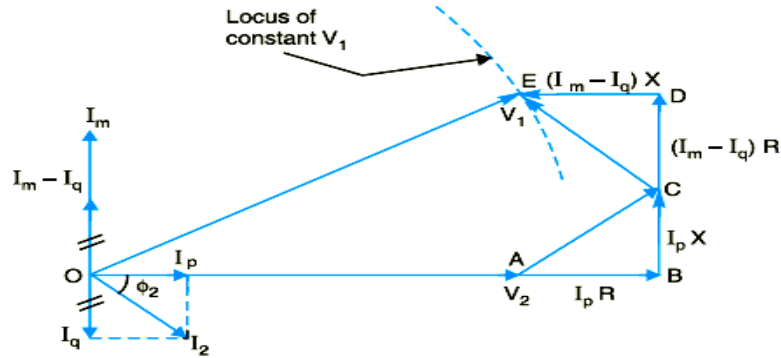
(i) Without synchronous condenser.

Fig. (i) shows the transmission line with resistance R and inductive reactance X per phase. The load current I can be resolved into two rectangular components viz I in phase with V and I at right angles to V . 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 V gives the sending end voltage V



(ii) With synchronous condenser

Now suppose that a synchronous condenser taking a leading current I_c is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. Note that since I_m and I_c are in direct opposition and that I_m must be greater than I_c , the four drops due to these two currents simplify to :
From this equation, the value of I_m can be calculated to obtain any desired ratio of V_1 / V_2 for a m



$(I_m - I_c) R$ in phase with I_m

and $(I_m - I_c) X$ 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
$$V_1^2 = [V_2 + I_p R - (I_m - I_c) X]^2 + [I_p X + (I_m - I_c) R]^2$$

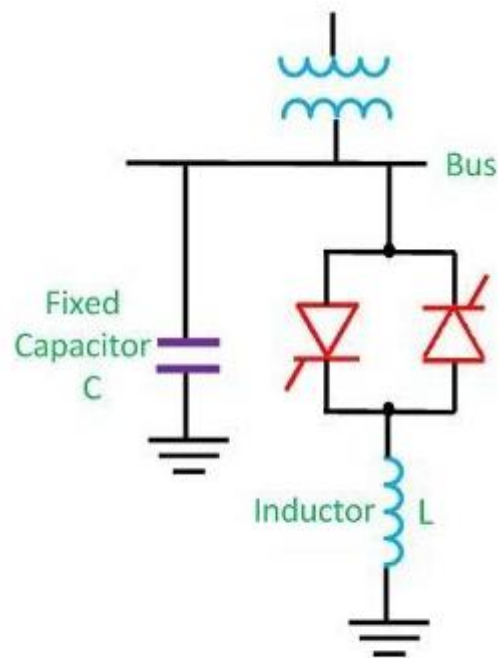
$$\text{kVAR capacity of condenser} = \frac{3 V_2 I_m}{1000}$$

5.7 Introduction to FACTS Technology

Flexible alternating current transmission systems (FACTS) controllers represent one of the most important technological advances in recent years, both enhancing controllability and increasing power transfer capacity of electric power transmission networks

5.7.1 Static VAR Compensator (SVC)

A static VAR compensator is a parallel combination of controlled reactor and fixed shunt capacitor shown in the figure below. The thyristor switch assembly in the SVC controls the reactor. The firing angle of the thyristor controls the voltage across the inductor and thus the current flowing through the inductor. In this way, the reactive power draw by the inductor can be controlled.



Static VAR Compensator

Static-var-compensator-compressor(1)The SVC is capable of step less adjustment of reactive power over an unlimited range without any time delay. It improves the system stability and system power factor. Most commonly used SVC scheme are as follows.

Thyristor controlled reactor (TCR)

Thyristor-switched capacitor (TSC)

Self Reactor (SR)

Thyristor controlled reactor – Fixed capacitor (TCR-FC)

Thyristor-switched capacitor – Thyristor controlled reactor (TSC-TCR)

Advantage of Static VAR Compensator

It increased the power transmission capability of the transmission lines.

It improved the transient stability of the system.

It controlled the steady state and temporary overvoltages.

It improved the load power factor, and therefore, reduced line losses and improved system capability.

Static VAR compensator has no rotating parts and is employed for surge impedance compensation and compensation by sectionalizing a long transmission line.

