EE8402 Transmission and Distribution

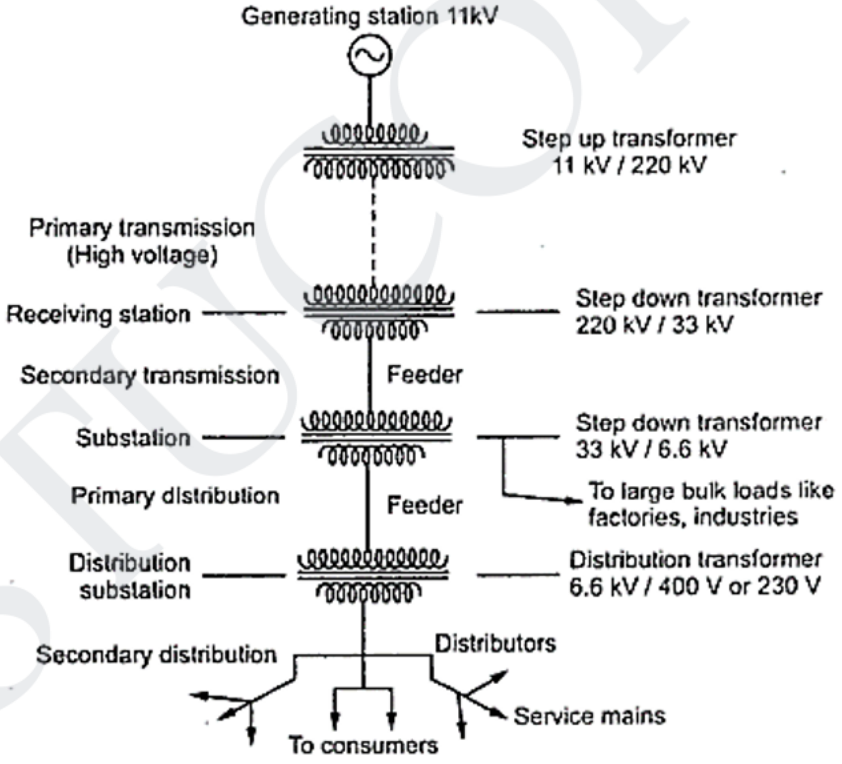
UNIT I- TRANSMISSION LINE PARAMETERS

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

INTRODUCTION

The transmission line performance is based on its electrical parameters such as resistance, inductance and capacitance. As we know the transmission line are used for delivering electrical power from one end to other end or one node to other node, the path of power flow i.e. the transmission line can be represented as an electrical circuit having its parameters connected in a particular pattern. Since the transmission line consists of conductors carrying power, we need to calculate the resistance, inductance and capacitance of these conductors.

STRUCTURE OF POWER SYSTEM



Primary Transmission:

It is basically with the help of overhead transmission line for the economic aspects, the voltage level is increased to 132KV, 220kV or more, with the help of stepup transformer. Hence this transmission is also called as high voltage transmission. The primary transmission uses 3 phase 3 wire system.

Secondary Transmission

The primary transmission line continues via transmission towers till the receiving stations, at the receiving stations the voltage level is reduced to 22kV or 33kV using step down transformer. There can be more than one receiving stations. Then at reduced voltage level of 22kV or 3kV, the power is then transmitted to various substations using overhead 3 phase 3 wire system. This is secondary transmission. The conductors used for the secondary transmission are called feeders.

Primary Distribution.

At the substation the voltage level is reduced to 6.6 kV, 3.3kV or 11kV with the help of step down transformers. It uses three-phase three wire underground system. And the power is further transmitted to the local distribution centre. This is primary distribution also called high voltage distribution for large consumers like factories and industries; the power is directly transmitted to such loads from a substation.

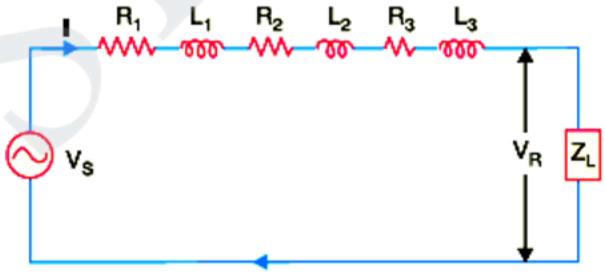
Secondary Distribution:

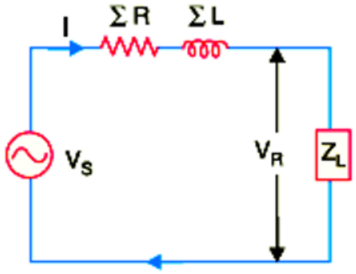
At the local distribution centres, there are step down distribution transformers. The voltage level of 6.6kV, 11kV is further reduced to 230 V. The power is then transmitted using distributors and service mains to the consumers.

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

CONSTANTS OF A TRANSMISSION LINE

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





(*i*) Resistance.

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

(*ii*) Inductance.

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

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

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.

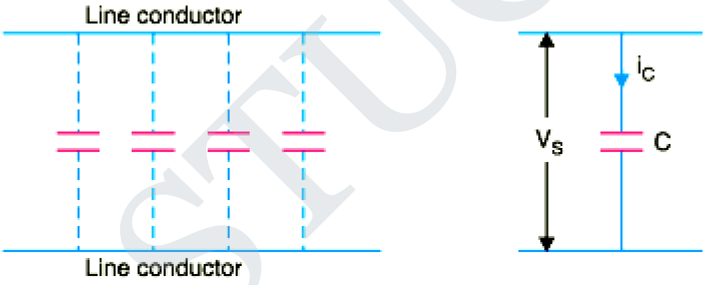
(*iii*) Capacitance. We know that any two conductors separated by an insulating material consti-tute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore, capacitance exists between any two overhead line conductors. The capacitance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

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

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

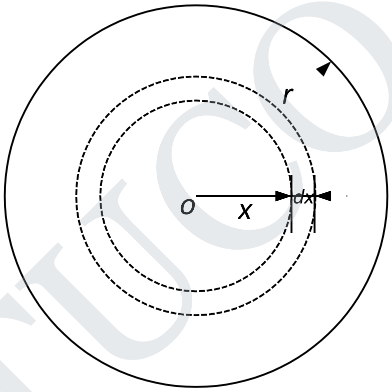
$$R_2 = R_1 \left[1 + \alpha_1 (t_2 - t_1)\right]$$

where $\alpha_1 = \dfrac{\alpha_0}{1 + \alpha_0 t_1}$

α_0 = temperature coefficient at 0° C

INDUCTANCE OF SOLID CONDUCTOR DUE TO INTERNAL FLUX

Let us consider a solid conductor of radius 'r' cm and the current flowing is 'I' A as shown in Fig.-1.1.



INTERNAL FLUX LINKAGE OF A ROUND CONDUCTOR.

As we know Ampere's law states that the magnetomotive force (mmf) in ampere-turns around a closed path is equal to the net current in amperes enclosed by the path. Mathematically is written as (1.3).

$$mmf = \oint H \bullet ds = I$$

Where H is the magnetic field intensity in At/m, s is the distance along the path in meter.

Let us consider a tubular element of thickness 'dx' of the conductor at a distance 'x' from the center of the conductor and the field intensity as 'H_x' at 'x'. It is constant at all points that are at a distance

$$\oint H_x \bullet dx = I_x \Rightarrow 2\pi x H_x = I_x \quad (1.4)$$

' x'

$$\therefore H_x = \frac{I_x}{2\pi x} \quad (1.5)$$

from the center of the conductor. Therefore 'H_X' is constant over the concentric circular path with a radius of 'x' and is tangent to it. Let the current enclosed by this path is 'I_X'. Hence by (1.3) we can write as follows.

Assuming the current density to be uniform thorugh out the cross section of the conductor, the current at a radius of 'x' is given by (1.6)

$$I_x = \frac{2\pi x^2}{2\pi r^2} I \quad (1.6)$$

Substituting (1.6) in (1.5) we get

$$H_x = \frac{x}{2\pi r^2} I \quad (1.7)$$

The flux density at a distance of 'x' is given by

$$B_x = \mu H_x = \mu_0 \mu_r H_x \quad (1.8)$$

Considering the unit length of the conductor i.e. one metre, the flux in the tubular element of thickness 'dx' of the conductor can be given by (1.9).

$$d\phi_x = B_x dx \quad (1.9)$$

Combining (1.7), (1.8) and (1.9)

$$d\phi_x = \mu \frac{I}{2\pi r^2} x dx \quad (1.9)$$

The flux linkage at 'x' can be given by

$$d\lambda_x = \frac{\pi x^2}{\pi r^2} d\phi_x = \mu \frac{I}{2\pi r^4} x^3 dx \quad (1.10)$$

The total internal flux linkage can be obtained by integrating (1.10) over the range of 'x' , i.e., from '0' to 'r' as follows.

$$\lambda = \int_0^r d\lambda_x = \int_0^r \mu \frac{I}{2\pi r^4} x^3 dx \tag{1.11}$$

$$\lambda = \mu \frac{I}{8\pi} \tag{1.12}$$

For relative permeability to be $\mu_r = 1$ we have $\mu_0 = 4\pi \text{X} 10^{-7}$, hence (1.12) can be written as follows, which is the flux linkage due to internal flux.

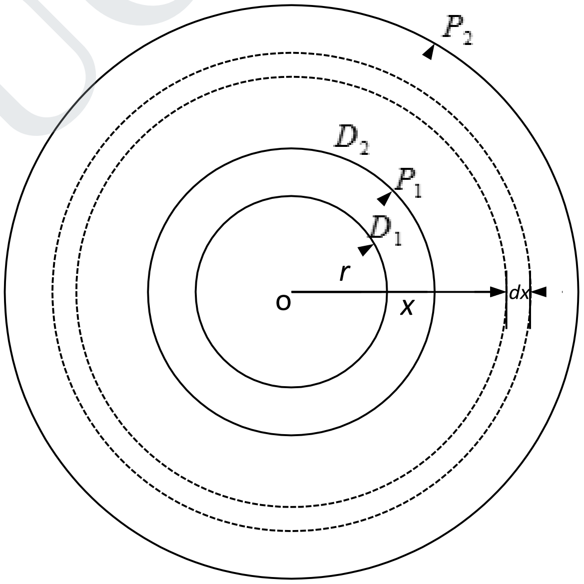
$$\lambda_{\text{int}} = \frac{I}{2} \text{X} 10^{-7} \text{ Wb-T/m} \tag{1.13}$$

Hence the inductance of the conductor due to internal flux is obtained by using (1.2) and (1.13).

$$L_{\text{int}} = \frac{\lambda_{\text{int}}}{I} = \frac{1}{2} \text{X} 10^{-7} \text{ H/m} \tag{1.14}$$

INDUCTANCE OF SOLID CONDUCTOR DUE TO EXTERNAL FLUX

Now we shall calculate the inductance of solid conductor due to flux linking with the conductor externally. Let us consider two points P1 & P2 at a distance of D1 &D2 at a center of the conductor and external to it. Let us consider a tubular element of thickness 'dx' of the conductor at a distance 'x' . as shown in Fig.-1.2.



The current enclosed by the tubular element is the total current i.e. I ' . Hence the field intensity is given by (1.15).

$$H_x = \frac{I}{2\pi x} \tag{1.15}$$

The flux density at a distance of ' x' is given by

$$B_x = \mu H_x = \mu_0 \mu_r H_x \tag{1.16}$$

Considering the unit length of the conductor i.e. one metre, the flux in the tubular element of thickness ' dx' of the conductor can be given by (1.17).

$$d\phi_x = B_x dx \tag{1.17}$$

Combining (1.15), (1.16) and (1.17)

$$d\phi_x = \mu \frac{I}{2\pi x} dx \tag{1.18}$$

The flux linkage at ' x' can be given by

$$d\lambda_x = \mu \frac{I}{2\pi x} dx \tag{1.19}$$

The total internal flux linkage can be obtained by integrating (1.19) between two points ' P_1'&' P_2' as follows.

$$\lambda = \int_{D_1}^{D_2} d\lambda_x = \int_{D_1}^{D_2} \mu \frac{I}{2\pi x} dx \tag{1.20}$$

$$\lambda = \mu \frac{I}{2\pi} \ln \frac{D_2}{D_1} \tag{1.21}$$

For relative permeability to be $\mu_r = 1$ we have $\mu_0 = 4\pi \, X 10^{-7}$, hence (1.12) can be written as follows, which is the flux linkage due to external flux.

$$\lambda_{ext} = 2\,X\,10^{-7} I \ln \frac{D_2}{D_1} \text{ Wb-T/m} \tag{1.22}$$

Hence the inductance of the conductor due to external flux is obtained by using (1.2) and (1.22).

$$L_{ext} = \frac{\lambda_{ext}}{I} = 2\,X\,10^{-7} \ln \frac{D_2}{D_1} \quad \text{(H/m)} \tag{1.23}$$

Therefore the total inductance due to internal and external flux can be given by combining (1.14) and (1.23).

$$L = L_{\text{int}} + L_{ext} = \frac{1}{2} X 10^{-7} + 2 X 10^{-7} \ln \frac{D_2}{D_1} \quad \text{(H/m)} \qquad (1.23)$$

$$L = 2 X 10^{-7} \left(\frac{1}{4} + \ln \frac{D_2}{D_1} \right) \quad \text{(H/m)} \qquad (1.24)$$

Considering the flux linking with the conductor up to a point 'P' at a distance 'D' from the center of the conductor (1.24) can be modified as

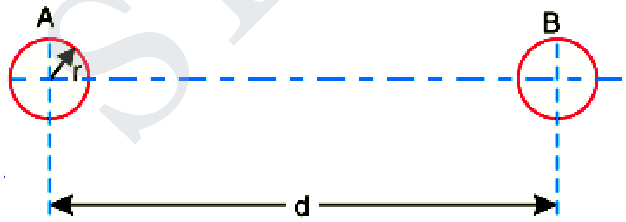
$$L = 2 X 10^{-7} \left(\frac{1}{4} + \ln \frac{D}{r} \right) \quad \text{(H/m)} \qquad (1.25)$$

Or we can write

$$L = 2 X 10^{-7} \left(\ln \frac{D}{e^{-\frac{1}{4}} r} \right) = 2 X 10^{-7} \left(\ln \frac{D}{r'} \right) \quad \text{(H/m)} \qquad (1.26)$$

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. 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

$$\text{Now,} \quad I_A + I_B = 0 \quad \text{or} \quad -I_B = I_A$$

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

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

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

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

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

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

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

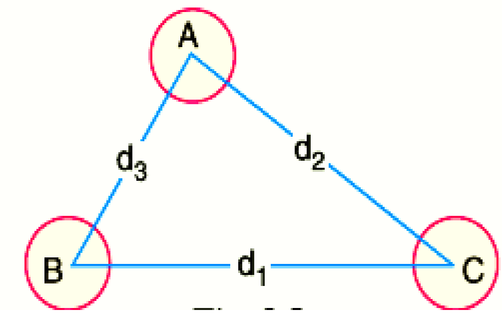
$$\text{Loop inductance} = 2\,L_A \text{ H/m} = 10^{-7}\left[1 + 4\log_e \frac{d}{r}\right] \text{H/m}$$

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

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

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 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 current I_B

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

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

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

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

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

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

As $\quad I_A + I_B + I_C = 0,$

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

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, d1 = d2 = d3 = d. Under such conditions, the flux Derived in a similar way, the expressions for inductance are the same for conductors B and C**.**

$$
\begin{aligned}
\psi_A &= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - I_B \log_e d - I_C \log_e d\right] \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A - (I_B + I_C)\log_e d\right] \\
&= \frac{\mu_0}{2\pi}\left[\left(\frac{1}{4} - \log_e r\right) I_A + I_A \log_e d\right] \qquad (\because I_B + I_C = -I_A) \\
&= \frac{\mu_0\, I_A}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ werber-turns/m} \\
L_A &= \frac{\psi_A}{I_A}\text{ H / m} = \frac{\mu_0}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m} \\
&= \frac{4\pi \times 10^{-7}}{2\pi}\left[\frac{1}{4} + \log_e \frac{d}{r}\right] \text{ H/m} \\
L_A &= 10^{-7}\left[0\cdot 5 + 2\log_e \frac{d}{r}\right] \text{ H/m}
\end{aligned}
$$

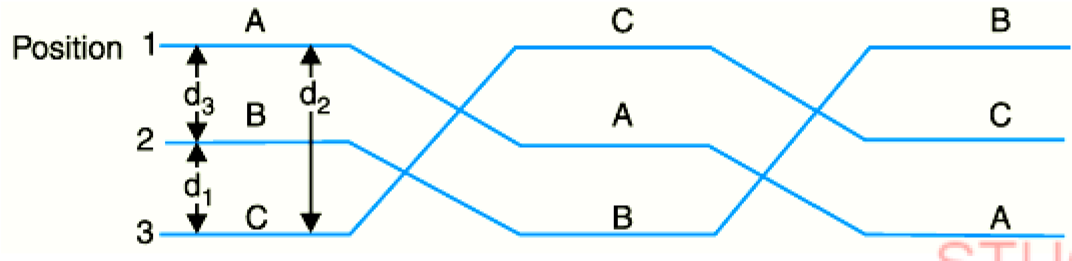
2.2.3 UNSYMMETRICAL SPACING

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 :



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

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

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

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

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

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

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

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

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

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

$\therefore$ Inductance of conductor A is

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

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

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

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

Similarly inductance of conductors B and C will be :

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

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

Inductance of each line conductor

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

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

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

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

$$d = \sqrt[3]{d_1\, d_2\, d_3}$$

The distance d is known as equivalent equilateral spacing for un symmetrically transposed line.

INDUCTANCE OF BUNDLE CONDUCTOR

In extra high voltage transmission line bundle conductors are used to reduce the effect of corona. The bundle conductors consists of two or more sub-conductors as shown in Fig.-1.9.

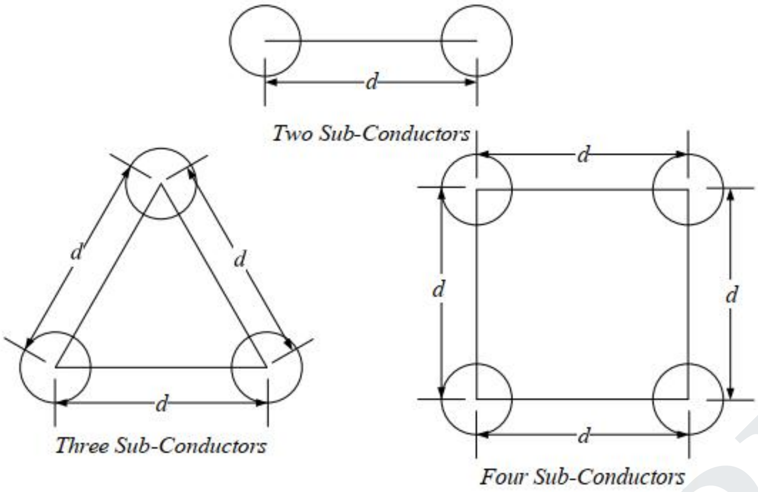


FIG.- BUNDLE CONDUCTORS

The inductance of bundle conductors can be calculated by determining its self GMD as follows.

For a bundle conductor having two sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[4]{(D_s X d)^2} = \sqrt{D_s d}$$

For a bundle conductor having three sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[9]{(D_s X d X d)^3} = \sqrt[3]{D_s d^2}$$

For a bundle conductor having four sub-conductors the self GMD is given by

$$D_{s,bundle} = \sqrt[16]{(D_s X d X d X \sqrt{2} d)^4} = 1.09\sqrt[4]{D_s d^3}$$

The bundle conductors have reduced reactance. Increasing the number of sub-conductors reduces the reactance because of increased GMR of the bundle. For the calculation of inductance

CAPACITANCE OF LONG SOLID CONDUCTOR LINE

The transmission line also have capacitance due to charge accumulated on the conductors. It can be determined by fundamental Coulombs Law. Let us consider a solid conductor as shown in Fig.-2.1 having radius ' r' . The electric flux density at ‘x’ meters from the conductor can be computed by imaging a cylindrical surface concentric with the conductor fron the conductor.

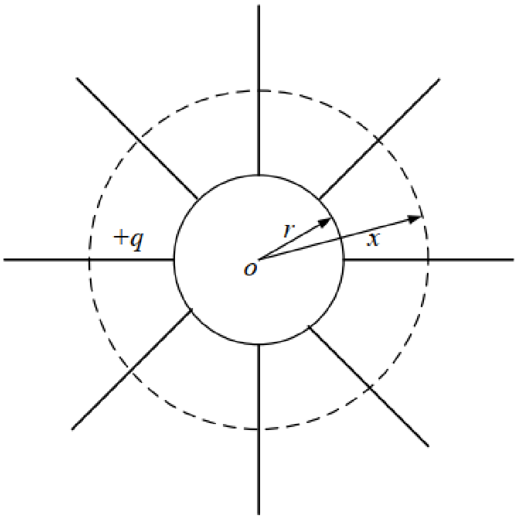


FIG.- SOLID CONDUCTOR HAVING CHARGE 'q'

The cylindrical surface is the surface of equipotential and the electric flux density on the surface is equal to the flux leaving the conductor per unit length divided by the area of the surface in an axial length. The electric flux density is given by (2.1).

$$D_f = \frac{q}{2\pi x} C|/m^2$$

Where ‘d’ is the charge on the conductor per unit length. The electric filed intensity defined as the ratio of electric flux density to the permittivity of the medium and given by

CAPACITANCE OF A SINGLE PHASE TWO-WIRE LINE

$$E = \frac{q}{2\pi xk} V/m \tag{2.2}$$

Let us take two points 'P_1 & P_2' be located at distances 'D_1 & D_2' respectively from the center of the conductor as shown in Fig.-2.2.

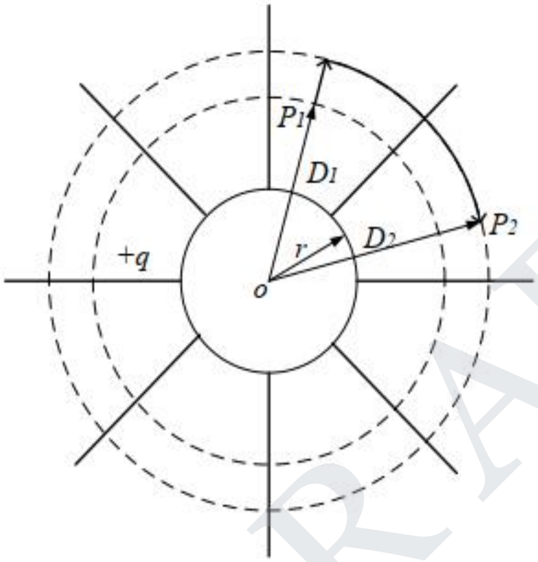


FIG.-2.2 POTENTIAL DIFFERENCE BETWEEN TWO POINTS 'P_1 & P_2'

The conductor is an equipotential surface in which we can assume that the uniformly distributed charge is concentrated at the center of the conductor. The potential difference 'V_{12}' between the points 'P_1 & P_2' is the work done in moving a unit of charge from 'P_2' to 'P_1'. Therefore the voltage drop between the two points can be computed by integrating the field intensity over a radial path between the equipotential surfaces and given by (2.3).

$$V_{12} = \int_{D_1}^{D_2} E dx = \int_{D_1}^{D_2} \frac{q}{2\pi xk} dx = \frac{q}{2\pi k} \ln \frac{D_2}{D_1} \text{ (V)} \tag{2.3}$$

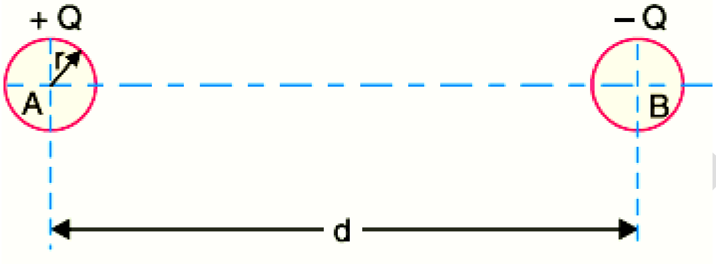
The capacitance between the conductors of two wire line is defined as charge on the conductors per unit of potential difference between them. It can be given by (2.4)

$$C = \frac{q}{V} (F/m) \tag{2.4}$$

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

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

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



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

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

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

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

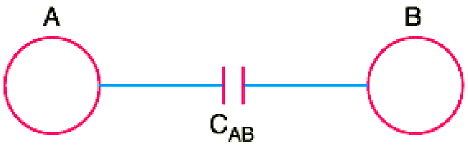
$$V_{AB} = 2V_A = \frac{2Q}{2\pi\,\varepsilon_0}\log_e \frac{d}{r} \text{ volts}$$

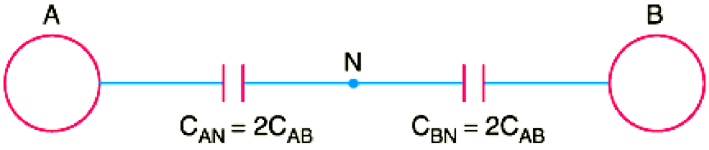
Capacitance, $$C_{AB} = Q/V_{AB} = \frac{Q}{\frac{2Q}{2\pi\,\varepsilon_0}\log_e \frac{d}{r}} \text{ F/m}$$

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

Capacitance to neutral

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





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

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

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.

CAPACITANCE OF A 3-PHASE OVERHEAD LINE

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

(i) Symmetrical Spacing

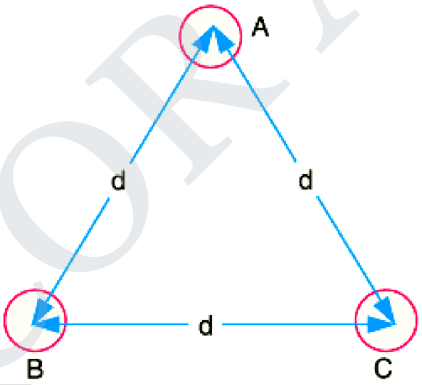


Fig shows the three conductors A, B and C of the 3-phase overhead transmission line having charges Q_A , Q_B and Q_C per meter length respectively. Let the conductors be equidistant (d meters) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line.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

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

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

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

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

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

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

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

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

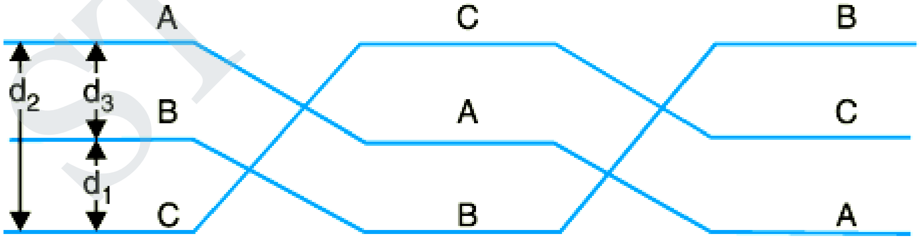
$$C_A = \frac{Q_A}{V_A} = \frac{Q_A}{\frac{Q_A}{2\pi\,\varepsilon_0}\log_e \frac{d}{r}}\ \text{F / m} = \frac{2\pi\,\varepsilon_0}{\log_e \frac{d}{r}}\ \text{F / m}$$

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

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

ii) Unsymmetrical spacing.

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



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

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

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

Average voltage on condutor A is

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

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

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

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

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

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

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

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

Capacitance from conductor to neutral is

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

CAPACITANCE OF BUNDLE CONDUCTOR

The capacitance of bundles conductor can be calculated as above and given by (2.22)

$$C_{an} = \frac{2\pi k}{\ln\left(D_{eq}/D_{sC,bundle}\right)} \text{ (F/m to neutral)} \tag{2.22}$$

Where '$D_{sC,bundle}$' is the modified GMR of the bundle conductor and can be given as follows for different bundle conductors as shown in Fig.-1.9.

For a bundle conductor having two sub-conductors

$$D_{sC,bundle} = \sqrt[4]{(r X d)^2} = \sqrt{rd}$$

For a bundle conductor having three sub-conductors

$$D_{sC,bundle} = \sqrt[9]{(r X d X d)^3} = \sqrt[3]{rd^2}$$

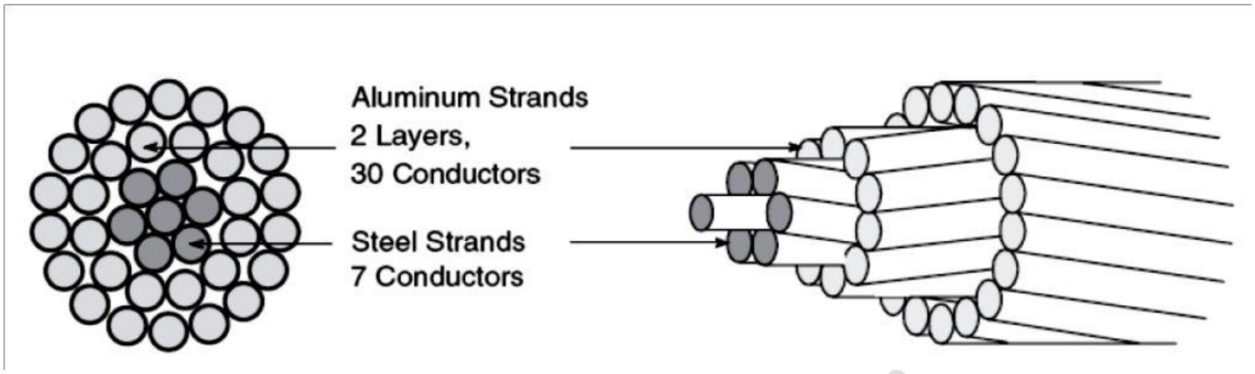
For a bundle conductor having four sub-conductors

$$D_{sC,bundle} = \sqrt[16]{\left(r X d X d X \sqrt{2}d\right)^4} = 1.09\sqrt[4]{rd^3}$$

Earth affects the calculation of capacitance of three-phase lines as its presence alters the electric field lines. Usually the height of the conductors placed on transmission towers is much larger than the spacing between the conductors. Therefore the effect of earth can be neglected for capacitance calculations, especially when balanced steady state operation of the power system is considered. However for unbalanced operation when the sum of the three line currents is not zero, the effect of earth needs to be considered.

STRANDED AND BUNDLE CONDUCTOR EFFECT

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



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

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

APPLICATION OF SELF-GMD AND MUTUAL-GMD

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

(i) Self-GMD (Ds)

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

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

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

In this expression, the term 2 × 10^{-7} × (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 × 10^{-7} × (1/4) shall be eliminated. The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage. It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = 0·7788 r. Using self-GMD, the eq. (i) becomes :

Inductance/conductor/m = $2 \times 10\text{-}7 \log_e d/ Ds$ *
Where
Ds = GMR or self-GMD = 0·7788 r

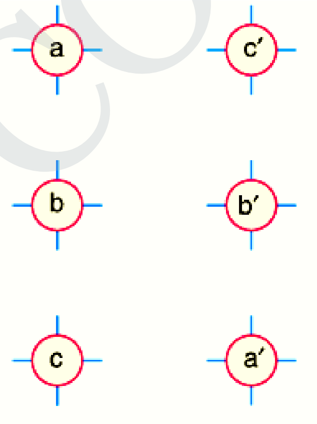
It may be noted that self-GMD of a conductor depends upon the size and shape of the conductor and is independent of the spacing between the conductors.

(ii) Mutual-GMD

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

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

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



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

Self-GMD of conductor = 0·7788 r

Self-GMD of combination aa’ is

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

Self-GMD of combination bb' is

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

Self-GMD of combination cc' is

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

Equivalent self-GMD of one phase

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

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

Mutual-GMD between phases A and B is

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

Mutual-GMD between phases B and C is

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

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

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

Inductance Formulas in Terms of GMD

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

(i) Single phase line

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

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

(ii) Single circuit 3-ϕ line

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

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

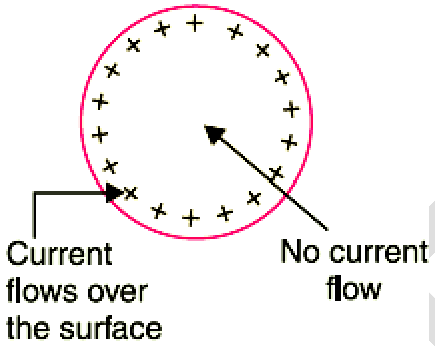
(iii) Double circuit 3-ϕ line

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

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

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**.

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.

Apart from the skin effect the non uniformity of current distribution is also caused by proximity effect. Consider a two wire line as shown in figure. Each line conductor can be divided into sections of equal cross sectional area (say three sections). Pairs aa`, bb` and cc` can form three loops in parallel. The flux linking aa` (and therefore its inductance) is the least and it increases somewhat for the loops bb` and cc`. Thus the density of AC flowing through the conductors is the highest at the inner edges (aa`) of the conductors and is the least at the outer edges (cc`). This type of non-uniform AC current distribution becomes more pronounced as the distance between the conductors is reduced. Like skin effect the non-uniformity current distribution also increases the effective conductor resistance. For normal spacing of overhead line this effect is negligible. However for underground cables where conductors are located close to each other, proximity effect always causes an appreciable increase in effective conductor resistance.