5.7.2 TCSC

The basic Thyristor Controlled Series Capacitor scheme was proposed in 1986 by Vithayathil with others as a method of "rapid adjustment of network impedance". A TCSC can be defined as 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. In a practical TCSC implementation, several such basic compensators may be connected in series to obtain the desired voltage rating and operating characteristics. However, the basic idea behind

the TCSC scheme is to provide a continuously variable capacitor by means of partially canceling the effective compensating capacitance by the TCR. The basic conceptual TCSC module comprises a series capacitor, C , in parallel with a thyristor controlled reactor.

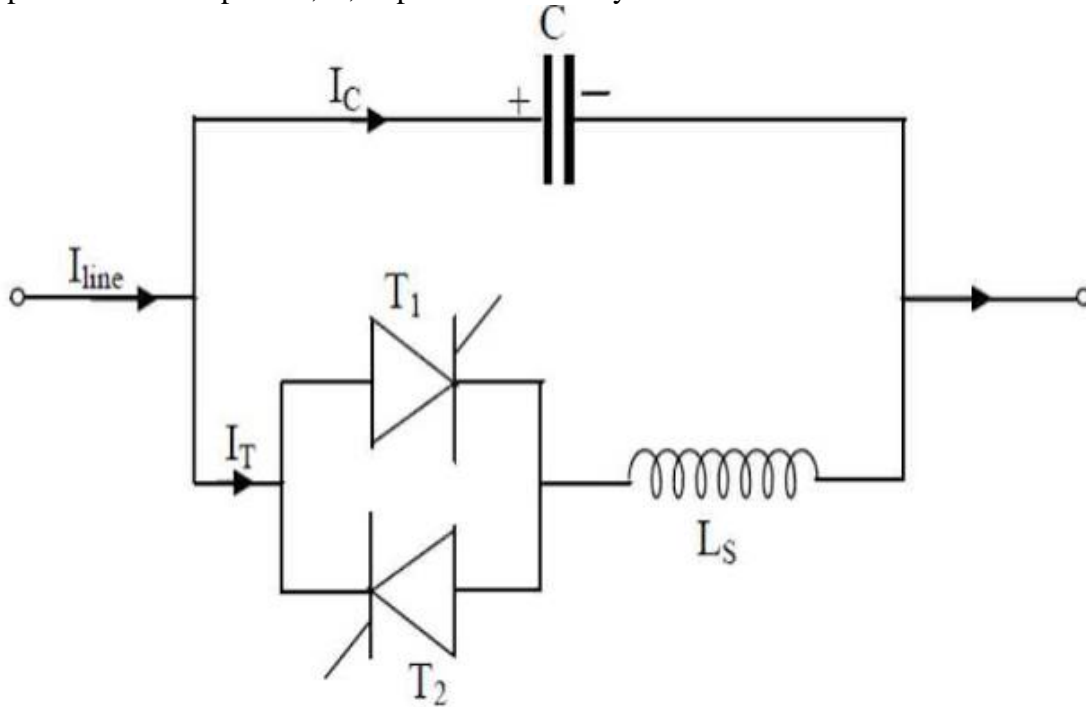


Figure: Structure of TCSC

A TCSC is a series-controlled capacitive reactance that can provide continuous control of power on the ac line over a wide range. From the system viewpoint, the principle of variable-series compensation is simply to increase the fundamental-frequency voltage across a Fixed Capacitor (FC) in a series compensated line through appropriate variation of the firing angle, α . This enhanced voltage changes the effective value of the series capacitive reactance. A simple understanding of TCSC functioning can be obtained by analyzing the behavior of a variable inductor connected in parallel with an FC. The maximum voltage and current limits are design values for which the thyristor valve, the reactor and capacitor banks are rated to meet specific application requirements.

5.7.3 STATCOM

A STATCOM is a controlled reactive-power source. It provides the desired reactive-power generation and absorption entirely by means of electronic processing of the voltage and current waveforms in a voltage-source converter (VSC).

A single-line STATCOM power circuit is shown in Fig.(a), where a VSC is connected to a utility bus through magnetic coupling.