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.

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

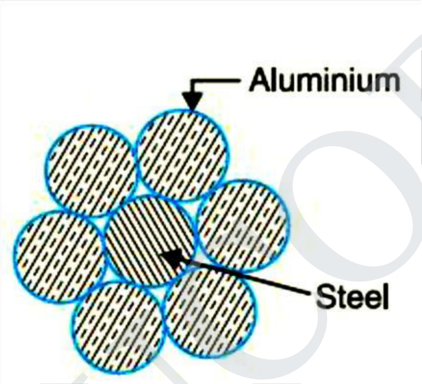
Aluminium is cheap and light as compared to copper but it has much smaller conductivity and tensile strength. The relative comparison of the two materials is briefed below:

(*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 conductorthus 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.

UNIT II MODELLING AND PERFORMANCE OF TRANSMISSION LINES

Performance of Transmission lines - short line, medium line and long line – equivalent circuits, phasor diagram, attenuation constant, phase constant, surge impedance - transmission efficiency and voltage regulation, real and reactive power flow in lines – Power Circle diagrams - Formation of Corona – Critical Voltages – Effect on Line Performance.

INTRODUCTION

We have derived expression for resistance, inductance and capacitance for ransmission line in last two chapters. It can be seen that all these parameters depend upon the size of conductors and its configuration. Furthermore we also conclude that the parameters depend upon the length of the transmission line. In fact these parameters are distributed throughout the transmission line not just single element. The circuit consisting of these parameters are shown in Fig.3.1 below.

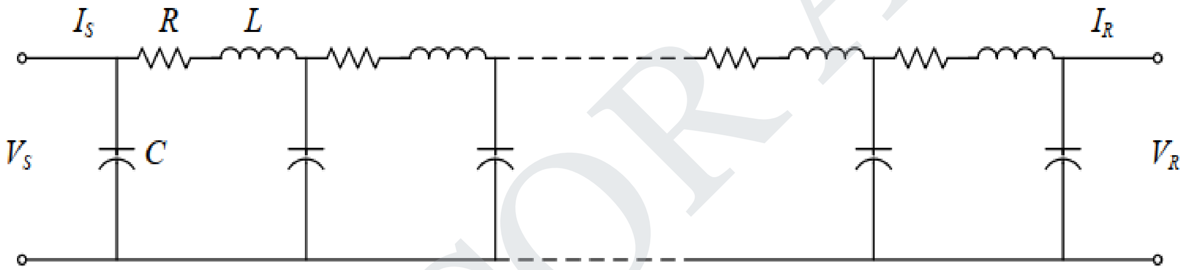


FIG.- . TRANSMISSION LINE PARAMETERS

The resistance and inductance are known as series parameters and hence forms series impedance of the transmission line. The capacitance is known as shunt parameters and hence forms shunt admittance. The transmission line can be represented as two port network as shown in Fig.-3.2 such that we can write:

$$V_S = AV_R + BI_R$$

$$I_S = CV_R + DI_R$$

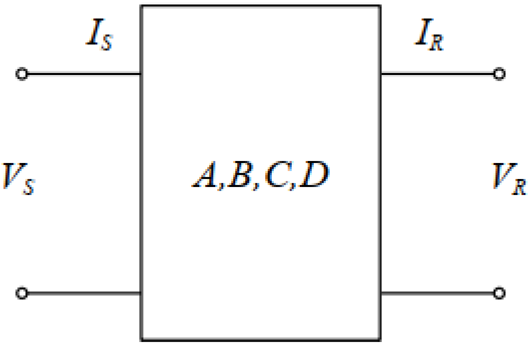


FIG.- TWO PORT EQUIVALENT OF TRANSMISSION LINE

The performance of the transmission line depend upon the total value of series impedance and shunt admittance. This is the reason that the transmission line is classified into three categories.

Short length transmission line (Generally up to 80 kms)

Medium length transmission line (Generally up to 80 to 240 kms)

Long length transmission line (Generally above 240 kms)

The total series impedance and shunt admittance of the transmission line is given by

$$Z= (R+j\omega L)l$$

$$Y = j\omega Cl$$

Where ‘l’ is the length of the transmission line in kms ‘z’&’y’are the total series impedance and shunt admittance respectively.

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 moderatly 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 tranmission line must consider the fact that the constants of the line are not lumped but are distributed unfiormly 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

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

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

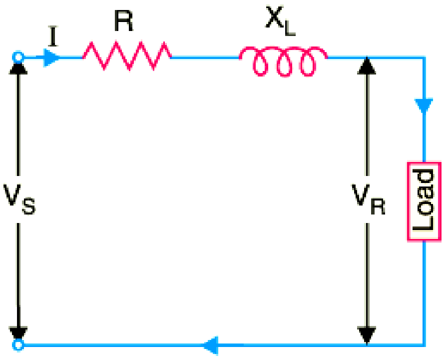
PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

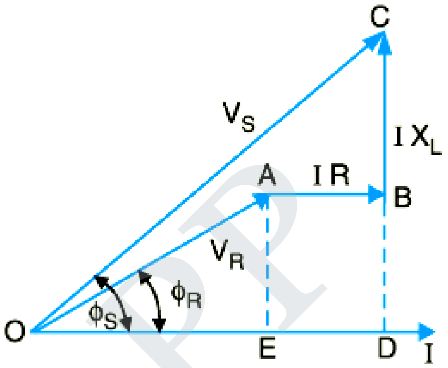
As stated earlier, the effects of line capacitance are neglected for a short transmission line. Therefore, while studying the performance of such a line, only resistance and inductance of the line are taken into account. The equivalent circuit of a single phase short transmission line is shown in Fig.

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

Let

I = load current
R = loop resistance i.e., resistance of both conductors
X_L= loop reactance
V_R = receiving end voltage
cos φ_R = receiving end power factor (lagging)
V_S= sending end voltage
cos φ_S= sending end power factor





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

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

or

$$V_S^2 = (OE + ED)^2 + (DB + BC)^2$$

$$= (V_R \cos\phi_R + IR)^2 + (V_R \sin\phi_R + IX_L)^2$$

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

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

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

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

Line losses $= I^2 R$

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

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

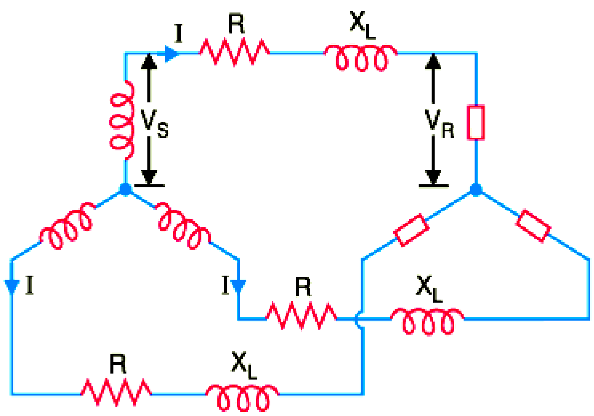
$$= \frac{V_R\, I_R \cos\phi_R}{V_R\, I_R \cos\phi_R + I^2 R} \times 100$$

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

OC = OF = OA + AF = OA + AG + GF
= OA + AG + BH
V_s= V_R + IR cos φ_R + I X_L sin φ_R

THREE-PHASE SHORT TRANSMISSION LINES

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally 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, Vs and V_R are the phase voltages, whereas R and X_L are the resistance S and inductive reactance per phase respectively.



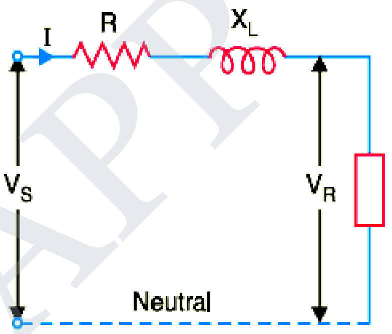


Fig (*i*) shows a *Y*-connected generator supplying a balanced *Y*-connected load through a transmission line. Each conductor has a resistance of *R* Ω and inductive reactance of *X* Ω. Fig. (ii) shows one phase separately. The calculations can now be made in the same way as for a single phase line.

Effect of Load p.f. on Regulation and Efficiency

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

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

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

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

The following conclusions can be drawn from the above expressions :
(*i*) When the load p.f. is lagging or unity or such leading that $I R \cos \varphi_R > I X_L \sin \varphi_R$, then voltage regulation is positive *i.e.* , receiving end voltage V_R will be less than the sending end voltage V_S . (*ii*) For a given V_R and *I*, the voltage regulation of the line increases with the decrease in p.f. for lagging loads.

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

2. Effect on transmission efficiency.
The power delivered to the load depends upon the power factor.

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

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

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

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

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. $\cos \varphi_R$. 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,

MEDIUM TRANSMISSION LINES

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

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

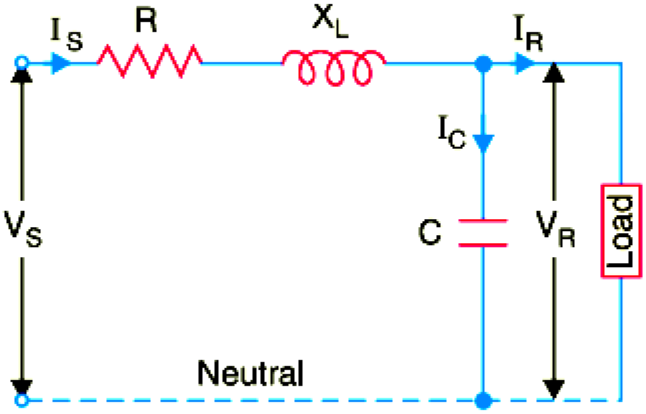
The capacitance is uniformly distributed over the entire length of the line. However, in order to make the calculations simple, the line capacitance is assumed to be lumped or concentrated in the form of capacitors shunted across the line at one or more points. Such a treatment of localising the line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

(i) End condenser method
(ii) Nominal T method
(iii) Nominal π method.

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

i)End Condenser Method

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



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

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

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

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

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

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

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

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

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

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

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

Limitations

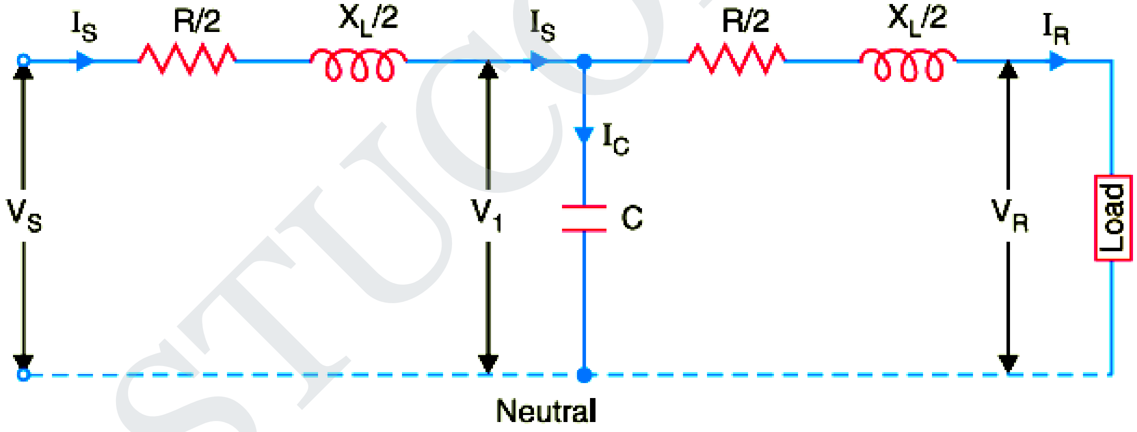
Although end condenser method for the solution of medium lines is simple to work out calculations, yet it has the following drawbacks :

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

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

ii)Nominal T Method

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



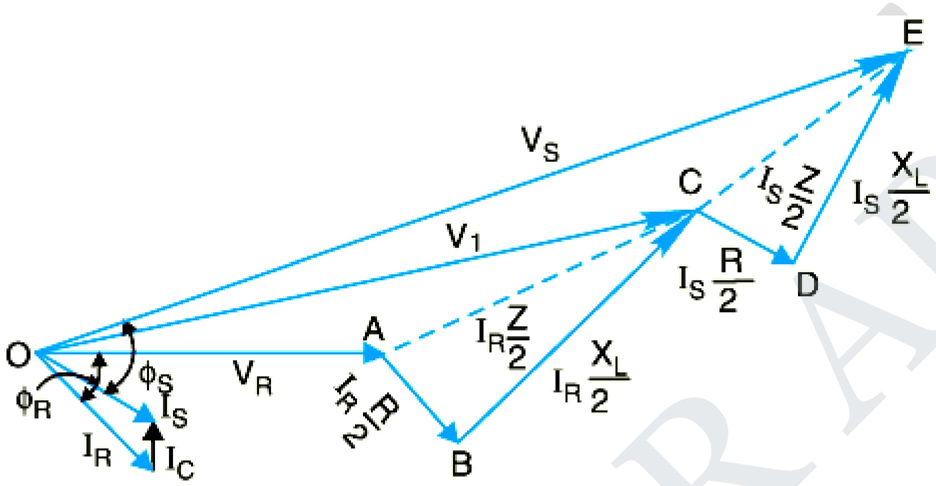
Let

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

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

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

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



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

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

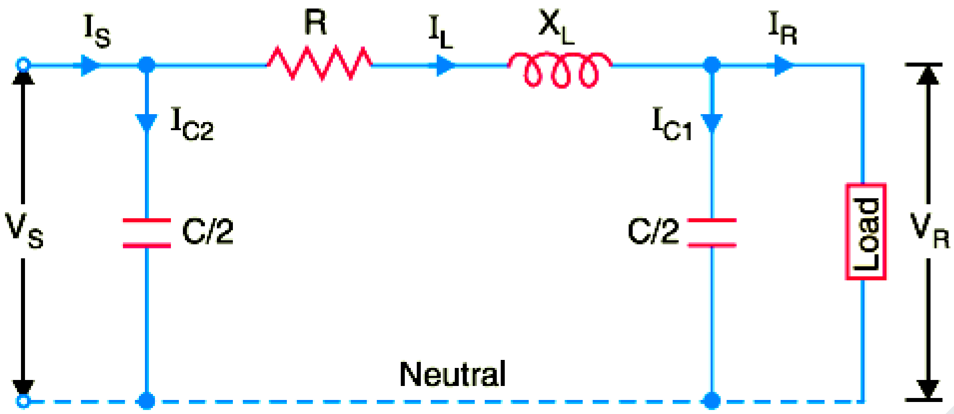
Capacitive current, $\vec{I_C} = j\,\omega\,C\,\vec{V_1} = j\,2\pi f\,C\,\vec{V_1}$

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

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

iii) Nominal π Method

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



Let

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

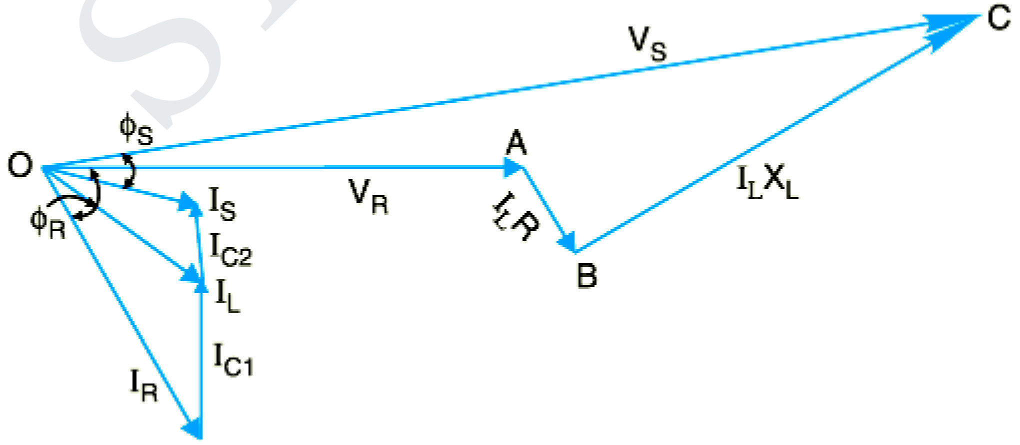
The *phasor diagram for the circuit is shown in Fig. Taking the receiving end voltage as the reference phasor, we have,

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

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

Charging current at load end is

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



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

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

Charging current at the sending end is

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

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

LONG TRANSMISSION LINES

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

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

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

(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.

ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD)

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

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

Let

z = series impedance of the line per unit length
y = shunt admittance of the line per unit length
V = voltage at the end of element towards receiving end
V + dV = voltage at the end of element towards sending end
I + dI = current entering the element dx
I = current leaving the element dx

Then for the small element dx,
z dx = series impedance
y dx = shunt admittance

Obviously, dV = I z dx

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

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

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

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

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

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

The solution of this differential equation is

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

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

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

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

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

The solution of this differential equation is

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

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

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

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

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

$$\therefore \quad V_R = k_1$$

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

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

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

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

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

and

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

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

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

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

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

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

where Y = total shunt admittance of the line

Z = total series impedance of the line

Therefore, expressions for V_S and I_S become :

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

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

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

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

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 coor- dinates, The basic relationshipupon 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

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

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

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

POWER FLOW IN A TRANSMISSION LINE

The power flow in a transmission line can be calculated by considering the system shown in Fig.-3.7. It consists of a single transmission line connected between two buses. These buses are Sending end bus and Receiving end bus

FIG.-. TRANSMISSION LINE POWER FLOW

The line is characterized by its line constants as follows

$$A = |A|\angle\alpha, B = |B|\angle\beta$$

So that the power received at the receiving end is given by

$$S_R = P_R + jQ_R = V_R I_R^*$$

As we know the line equation in terms of $ABCD$ constant are

$$V_S = AV_R + BI_R$$

$$I_S = CV_R + DI_R$$

$$I_R = \frac{V_S - AV_R}{B}$$

$$I_R^* = \left(\frac{V_S - AV_R}{B}\right)^*$$

$$I_R^* = \frac{(|V_S|\angle-\delta) - (|A|\angle-\alpha)(|V_R|\angle 0)}{(|B|\angle-\beta)}$$

We have

$$P_R + jQ_R = (|V_R|\angle 0)\frac{(|V_S|\angle-\delta) - (|A|\angle-\alpha)(|V_R|\angle 0)}{(|B|\angle-\beta)}$$

APPROXIMATION OF POWER FLOW EQUATION

For the transmission line series resistance is very less as compared to series reactance and $|A| \approx 1.0, \alpha \approx 0.0, |B| = Z \approx X, \beta \approx 90^\circ$

Hence (3.45) can be fairly approximated as (3.47)

$$P_R = \frac{|V_R||V_S|}{X} Sin\,\delta \tag{3.47}$$

From (3.47) we conclude that the power transmitted over a transmission line is determined by the voltage at both the ends, the reactance of the line and phase difference between the voltages of both ends. Similarly the power flow between two buses can be given by (3.48)

$$P = \frac{|V_1||V_2|}{X_{12}} Sin(\delta_1 - \delta_2) \tag{3.48}$$

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.

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 is turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cummulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

Factors Affecting Corona

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

(i)Atmosphere

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

(ii) Conductor size.

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

(iii) Spacing between conductors.

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

(iv) Line voltage.

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

Important Terms

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

(i)Critical Disruptive Voltage

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

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

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

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

where g_o = breakdown strength of air at 76 cm of mercury and 25ºC

= 30 kV/cm (*max*) or 21·2 kV/cm (*r.m.s.*)

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

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

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

Under standard conditions, the value of δ = 1.

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

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

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

where m_o = 1 for polished conductors

= 0·98 to 0·92 for dirty conductors

= 0·87 to 0·8 for stranded conductors

(ii) Visual critical voltage

It is the minimum phase-neutral voltage at which corona glow appears all along the line conductors. It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage Vc but at a higher voltage Vv, called visual critical voltage. The phase-neutral effective value of visual critical voltage is given by the following empirical formula : where mV 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.

Corona-Effect on Line Performance.

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.

UNIT III - MECHANICAL DESIGN OF LINES

Mechanical design of OH lines – Line Supports –Types of towers – Stress and Sag Calculation – Effects of Wind and Ice loading. Insulators: Types, voltage distribution in insulator string, improvement of string efficiency, testing of insulators.

Mechanical design of OH lines

Electric power can be carried either by underground cables or overhead transmission and distribution lines. The underground cables are not typically used for power transmission due to two reasons.

1. Power is carried over long distances to remote load centres. Obviously, the installation costs for underground transmission will be huge.
2. Electric power has to be transferred at high voltages for economic reasons. It is very difficult to achieve proper insulation to the cables to withstand higher pressures.

Therefore, power transfer over long distances is done by using overhead lines. With the power demand increase and consequent voltage level rise, power transmission by overhead lines has assumed significant importance. Nevertheless, an overhead line is subjected to various weather conditions and other external interferences. This asks for the use of adequate mechanical safety factors in order to ensure the continuity of line operation. Typically, the strength of the line needs to be such so it can withstand the worst probable weather conditions. This course focuses on the different aspects of mechanical design of overhead lines.

Overhead Line Main Components

An overhead line may be used to transfer or distribute electric power. The proper overhead line operation depends to a big extent upon its mechanical design. While constructing an overhead line, it has to be verified that line mechanical strength is such so as to provide against the most probable weather conditions. Typically, the main elements of an overhead line are:

- Conductors which transfer power from the sending end station to the receiving end station.
- Supports which may be poles or towers. They keep the conductors at an appropriate level above the earth.
- Insulators that are connected to supports and insulate the conductors from the earth.
- Cross arms which give support to the insulators.
- Miscellaneous elements such as phase plates, danger plates, surge arrestors, etc.

Line Supports

The supporting structures for overhead line conductors are different pole and tower types called line supports. Typically, the line supports should have the following characteristics:

- Light in weight without the loss of mechanical strength

- Big mechanical strength to sustain the conductor weight and wind loads etc.
- Longer life span
- Easy conductor accessibility for maintenance
- Cheap in cost and economical to service

The line supports used for electric power transmission and distribution are of different types including wooden poles, steel poles, RCC poles and lattice steel towers. The selection of supporting structure for a specific case is dependent upon the line span, cross-sectional area, line voltage, cost and local circumstances.

Types :

Wooden poles:

They are made of seasoned wood and are appropriate for lines of moderate cross-sectional area and of shorter spans, say up to 50 metres. Such supports are cheap, easily available, provide insulating features and, hence, are widely used for distribution applications in rural locations as an economical proposition. Typically, the wooden poles tend to rot below the earth level, causing foundation failure. In order to avoid this, the portion of the pole below the earth level is impregnated with preservative substances like creosote oil. Double pole arrangements of the 'A' or 'H' type are typically used (Figure 2.) to obtain a bigger transverse strength than could be economically provided by means of single poles. The main disadvantages to wooden supports are:

o Tendency to rot below the earth level
o Relatively smaller life (20-25 years)
o Cannot be used for voltages above 20 kV
o Decreased mechanical strength
o Need occasional inspection

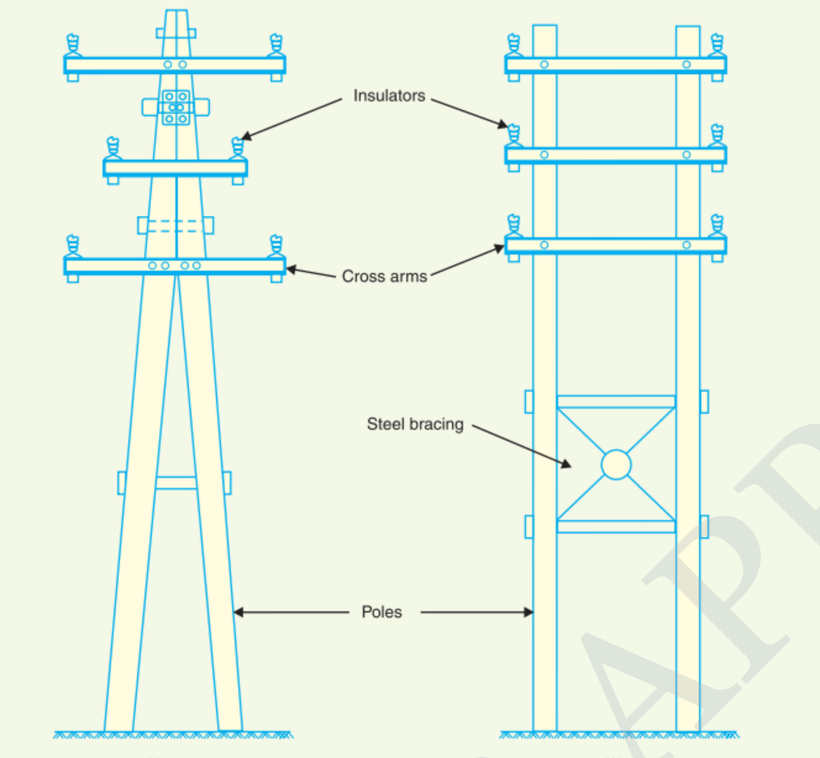


Fig. Wooden poles

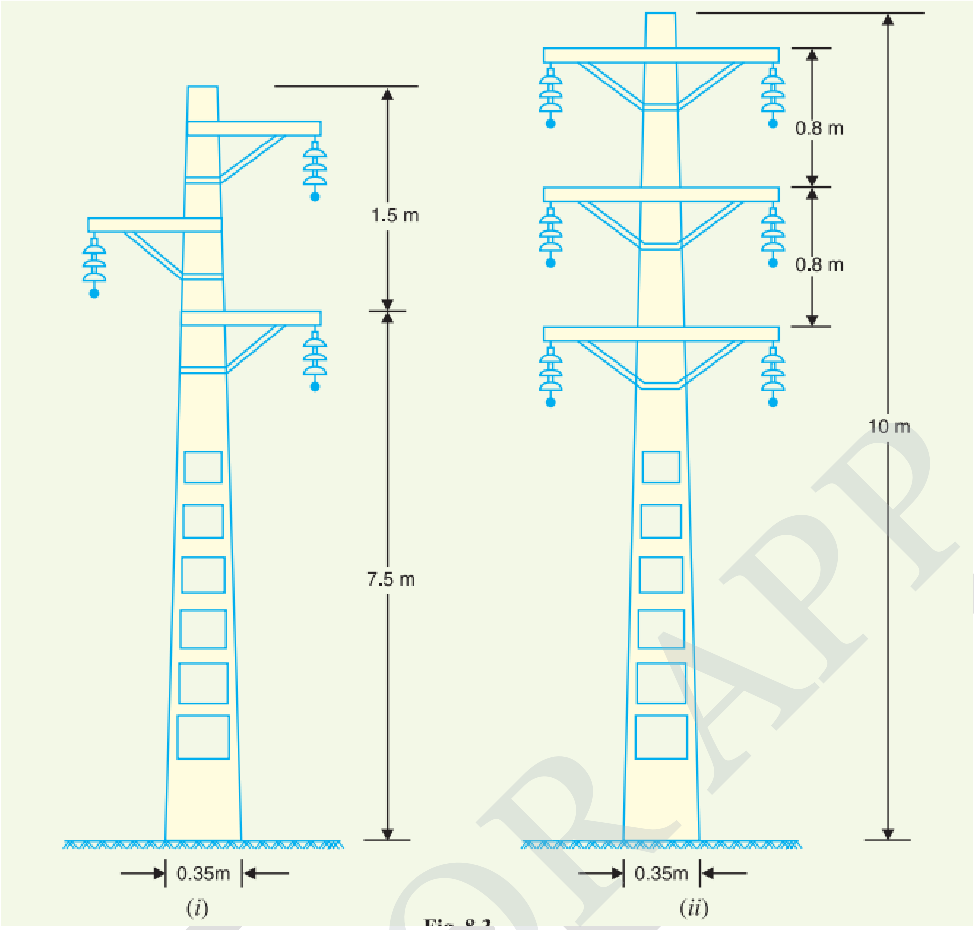
Steel poles.

The steel poles are typically used as a substitute for wooden poles. They have bigger mechanical strength, longer life and allow longer spans. Typically, such poles are used for distribution purposes in the cities. These supports need to be galvanised or painted in order to extend their life. The steel poles are of three types:

o Rail poles
o Tubular poles
o Rolled steel joints

RCC poles.

The reinforced concrete poles have recently become popular as line supports. They have bigger mechanical strength, longer life and allow longer spans than steel poles. Nevertheless, they give good outlook, need little maintenance and have good insulating features. Figure 3 presents RCC poles for single and double circuit. The holes in the poles allow climbing of poles and at the same time decrease the line support weight. The main issue with the use of these poles is the high transport cost owing to their heavy weight. Hence, such poles are typically produced at the site in order to avoid big transportation cost.



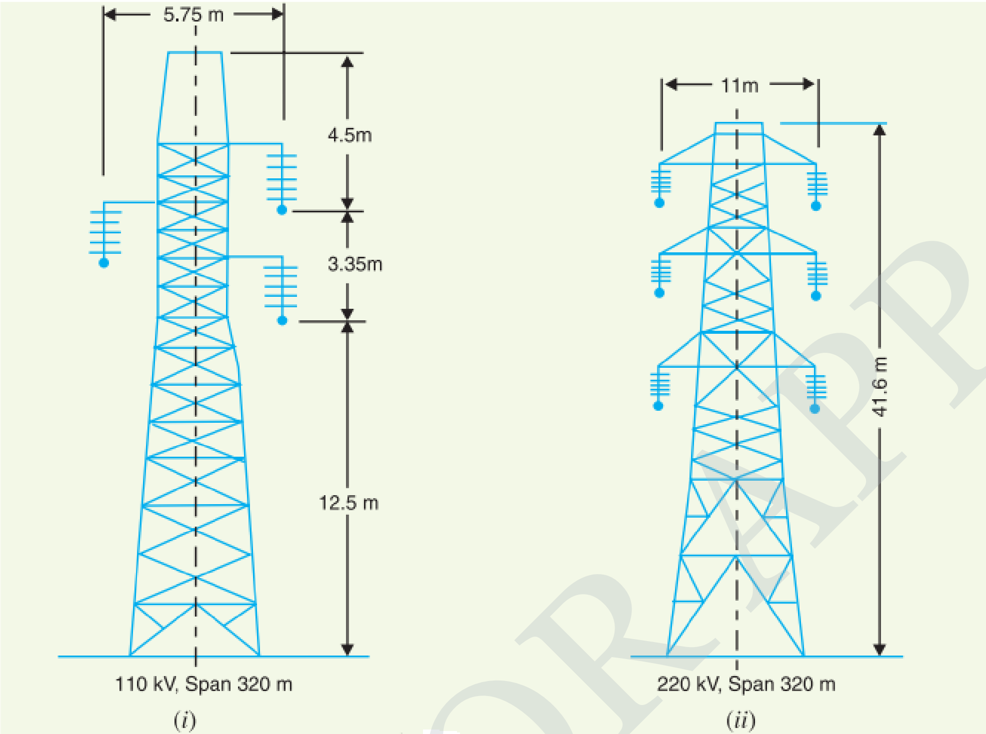
Towers

The electrical tower is defined as the tower which is used for carrying the high voltage (above 230 kV) transmission lines. Such types of towers are made up aluminium or steel which gives them strength for supporting the heavy electrical conductor.

In reality, wooden, steel and reinforced concrete poles are used for distribution installations at low voltages, say up to 11 kV. Nevertheless, for long distance transmission at higher voltage, steel towers are invariably used. Steel towers have bigger mechanical strength, longer life, can sustain most severe climatic conditions and allow the use of longer spans. The risk of interrupted operation due to broken or punctured insulation is significantly decreased owing to longer spans. Typically, tower footings are earthed by driving rods into the ground. This decreases the lightning troubles as each tower acts as a lightning conductor. Figure 3(a) shows a single circuit tower. Nevertheless, at a moderate extra cost, double circuit tower can be provided as presented in Figure 3(b). The double circuit has the benefit that it ensures continuity of supply. In situation there is breakdown of one circuit, the continuity of supply can be kept by the other circuit.

Tower is also classified as

- **Tangent Tower** – It is used for a straight run of the line. Suspension insulators are used with these towers.
- **Deviation Tower** – It is used in a line where the transmission line changes direction.



110 kV, Span 320 m
(*i*)

220 kV, Span 320 m
(*ii*)

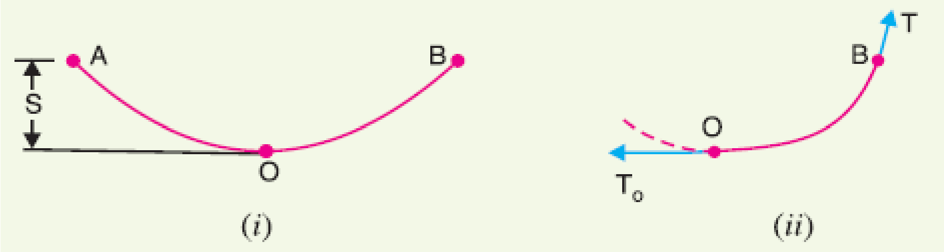
Fig. Steel Towers

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 σαγ.