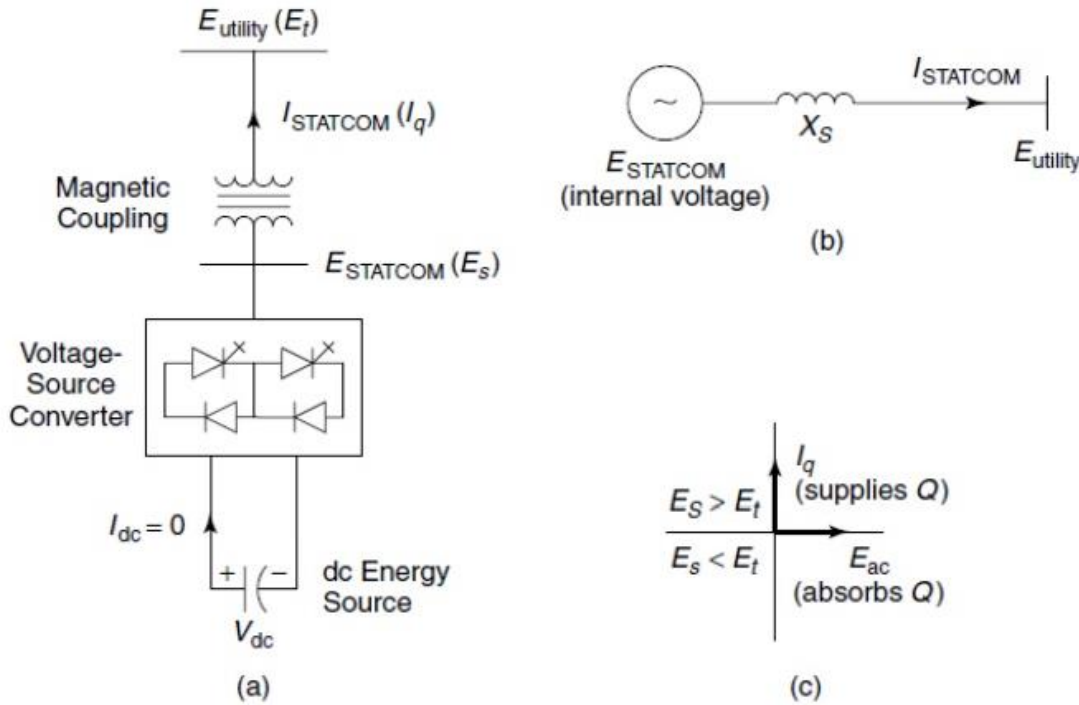
In Fig. (b), a STATCOM is seen as an adjustable voltage source behind a reactance meaning that capacitor banks and shunt reactors are not needed for reactive-power generation and absorption, thereby giving a STATCOM a compact design, or small footprint, as well as low noise and low magnetic impact.

The exchange of reactive power between the converter and the ac system can be controlled by varying the amplitude of the 3-phase output voltage, E_s , of the converter, as illustrated in Fig. (c).

If the amplitude of the output voltage is increased above that of the utility bus voltage, E_t , then a

current flows through the reactance from the converter to the ac system and the converter generates capacitive-reactive power for the ac system.

If the amplitude of the output voltage is decreased below the utility bus voltage, then the current flows from the ac system to the converter and the converter absorbs inductive-reactive power from the ac system.



The STATCOM principle diagram: (a) a power circuit;(b) an equivalent circuit;(c) a power exchange

The STATCOM principle diagram: (a) a power circuit;(b) an equivalent circuit;(c) a power exchange

Ø If the output voltage equals the ac system voltage, the reactive-power exchange becomes zero, in which case the STATCOM is said to be in a floating state.

Ø Adjusting the phase shift between the converter-output voltage and the ac system voltage can similarly control real-power exchange between the converter and the ac system. In other words, the converter can supply real power to the ac system from its dc energy storage if the converter-output voltage is made to lead the ac-system voltage.

Ø On the other hand, it can absorb real power from the ac system for the dc system if its voltage lags behind the ac-system voltage.

Ø A STATCOM provides the desired reactive power by exchanging the instantaneous reactive power among the phases of the ac system.

Ø The mechanism by which the converter internally generates and/ or absorbs the reactive power can be understood by considering the relationship between the output and input powers of the converter. The converter switches connect the dc-input circuit directly to the ac-output circuit. Thus the net instantaneous power at the ac-output terminals must always be equal to the net instantaneous power at the dc-input terminals (neglecting losses).