Fig. shows a conductor suspended between two equilevel supports *A* and *B*. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is *O* and the sag is *S*. The following points may be noted:



(***i***) When the conductor is suspended between two supports at the same level, it takes the shape of catenary. However, if the sag is very small compared with the span, then sag-span curve is like a parabola.

(***ii***) The tension at any point on the conductor acts tangentially. Thus tension *TO* 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.

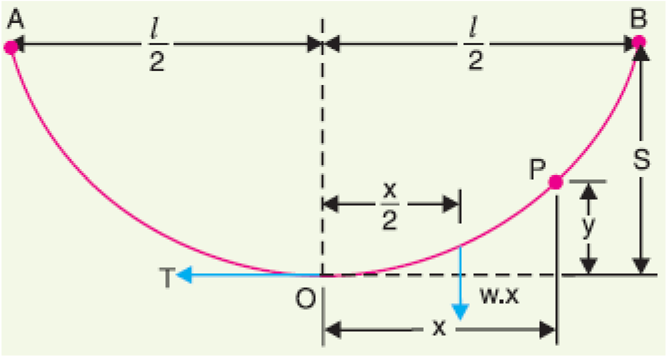
(***iv***) The tension at supports is approximately equal to the horizontal tension acting at any point on the wire. Thus if *T* is the tension at the support *B*, then *T* = *TO*.

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

Calculation of Sag

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

(***i***) Ωηεν συππορτσ αρε ατ εθυαλ λεϖελσ. Consider a conductor between two equilevel supports *A* and *B* with *O* as the lowest point as shown in Fig. It can be proved that lowest point will be at the mid-span.



Let

l = Length of span

w = Weight per unit length of conductor

T = Tension in the conductor.

Consider a point P on the conductor. Taking the lowest point O as the origin, let the coordinates of point P be x and y. Assuming that the curvature is so small that curved length is equal to its horizontal projection (*i.e.*, $OP = x$), the two forces acting on the portion OP of the conductor are :

(***a***) The weight wx of conductor acting at a distance $x/2$ from o

(***b***) The tension T acting at O.

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

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

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

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

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

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

(***ii***) Ωηεν συππορτσ αρε ατ υνεθυαλ λεϖελσ. In hilly areas, we generally come across conductors suspended between supports at unequal levels. Fig. shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O.

Let

l = Span length

h = Difference in levels between two supports

$x1$ = Distance of support at lower level (*i.e.*, A) from O

$x2$ = Distance of support at higher level (*i.e.* B) from O

T = Tension in the conductor

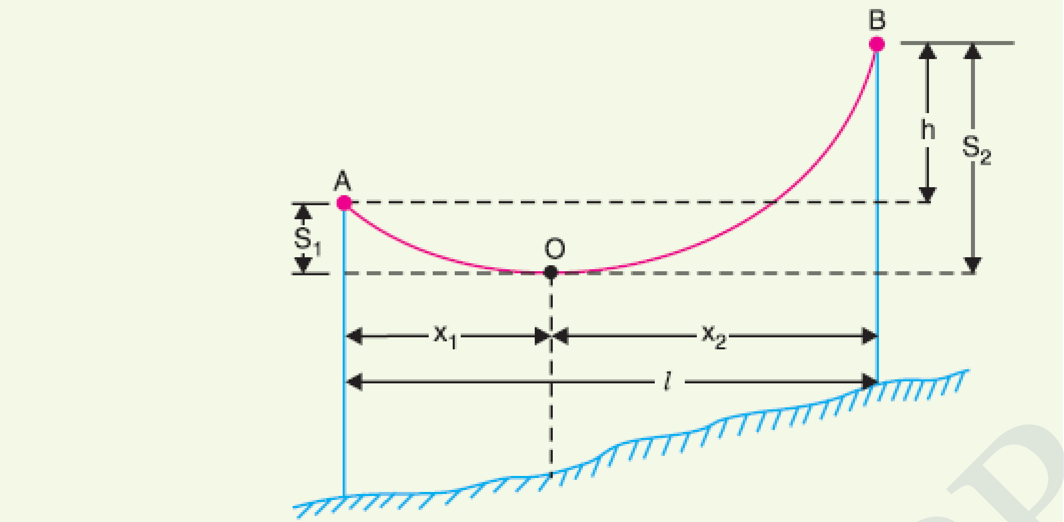


Fig. 8.25

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

$$\therefore \quad S_2 - S_1 = \frac{w\,l}{2T}(x_2 - x_1) \qquad [\because x_1 + x_2 = l]$$

But
$$S_2 - S_1 = h$$

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

or
$$x_2 - x_1 = \frac{2\,Th}{w\,l} \qquad ...(ii)$$

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

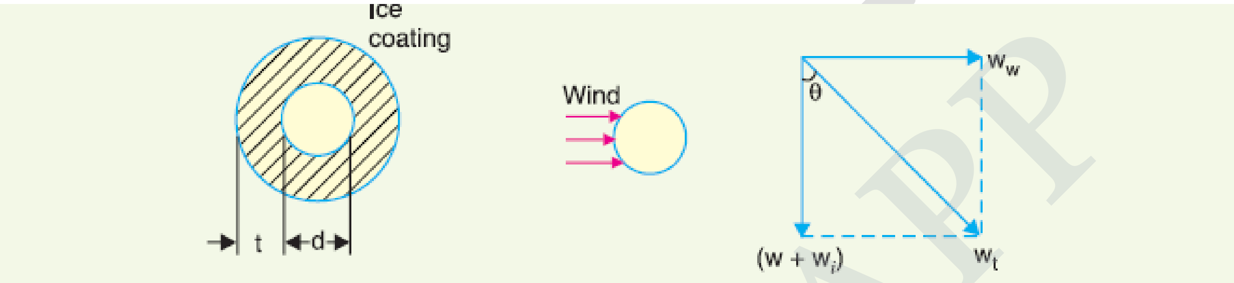
$$x_1 = \frac{l}{2} - \frac{T\,h}{w\,l}$$

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

Having found *x*1 and *x*2, values of *S*1 and *S*2 can be easily calculated.

Effect of wind and ice loading.

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



(*i*) (*ii*) (*iii*)

Fig. 8.26

Total weight of conductor per unit length is

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

where w = weight of conductor per unit length

= conductor material density × volume per unit length

w_i = weight of ice per unit length

= density of ice × volume of ice per unit length

$= \text{density of ice} \times \frac{\pi}{4}[(d + 2t)^2 - d^2] \times 1$

$= \text{density of ice} \times \pi\, t\,(d + t)$*

w_w = wind force per unit length

= wind pressure per unit area × projected area per unit length

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

When the conductor has wind and ice loading also, the following points may be noted :

(i) The conductor sets itself in a plane at an angle θ to the vertical where

$$\tan\theta = \frac{w_w}{w + w_i}$$

(ii) The sag in the conductor is given by :

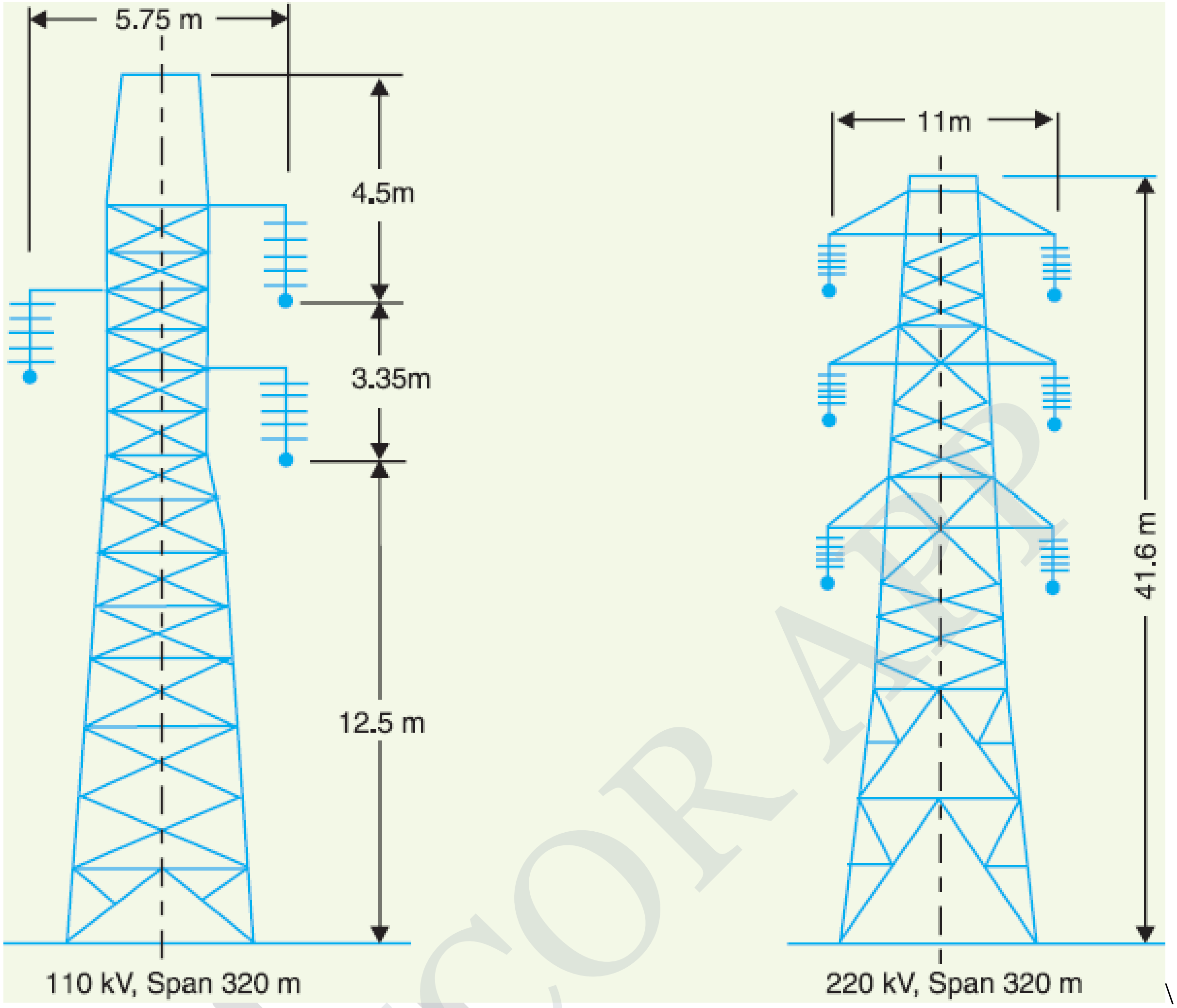
$$S = \frac{w_t\, l^2}{2T}$$

Hence S represents the slant sag in a direction making an angle θ to the vertical. *If no specific mention is made in the problem, then slant slag is calculated by using the above formula.*

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

Insulators

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports *i.e.*, line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of *insulators*. The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth. In general, the insulators should have the following desirable properties :



(i) High mechanical strength in order to withstand conductor load, wind load etc.

(ii) High electrical resistance of insulator material in order to avoid leakage currents to earth.

(iii) High relative permittivity of insulator material in order that dielectric strength is high.

(iv) The insulator material should be non-porous, free from impurities and cracks otherwise the permittivity will be lowered.

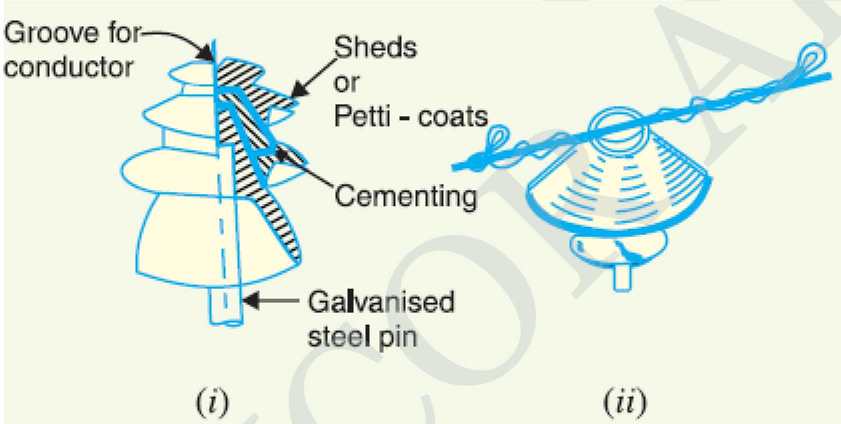
(v) High ratio of puncture strength to flashover.

The most commonly used material for insulators of overhead line is *porcelain* but glass, steatite and special composition materials are also used to a limited extent. Porcelain is produced by firing at a high temperature a mixture of kaolin, feldspar and quartz. It is stronger mechanically than glass, gives less trouble from leakage and is less effected by changes of temperature.

Types of Insulators

The successful operation of an overhead line depends to a considerable extent upon the proper selection of insulators. There are several types of insulators but the most commonly used are pin type, suspension type, strain insulator and shackle insulator.

1. Pin type insulators. The part section of a pin type insulator is shown in Fig. 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 upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.



Causes of insulator failure. Insulators are required to withstand both mechanical and electrical stresses. The latter type is pirmarily due to line voltage and may cause the breakdown of the insulator. The electrical 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. Fig. 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 *i.e.*,

$$\text{Safety factor of insulator} = \frac{\text{Puncture strength}}{\text{Flash - over voltage}}$$

It is desirable that the value of safety factor is high so that flash-over takes place before the insulator gets punctured. For pin type insulators, the value of safety factor is about 10.

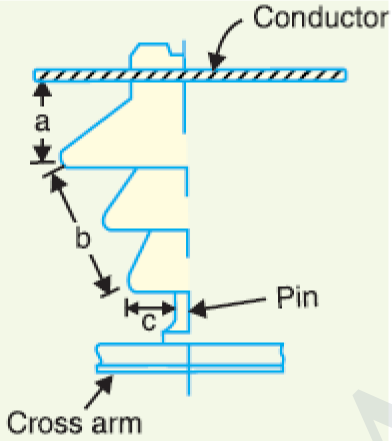
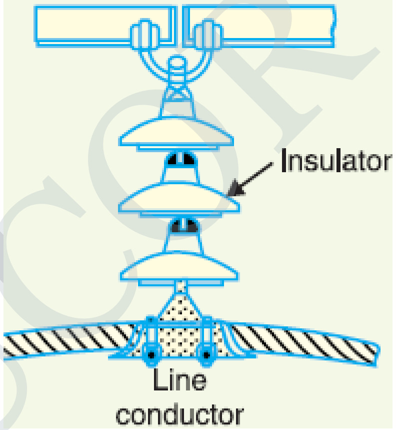


Fig. 8.6



2 Suspension type insulators. The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Fig. . They 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

(i) Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.

(ii) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV.

Depending upon the working voltage, the desired number of discs can be connected in series.

(*iii*) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

(*iv*) The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.

(*v*) In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.

(*vi*) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial 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 Fig. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.

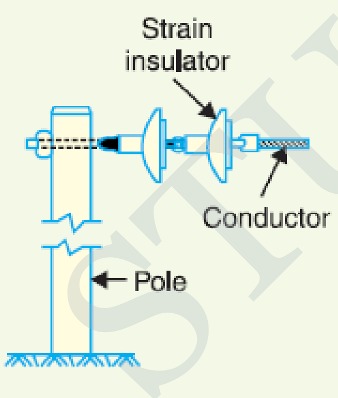


Fig. 8.8. Strain insulator.