Ø Assume that the converter is operated to supply reactive-output power. In this case, the real power provided by the dc source as input to the converter must be zero.

Ø Furthermore, because the reactive power at zero frequency (dc) is by definition zero, the dc source supplies no reactive power as input to the converter and thus clearly plays no part in the generation of reactive-output power by the converter.

Ø In other words, the converter simply interconnects the three output terminals so that the reactive-output currents can flow freely among them. If the terminals of the ac system are regarded in this context, the converter establishes a circulating reactive-power exchange among the phases. However, the real power that the converter exchanges at its ac terminals with the ac system must, of course, be supplied to or absorbed from its dc terminals by the dc capacitor.

Ø Although reactive power is generated internally by the action of converter switches, a dc capacitor must still be connected across the input terminals of the converter.

Ø The primary need for the capacitor is to provide a circulating-current path as well as a voltage source.

Ø The magnitude of the capacitor is chosen so that the dc voltage across its terminals remains fairly constant to prevent it from contributing to the ripples in the dc current. The VSC-output voltage is in the form of a staircase wave into which smooth sinusoidal current from the ac system is drawn, resulting in slight fluctuations in the output power of the converter.

Ø However, to not violate the instantaneous power-equality constraint at its input and output terminals, the converter must draw a fluctuating current from its dc source.

Ø Depending on the converter configuration employed, it is possible to calculate the minimum capacitance required to meet the system requirements, such as ripple limits on the dc voltage and the rated-reactive-power support needed by the ac system.

Ø The VSC has the same rated-current capability when it operates with the capacitive- or inductive-reactive current.

Ø Therefore, a VSC having a certain MVA rating gives the STATCOM twice the dynamic range in MVAR (this also contributes to a compact design). A dc capacitor bank is used to support (stabilize) the controlled dc voltage needed for the operation of the VSC.

Ø The reactive power of a STATCOM is produced by means of power-electronic equipment of the voltage-source-converter type.

Ø The VSC may be a 2- level or 3-level type, depending on the required output power and voltage . A number of VSCs are combined in a multi-pulse connection to form the STATCOM. In the steady state, the VSCs operate with fundamental-frequency switching to minimize converter losses. However, during transient conditions caused by line faults, a pulse width–

modulated (PWM) mode is used to prevent the fault current from entering the VSCs . In this way, the STATCOM is able to withstand transients on the ac side without blocking.

Advantages of STATCOM

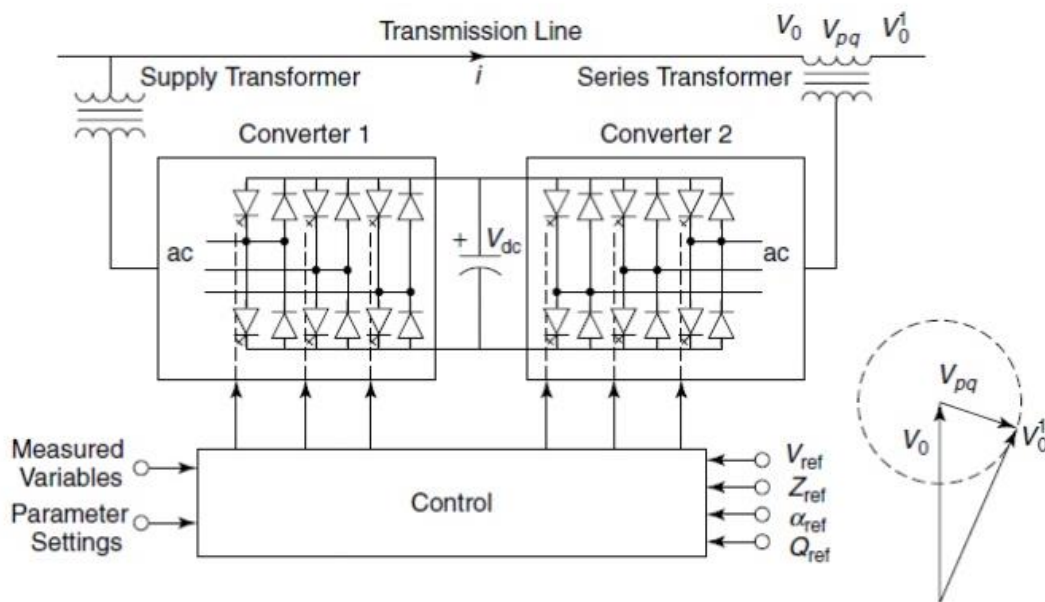
1. It occupies a small footprint, for it replaces passive banks of circuit elements by compact electronic converters;
2. It offers modular, factory-built equipment, thereby reducing site work and commissioning time; and
3. It uses encapsulated electronic converters, thereby minimizing its environmental impact.