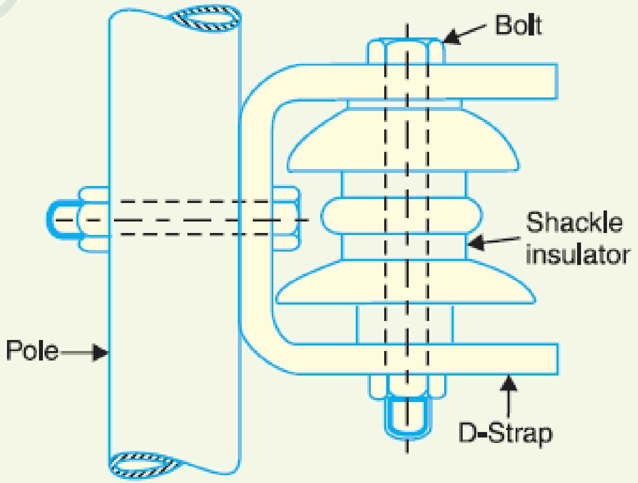
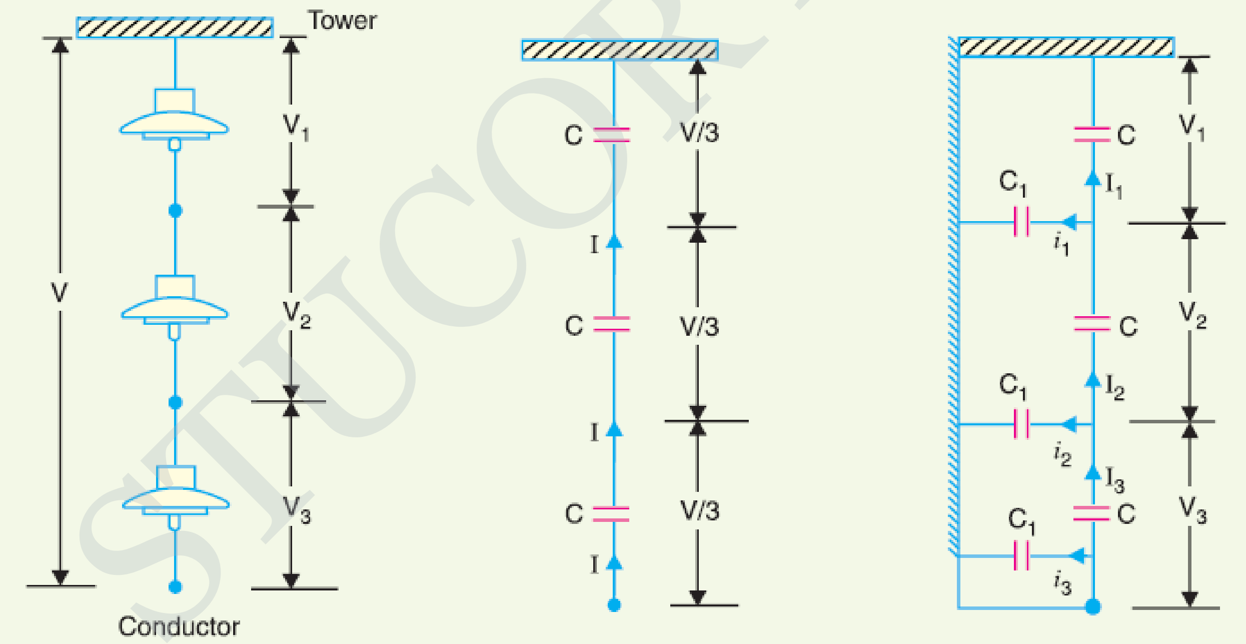


Fig. 8.9

4. Shackle insulators. In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm. Fig. shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

Potential Distribution over Suspension Insulator String

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. (*i*) shows 3-disc string of suspension insulators. The porcelain portion of each disc is inbetween two metal links. Therefore, each disc forms a capacitor *C* as shown in Fig. (*ii*). This is known as *mutual capacitance* or *self-capacitance*. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same *i.e.*, *V*/3 as shown in Fig. (*ii*). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as *shunt capacitance C*1. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. (*iii*)]. 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.(*iii*), *V*3 will be much more than *V*2 or *V*1.



(*i*) (*ii*) (*iii*)

The following points may be noted regarding the potential distribution over a string of suspension insulators :

(*i*) 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.

(*ii*) 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.

(iii) The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalise the potential across each unit. This is fully discussed in Art. 8.8.

(iv) If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective for d.c.

String Efficiency

As stated above, the voltage applied across the string of suspension insulators is not uniformly distributed across various units or discs. The disc nearest to the conductor has much higher potential than the other discs. This unequal potential distribution is undesirable and is usually expressed in terms of string efficiency.

The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as **string efficiency**

i.e.,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. 8.11 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.

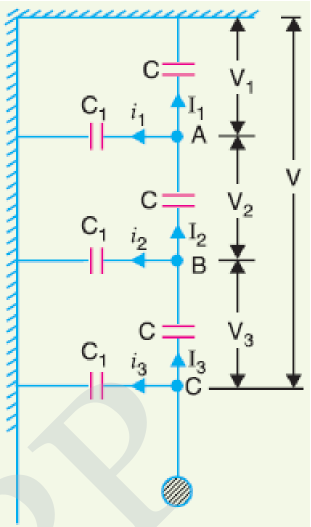


Fig. 8.11

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

$$I_2 = I_1 + i_1$$

or $$V_2 \omega C^* = V_1 \omega C + V_1 \omega C_1$$

or $$V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

$$\therefore \quad V_2 = V_1 (1 + K) \qquad ...(i)$$

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

$$I_3 = I_2 + i_2$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2)\, \omega C_1 \dagger$$

or $$V_3 \omega C = V_2 \omega C + (V_1 + V_2)\, \omega K C$$

or $$\begin{aligned} V_3 &= V_2 + (V_1 + V_2)K \\ &= KV_1 + V_2 (1 + K) \\ &= KV_1 + V_1 (1 + K)^2 \qquad [\because V_2 = V_1 (1 + K)] \\ &= V_1 [K + (1 + K)^2] \end{aligned}$$

$$\therefore \quad V_3 = V_1[1 + 3K + K^2] \qquad ...(ii)$$

Voltage between conductor and earth (*i.e.*, tower) is

$$\begin{aligned} V &= V_1 + V_2 + V_3 \\ &= V_1 + V_1(1 + K) + V_1 (1 + 3K + K^2) \\ &= V_1 (3 + 4K + K^2) \end{aligned}$$

$$\therefore \quad V = V_1(1 + K)(3 + K) \qquad ...(iii)$$

From expressions (*i*), (*ii*) and (*iii*), we get,

$$\frac{V_1}{1} = \frac{V_2}{1 + K} = \frac{V_3}{1 + 3K + K^2} = \frac{V}{(1 + K)(3 + K)} \qquad ...(iv)$$

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

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**

$$\text{Voltage across second unit from top, } V_2 = V_1 (1 + K)$$

$$\text{Voltage across third unit from top, } V_3 = V_1 (1 + 3K + K^2)$$

$$\%\text{age String efficiency} = \frac{\text{Voltage across string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100$$

$$= \frac{V}{3 \times V_3} \times 100$$

The following points may be noted from the above mathematical analysis :

(*i*) If $K = 0{\cdot}2$ (Say), then from exp. (*iv*), we get, $V2 = 1{\cdot}2\ V1$ and $V3 = 1{\cdot}64\ V1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(*ii*) The greater the value of K (= $C1/C$), the more non-uniform is the potential across the discs and lesser is the string efficiency.

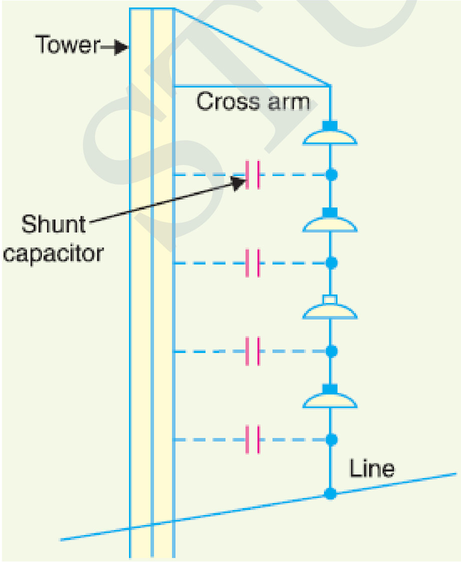
(*iii*) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one.

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 crossarm is approached. If the insulation of the highest stressed insulator (*i.e.* nearest to conductor) breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates to equalise the potential across the various units of the string *i.e.* to improve the string efficiency. The various methods for this purpose are:

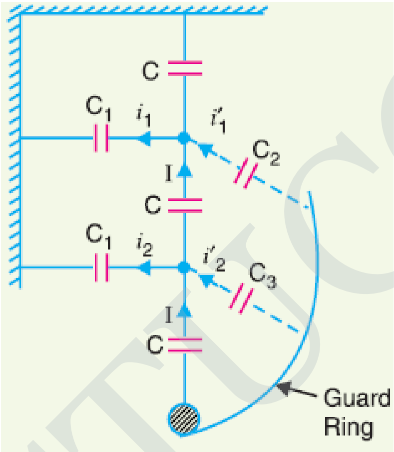
(i) By using longer cross-arms.

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, $K = 0{\cdot}1$ 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 equalise 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*21, *i*22 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



Important Points
While solving problems relating to string efficiency, the following points must be kept in mind:
(*i*) The maximum voltage appears across the disc nearest to the conductror (*i.e.*, line conductor).
(*ii*) The voltage across the string is equal to phase voltage *i.e.*, Voltage across string = Voltage between line and earth = Phase Voltage
(*iii*) Line Voltage = 3 √ Voltage across string

Testing of insulators

Following are the different types of tests that are carried out on **overhead line insulators.**

1. Flashover tests
2. Performance tests
3. Routine tests

Flashover tests of insulators

Three types of flashover tests are conducted before the insulator is said to have passed the flashover test.

1. Power frequency dry flashover test
2. Power frequency wet flashover test
3. Impulse frequency flashover test

Power frequency dry flashover test

The insulator to be tested is mounted in the same manner in which it is to be used. Then, a variable voltage source of power frequency is connected between the electrodes of the insulator. The voltage is gradually increased up to the specified voltage. This specified voltage is less than the minimum flashover voltage. The voltage at which surrounding air of the insulator breaks down and become conductive is known as **flashover voltage**. The insulator must be capable of withstanding the specified voltage for one minute without flashover.

Power frequency wet flashover test (Rain test)

In this test also, the insulator to be tested is mounted in the same manner in which it is to be used. Similar to the above test, a variable voltage source of power frequency is connected between the electrodes. Additionally, in this test, the insulator is sprayed with water at an angle of 45° in such a manner that its precipitation should not be more than 5.08 mm/min. The voltage is then gradually increased up to the specified voltage. The voltage is maintained at the specified value for 30 seconds or one minute and the insulator is observed for puncture or breakdown. If the voltage is maintained for one minute, this test is also called as **one-minute rain test**.

Impulse frequency flashover test

This test is to ensure that the insulator is capable of sustaining high voltage surges caused by lightning. The insulator under test is mounted in the same manner as in above tests. An impulse voltage generator which generates a very high voltage at a frequency of several hundred kilohertz is connected to the insulator. This voltage is applied to the insulator and spark-over voltage is noted. The ratio of impulse spark-over voltage to spark-over voltage at power frequency is called as the **impulse ratio**. This ratio should be approximately 1.4 for pin type insulators and 1.3 for suspension type insulators.

$$\therefore \text{Impulse Ratio} = \frac{\text{Impulse Frequency Flashover Voltage}}{\text{Power Frequency Flashover Voltage}}$$

Performance tests of insulators

1. Temperature cycle test
2. Puncture voltage test
3. Mechanical strength test
4. Electro-mechanical test
5. Porosity test

Temperature cycle test

In this test, the insulator under test is first heated in water at 70° for one hour. Then the insulator is immediately cooled at 7° for another hour. This cycle is repeated three times. Then the insulator is dried and its glazing is thoroughly observed for any damages or deterioration.

Puncture voltage test

The purpose of this test is to determine the puncture voltage. The insulator to be tested is suspended in insulating oil. A voltage is applied and increased gradually until the puncture takes place. The voltage at which insulator starts to puncture is called as **puncture voltage**. This voltage is usually 30% higher than that of the dry flash-over voltage for a suspension type insulators.

Mechanical strength test

In this test, the insulator under test is applied by 250% of the maximum working load for one minute. This test is conducted to determine the ultimate mechanical strength of the insulator.

Electro-mechanical test

This test is conducted only for suspension type insulators. In this test, a tensile stress of 250% of maximum working tensile stress is applied to the insulator. After this, the insulator is tested for 75% of dry spark-over voltage.

Porosity test

In this test, a freshly manufactured insulator sample is broken into pieces. These pieces are then immersed into a 0.5% to 1% alcohol solution fuchsine dye under pressure of 150 kg/cm^2 for several hours (say 24 hours). After that, the pieces are removed from the solution and examined for the penetration of the dye into it. This test indicates the degree of porosity.

Routine tests of insulators

1. High voltage test
2. Proof load test
3. Corrosion test

High voltage test

This test is usually carried out for pin insulators. In this test, the insulator is inverted and placed into the water up to the neck. The spindle hole is also filled with water and a high voltage is applied for 5 minutes. The insulator should remain undamaged after this test.

Proof load test

In this test, each insulator is applied with 20% in excess of working mechanical load (say tensile load) for one minute. The insulator should remain undamaged after this test.

Corrosion test

In this test, the insulator with its metal fitting is suspended into a copper sulfate solution for one minute. Then the insulator is removed from the solution and wiped and cleaned. This procedure is repeated for four times. Then the insulator is examined for any metal deposits on it. There should be zero metal deposits on the insulator.

UNIT IV UNDER GROUND CABILITYS

Underground cabilitys - Types of cabilitys – Construction of single core and 3 core Cabilitys - Insulation Resistance – Potential Gradient - Capacitance of Single-core and 3 core cabilitys - Grading of cabilitys - Power factor and heating of cabilitys– DC cabilitys.

UNDERGROUND CABLES

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

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

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

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

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

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

CONSTRUCTION OF CABLES

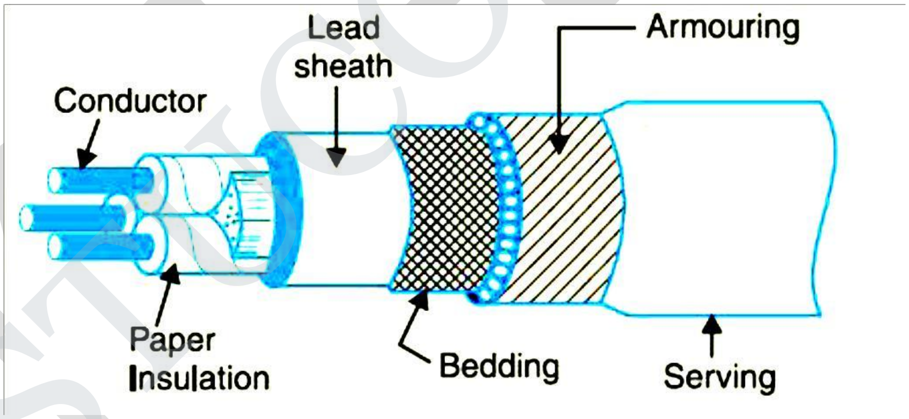


Fig shows the general construction of a 3-conductor cable. The various parts are

a)Cores or Conductors

A cable may have one or more than one core (conductor) depending upon the type ofservice 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 armouring.

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.

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-hygroscopici.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 form some major drawbacks viz., readily absorbs moisture, maximum safe temperature is low (about 38ºC), soft and liable to damage due to rough handling and ages when exposed to light. Therefore, pure rubber cannot be used as an insulating material.

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 150ºC. The whole process is called vulcanisation and the product obtained is known as vulcanised India rubber. Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using VIR insulation have tinned copper conductor. The VIR insulation is generally used for low and moderate voltage cables.

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 gell 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.

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.

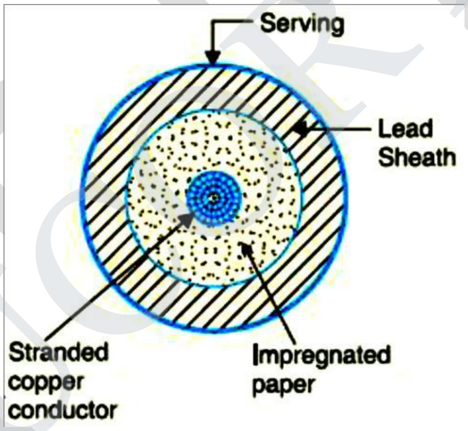
However, the latter method of classification is generally preferred,

- 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

according to which cables can be divided into the following groups:

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

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



For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand. Fig. shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (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.

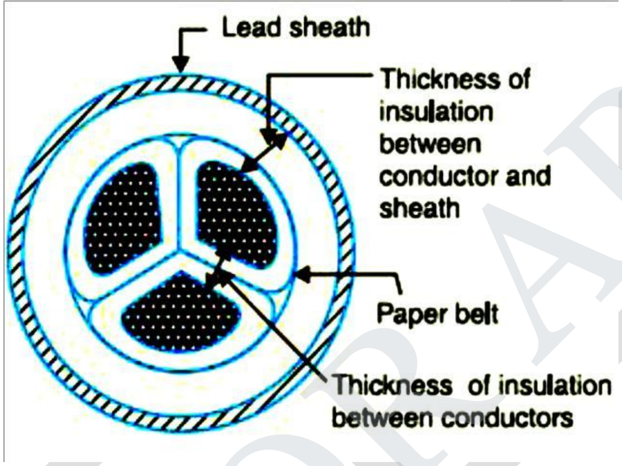
Cable For 3-Phase

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 areused. The following types of cables are generally used for 3-phase service :

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

1. Belted Cables

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



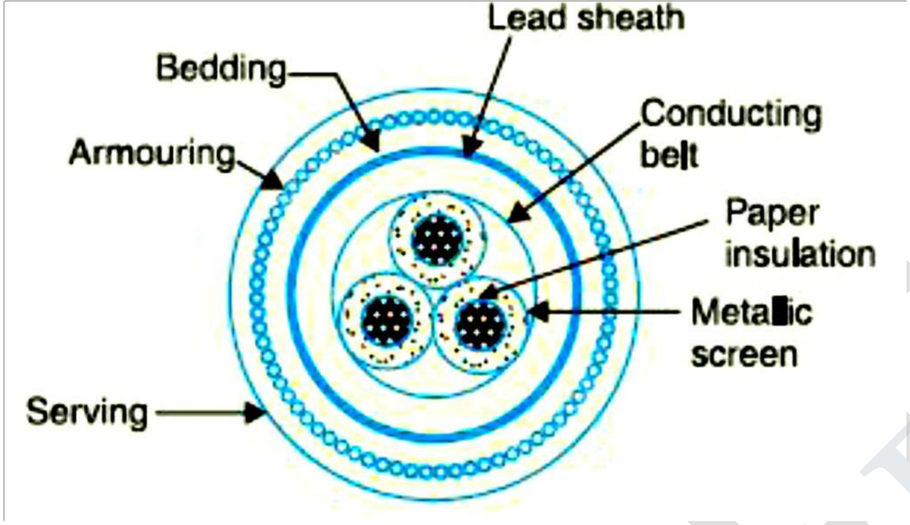
Another layer of impregnated paper tape, called paper belt is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of non circular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (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

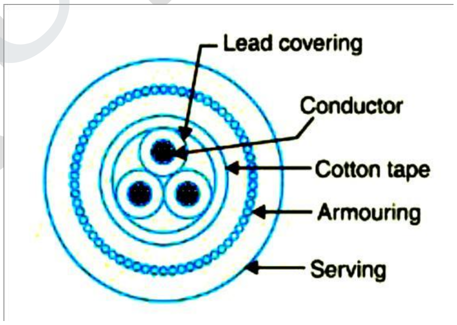


Fig. shows the constructional details of a 3-core S.L. (separate lead) type cable. It is basically H-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main 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.

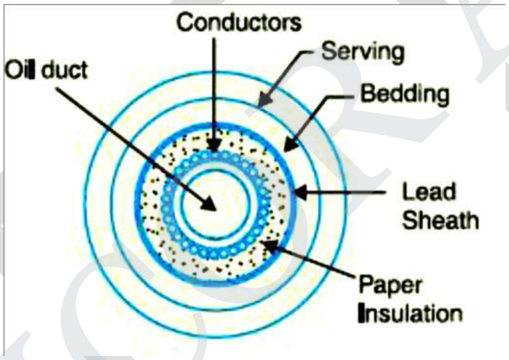
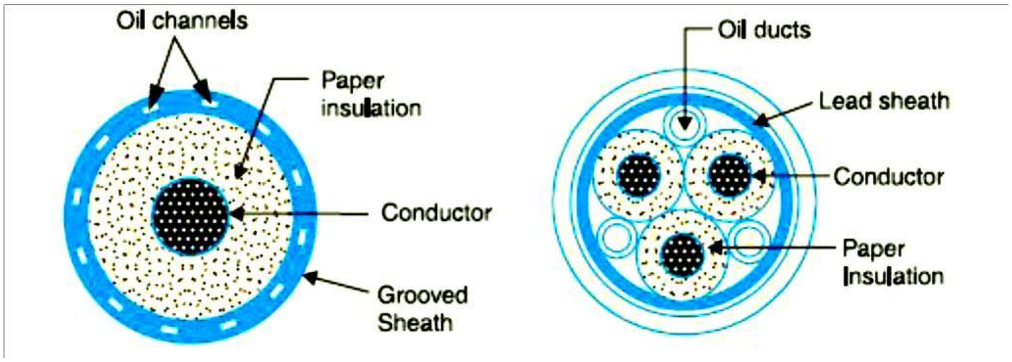


Fig. shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the center by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel 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 them etallic sheath as shown. In the 3-core oil-filler cable shown in Fig. the oil ducts are located in the filler spaces. These channels are composed of perforated metalribbon tubing and are at earth potential.

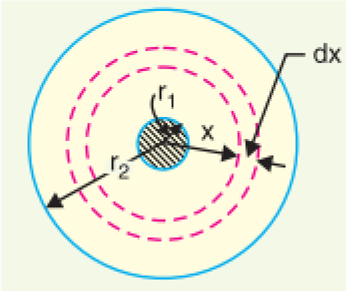


(ii)Gas Pressure Cable

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.

Insulation Resistance of a Single-Core Cable



The cable conductor is provided with a suitable thickness of insulating material in order to prevent leakage current. The path for leakage current is radial through the insulation. The opposition offered by insulation to leakage current is known as insulation resistance of the cable. For satisfactory operation, the insulation resistance of the cable should be very high.

Consider a single-core cable of conductor radius *r*1 and internal sheath radius *r*2 as shown in Fig. Let *l* be the length of the cable and ρ□be the resistivity of the insulation. Consider a very small layer of insulation of thickness *dx* at a radius *x*. The length through which leakage current tends to flow is *dx* and the area of X-section offered to this flow is 2*πxl*.

∴ Insulation resistance of considered layer

$$= \rho \frac{dx}{2\pi x l}$$

Insulation resistance of the whole cable is

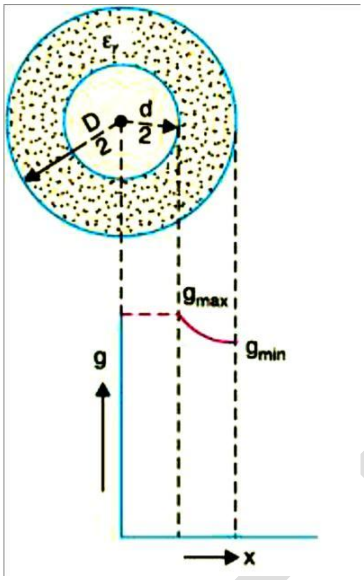
$$R = \int_{r_1}^{r_2} \rho \frac{dx}{2\pi x l} = \frac{\rho}{2\pi l} \int_{r_1}^{r_2} \frac{1}{x}\, dx$$

$$\therefore \quad R = \frac{\rho}{2\pi l} \log_e \frac{r_2}{r_1}$$

This shows that insulation resistance of a cable is inversely proportional to its length. In other words, if the cable length increases, its insulation resistance decreases and *vice-versa*.

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. The electric intensity at a point x metres from the centre of the cable is



$$E_x = \frac{Q}{2\pi\varepsilon_o\varepsilon_r x} \text{ volts/m}$$

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

$$g = E_x$$

or $$g = \frac{Q}{2\pi\varepsilon_o\varepsilon_r x} \text{ volts/m} \quad \text{...(i)}$$

As proved, potential difference V between conductor and sheath is

$$V = \frac{Q}{2\pi\varepsilon_o\varepsilon_r}\log_e\frac{D}{d} \text{ volts}$$

or $$Q = \frac{2\pi\varepsilon_o\varepsilon_r V}{\log_e\frac{D}{d}} \quad \text{...(ii)}$$

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

$$g = \frac{\frac{2\pi\varepsilon_o\varepsilon_r V}{\log_e D/d}}{2\pi\varepsilon_o\varepsilon_r x} = \frac{V}{x\log_e\frac{D}{d}} \text{ volts/m} \quad \text{...(iii)}$$

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

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

Minimum potential gradient is

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

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

The variation of stress in the dielectric is shown in Fig. It is clear that dielectric stress is maximum at the conductor surface and its value goes on decreasing as we move away from the conductor. It may be noted that maximum stress is an important consideration in the design of a cable. For instance, if a cable is to be operated at such a voltage that maximum stress is 5 kV/mm, then the insulation used must have a dielectric strength of at least 5 kV/mm, otherwise breakdown of the cable will become inevitable.

Most Economical Size of Conductor

It has already been shown that maximum stress in a cable occurs at the surface of the conductor. For safe working of the cable, dielectric strength of the insulation should be more than the maximums tress. Rewriting the expression for maximum stress, we get,

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

The values of working voltage V and internal sheath diameter D have to be kept fixed at certain values due to design considerations. This leaves conductor diameter d to be the only variable in exp.(i). For given values of V and D, the most economical conductor diameter will be one for which gmax has a minimum value. The value of gmax will be minimum when d loge D/d is maximum i.e.

$$\frac{d}{dd}\left[d \log_e \frac{D}{d}\right] = 0$$

$$\text{or} \quad \log_e \frac{D}{d} + d \cdot \frac{d}{D} \cdot \frac{-D}{d^2} = 0$$

$$\text{or} \quad \log_e (D/d) - 1 = 0$$

$$\text{or} \quad \log_e (D/d) = 1$$

$$\text{or} \quad (D/d) = e = 2{\cdot}718$$

Most economical conductor diameter is

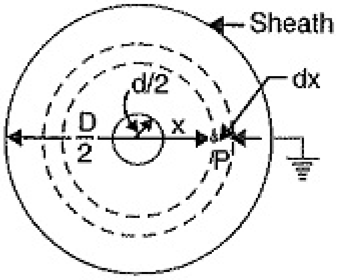
$$d = \frac{D}{2.718}$$

and the value of *gmax* under this condition is

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

Capacitance of Single Core Cable

A Capacitance of Single Core Cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a Capacitance of Single Core Cable with conductor diameter d and inner sheath diameter D (Fig. 11.13). Let the charge per metre axial length of the cable be Q coulombs and e be the permittivity of the insulation material between core and lead sheath. Obviously ε = ε0εr where εr is the relative permit-tivity of the insulation.



Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is =2 π x X 1 = 2 π x m2 Electric flux density at any point P on the considered cylinder is Electric flux density at any point P on the considered cylinder is

$$D_x = \frac{Q}{2\pi x} \text{ C/m}^2$$

Electric intensity at point P,

$$E_x = \frac{D_x}{\varepsilon} = \frac{Q}{2\pi x \varepsilon} = \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} \text{ volts/m}$$

The work done in moving a unit positive charge from point P through a distance dx in the direc-tion of electric field is Ex dx. Hence, the work done in moving a unit positive charge from conductor to sheath, which is the potential difference V between conductor and sheath, is given by:

$$V = \int_{d/2}^{D/2} E_x \, dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \varepsilon_0 \varepsilon_r} dx = \frac{Q}{2\pi \varepsilon_0 \varepsilon_r} \log_e \frac{D}{d}$$

Capacitance of the cable is

$$C = \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi\,\varepsilon_0\varepsilon_r}\log_e\frac{D}{d}}\ \text{F/m}$$

$$= \frac{2\pi\,\varepsilon_o\varepsilon_r}{\log_e(D/d)}\ \text{F/m}$$

$$= \frac{2\pi\times 8{\cdot}854\times 10^{-12}\times\varepsilon_r}{2{\cdot}303\log_{10}(D/d)}\ \text{F/m}$$

$$= \frac{\varepsilon_r}{41{\cdot}4\log_{10}(D/d)}\times 10^{-9}\ \text{F/m}$$

GRADING OF CABLES

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

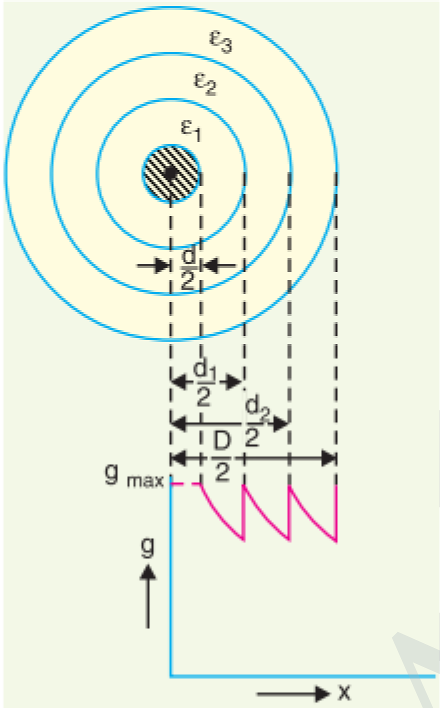
It has already been shown that electrostatic stress in a single core cable has a maximum value (gmax) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon gmax i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than gmax .If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily over strong. The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size.

Secondly, it may lead to the 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:

1. Capacitance grading
2. Intersheath grading

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 εr of any layer is inversely proportional to its distance from the centre. Under such conditions, the value of potential gradient at any point in the dieletric is constant and is independent of its distance from the centre.

In Fig. there are three dielectrics of outer diameter *d*1, *d*2 and *D* and of relative permittivity ε1, ε2 and ε3 respectively. If the permittivities are such that ε1 > ε2 > ε3 and the three dielectrics are worked at the same maximum stress, then,

$$\frac{1}{\varepsilon_1 d} = \frac{1}{\varepsilon_2 d_1} = \frac{1^{\dagger}}{\varepsilon_3 d_2}$$

or $$\varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

Potential difference across the inner layer is

$$V_1 = \int_{d/2}^{d_1/2} g\,dx = \int_{d/2}^{d_1/2} \frac{Q}{2\pi\,\varepsilon_0\,\varepsilon_1\,x}\,dx$$

$$= \frac{Q}{2\pi\,\varepsilon_0\,\varepsilon_1}\log_e\frac{d_1}{d} = \frac{g_{max}}{2}\,d\log_e\frac{d_1}{d}\left[\because\quad \frac{Q}{2\pi\,\varepsilon_0\,\varepsilon_1} = \frac{g_{max}}{2}\,d\right]$$

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

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

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

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

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

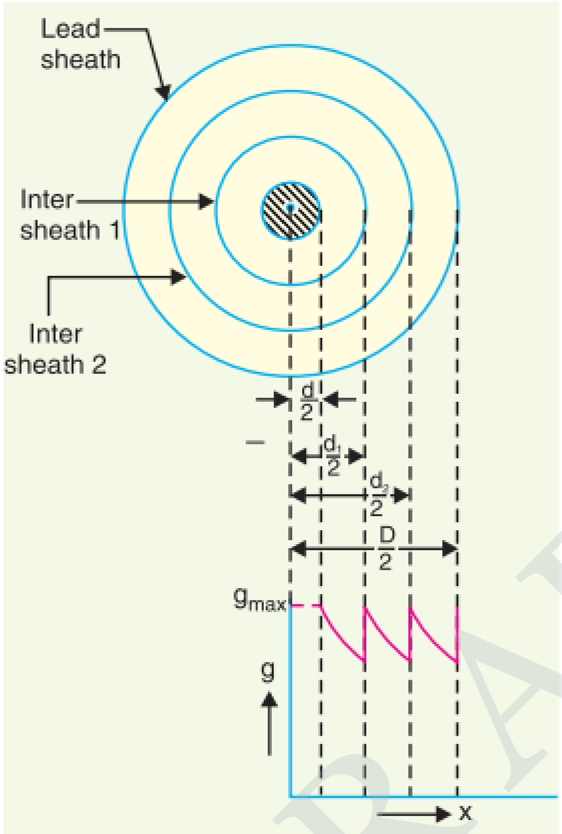
If the cable had homogeneous dielectric, then, for the same values of d, D and g_{max}, the permissible potential difference between core and earthed sheath would have been

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

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 inbetween the core potential and earth potential. This arrangement im-proves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

Consider a cable of core diameter *d* and outer lead sheath of diameter *D*. Suppose that two intersheaths of diameters *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 likea homogeneous single core cable.