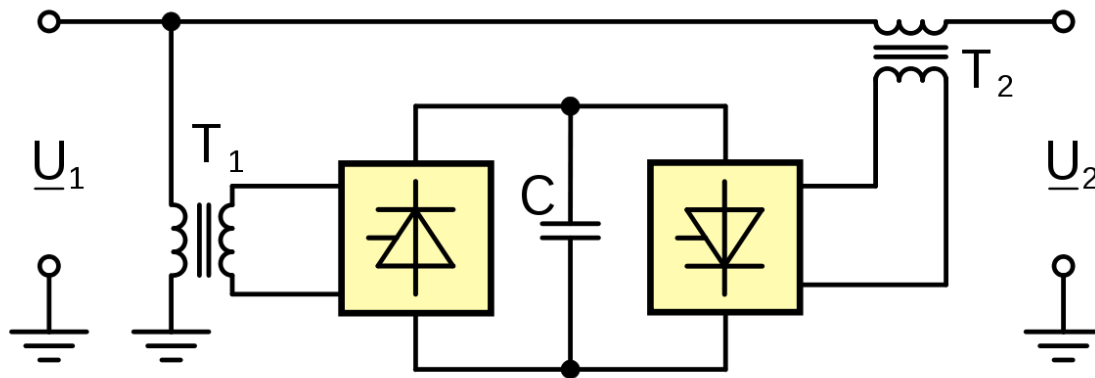
5.7.4 Unified Power Flow Controller (UPFC)

The UPFC is the most versatile FACTS controller developed so far, with all encompassing capabilities of voltage regulation, series compensation, and phase shifting.

Ø It can independently and very rapidly control both real- and reactive power flows in a transmission.

Ø It is configured as shown in Fig. and comprises two VSCs coupled through a common dc terminal.





The implementation of the UPFC using two “back – to –back” VSCs with a common DC-terminal capacitor

Ø One VSC converter 1 is connected in shunt with the line through a coupling transformer; the other VSC converter 2 is inserted in series with the transmission line through an interface transformer.

Ø The dc voltage for both converters is provided by a common capacitor bank.

Ø The series converter is controlled to inject a voltage phasor, V_{pq} , in series with the line, which can be varied from 0 to V_{pq} max. Moreover, the phase angle of V_{pq} can be independently varied from 00 to 3600.

Ø In this process, the series converter exchanges both real and reactive power with the transmission line.

Ø Although the reactive power is internally generated/ absorbed by the series converter, the real-power generation/ absorption is made feasible by the dc-energy–storage device that is, the capacitor.

Ø The shunt-connected converter 1 is used mainly to supply the real-power demand of converter 2, which it derives from the transmission line itself. The shunt converter maintains constant voltage of the dc bus.

Ø Thus the net real power drawn from the ac system is equal to the losses of the two converters and their coupling transformers.

Ø In addition, the shunt converter functions like a STATCOM and independently regulates the terminal voltage of the interconnected bus by generating/ absorbing a requisite amount of reactive power.

QUESTIONS :

Q.No	Question
1	Define EHV AC & HVDC Transmission
2	Show the need for compensation with a vector diagram
3	Discuss the limitations in EHVAC transmission
4	Distinguish between Monopolar & Bipolar link in HVDC transmission
5	What is the major role of FACTS devices in Power System
6	Define STATCOM
7	What are the advantages of HVDC transmission
8	List out the different modes of operation in TCSC.

Q.No	Question
1	Explain HVDC transmission system and its terminal equipments
2	List the applications of HVDC systems. Also Explain the technical reasons for adopting EHV AC transmission
3	Discuss in detail about the classification of HVDC transmission
4	Explain about the interconnection of HVDC & AC systems
5	Explain in detail about TCSC and its different modes of operation
6	What is meant by UPFC. Also discuss the operation benefit of UPFC in power system.
7	Explain about STATCOM and list out the advantages.

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