Maximum stress between core and intersheath 1 is

$$g_{1max} = \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}}$$

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

$$g_{3max} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

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

$$g_{1max} = g_{2max} = g_{3max} = g_{max} \text{ (say)}$$

$$\therefore \quad \frac{V_1}{\frac{d}{2}\log_e \frac{d_1}{d}} = \frac{V_2}{\frac{d_1}{2}\log_e \frac{d_2}{d_1}} = \frac{V_3}{\frac{d_2}{2}\log_e \frac{D}{d_2}}$$

As the cable behaves like three capacitors in series, therefore, all the potentials are in phase *i.e.* Voltage between conductor and earthed lead sheath is

$$V = V_1 + V_2 + V_3$$

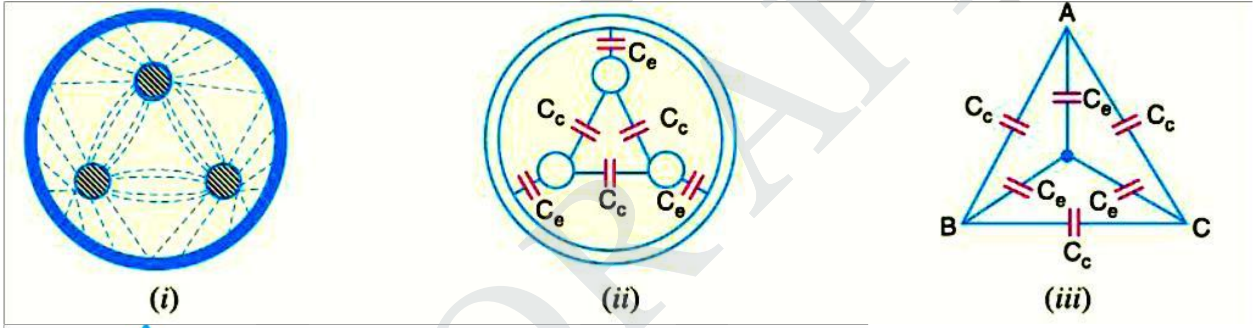
Inter sheath grading has three principal disadvantages. Firstly, there are complications in fixing the sheath potentials. Secondly, the inter sheaths are likely to be damaged during transportation and installation which might result in local concentrations of potential gradient. Thirdly, there are considerable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

Capacitance of 3-core Cable

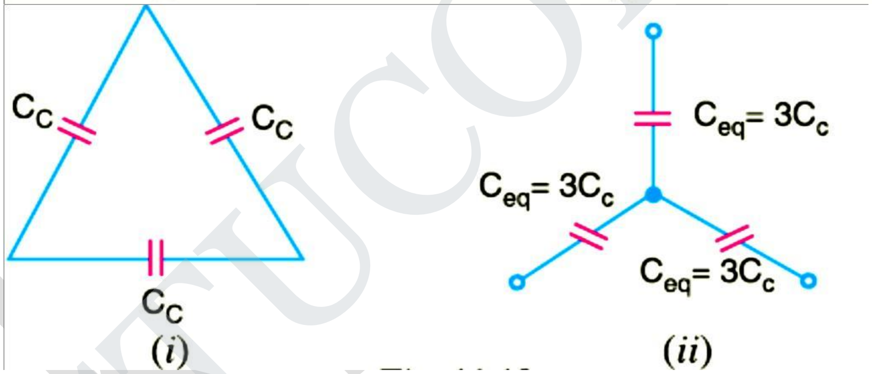
The capacitance of a cable system is much more important than that of overhead line because in cables

i. conductors are nearer to each other and to the earthed sheath
ii. they are separated bya 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 Cc and conductor-earth capacitances Ceas shown in Fig.(ii). The three Cc are delta connected whereas the three Ceare star connected, the sheath forming the star point

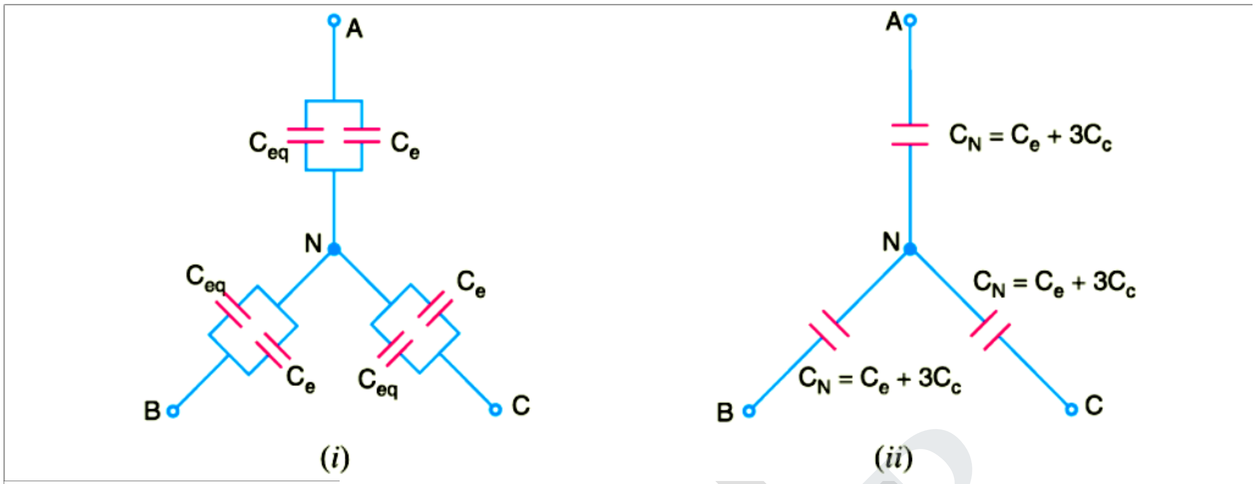


(i) (ii) (iii)



(i) (ii)

They lay of a belted cable makes it reasonable to assume equality of each Cc and each Ce. The three delta connected capacitances Cc (i)can be converted into equivalent star connected capacitances as shown in Fig. It can be easily *shown that equivalent star capacitance Ceqis equal to three times the delta capacitance Cc i.e. Ceq= 3Cc. 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.



$$\begin{aligned} C_N &= C_e + C_{eq} \\ &= C_e + 3C_c \end{aligned}$$

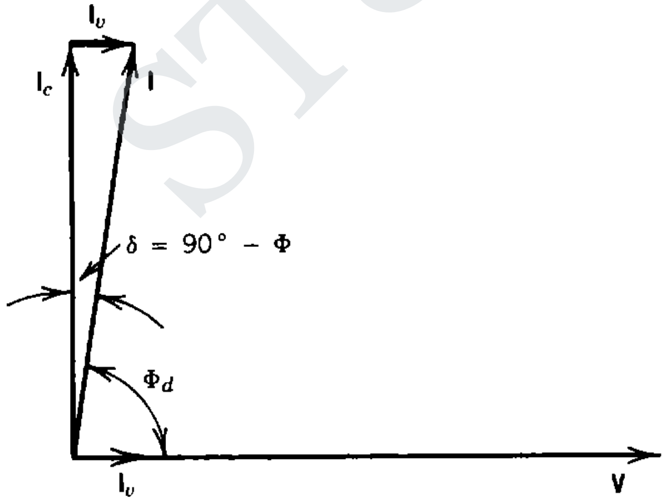
If *Vph* is the phase voltage, then charging current *IC* is given by ;

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

Power factor and heating of cabilitys

When a voltage is applied across a perfect dielectric, there is no dielectric loss because the capacitor current I_c is at 90^o ahead of the voltage V.

In practice, there is a small current component I_d (leakage current) that in phase with voltage V, so, the total current I leads the voltage V by an angle less than 90 as shown in figure.



Power factor of dielectric :

$$= \cos \phi_d = \cos (90-\delta) = \sin \delta$$

This provides a useful measure of the quality of the cable dielectric.

$$\cos \Phi_d = \frac{\text{losses in dielectric (W)}}{\text{apparent power (VA)}}$$

For a good dielectric insulation, ϕ_d is close to 90°.

$P_d = I.\ V.\ \cos\phi_d$

$\cos \phi_d = \sin\delta = \tan \delta = \delta$ (rad)

δ is called dielectric loss angle.

The dielectric Losses: P_d

$$P_d = I_d.V = I_c.\tan\delta.V = I_c.V.\delta \implies I_c = \omega CV$$

$$P_d = \omega CV^2\delta \qquad \delta \text{ is in radians}$$

C: Cable capacitance.

V: operating voltage

Since $\delta = 90 - \phi_d$ and $\delta < 0.5^o$ for most cables.

Here $\cos \phi_d$ should be very small under all operating conditions.

If it is large, the power loss is large and the insulation temperature rises. The rise in temperature causes a rise in power loss in the dielectric which again results in additional temperature rise. If the temperature continues to increase, the cable insulation will be damaged.

Heating of Cables

- Core loss - Copper loss in conductor
- Dielectric loss - Dielectric losses in cable insulation
- Intersheath loss - Losses in metallic sheathings and armouring

DC Cables

DC cable systems have a similar structure to AC cable systems, but they make much greater demands on the insulation material and on the joint technology. Many cable systems used in the DC grid have a paper-insulated, mass-impregnated insulation (MI). With this form of insulation, a large number of layers of paper are wrapped around the copper conductor and then impregnated with an impregnating compound.

This technology has been tried and tested and also offers yet another advantage: the insulating compound can rectify small faults in the insulation, rendering it to a certain degree “self-restoring”.

The main disadvantage of this technology is that the cable joints are extremely complicated to install as they have to be wrapped on site. Of late, cables with plastic insulation have started to be used. Initial experiences with these are currently being gained in the voltage level up to 320 kilovolts.

Advantages:

- No reactive power required during operation (one-off charging capacity at switch-on)
- Longer cable routes are possible
- Statutory prioritisation of underground cables for DC links

Problems

1.Compute the capacitance of the cable per phase, charging current per phase and total charging KVAR of a 33kv 3 phase underground feeder, 4km long uses three single core cables. The diameter of each conductor is 2.5cm and an insulation thickness of 0.5 cm mm and the relative permittivity of 3.

Solution.

(i) Capacitance of cable/phase, $C = \dfrac{\varepsilon_r\ l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9}$ F

Here $\varepsilon_r = 3$; $l = 4\text{ km} = 4000\text{ m}$

$d = 2 \cdot 5$ cm ; $D = 2.5 + 2 \times 0.5 = 3.5$ cm

Putting these values in the above expression, we get,

$$C = \frac{3 \times 4000 \times 10^{-9}}{41 \cdot 4 \times \log_{10}(3 \cdot 5 / 2 \cdot 5)} = \mathbf{1984 \times 10^{-9}\ F}$$

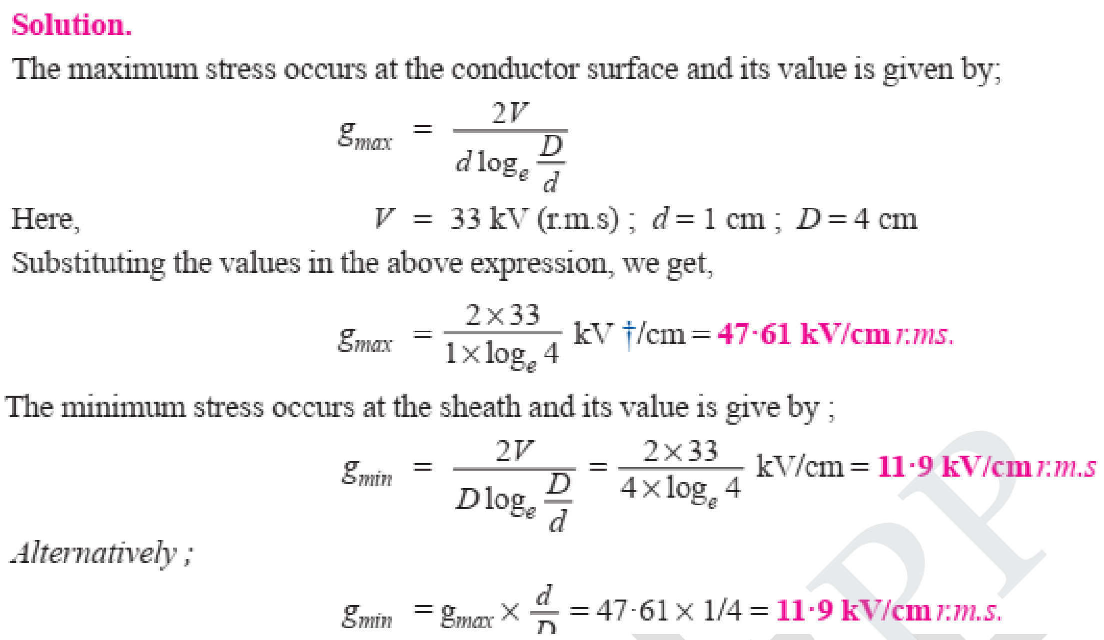
(ii) Voltage/phase, $V_{ph} = \dfrac{33 \times 10^3}{\sqrt{3}} = 19 \cdot 05 \times 10^3$ V

Charging current/phase, $I_C = \dfrac{V_{ph}}{X_C} = 2\pi f C V_{ph}$

$$= 2\pi \times 50 \times 1984 \times 10^{-9} \times 19 \cdot 05 \times 10^3 = \mathbf{11 \cdot 87\ A}$$

(iii) Total charging kVAR $= 3 V_{ph} I_C = 3 \times 19 \cdot 05 \times 10^3 \times 11 \cdot 87 = \mathbf{678 \cdot 5 \times 10^3\ kVAR}$

2.Compute the maximum and minimum stress in insulation of a 33kv single core cable has a conductor diameter of 1cm and a sheath of inside diameter 4cm. (5)



Solution.

The maximum stress occurs at the conductor surface and its value is given by;

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

Here, $V = 33$ kV (r.m.s) ; $d = 1$ cm ; $D = 4$ cm

Substituting the values in the above expression, we get,

$$g_{max} = \frac{2 \times 33}{1 \times \log_e 4} \text{ kV }^{\dagger}\text{/cm} = \mathbf{47 \cdot 61 \ kV/cm} \ r.ms.$$

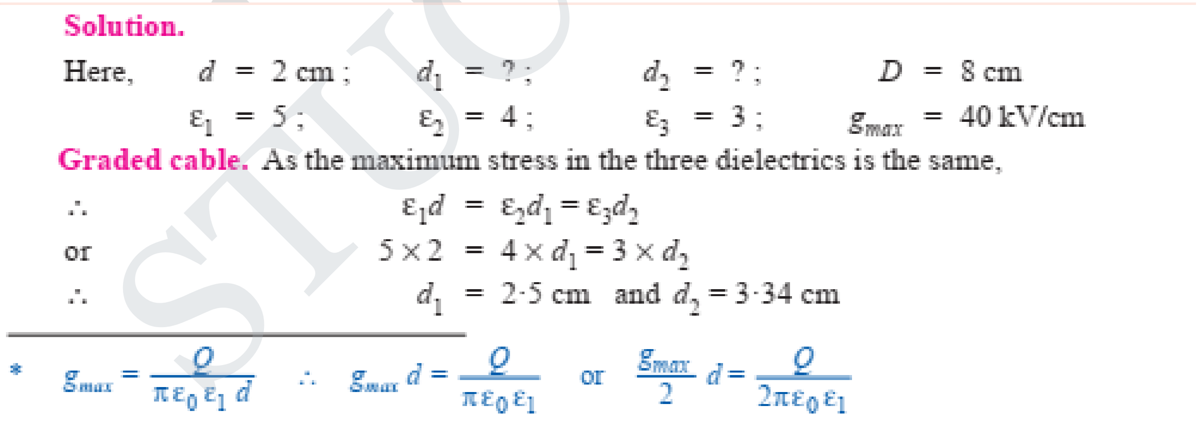
The minimum stress occurs at the sheath and its value is give by ;

$$g_{min} = \frac{2V}{D \log_e \frac{D}{d}} = \frac{2 \times 33}{4 \times \log_e 4} \text{ kV/cm} = \mathbf{11 \cdot 9 \ kV/cm} \ r.m.s$$

Alternatively ;

$$g_{min} = g_{max} \times \frac{d}{D} = 47 \cdot 61 \times 1/4 = \mathbf{11 \cdot 9 \ kV/cm} \ r.m.s.$$

3.A single-core lead sheathed cable is graded by using three dielectrics of relative permittivity 5, 4 and 3 respectively. The conductor diameter is 2 cm and overall diameter is 8 cm. If the three dielectrics are worked at the same maximum stress of 40 kV/cm, find the safe working voltage of the cable.What will be the value of safe working voltage for an ungraded cable, assuming the same conductor and overall diameter and the maximum dielectric stress ?



Solution.

Here, $d = 2$ cm ; $d_1 = ?$; $d_2 = ?$; $D = 8$ cm

$\varepsilon_1 = 5$; $\varepsilon_2 = 4$; $\varepsilon_3 = 3$; $g_{max} = 40$ kV/cm

Graded cable. As the maximum stress in the three dielectrics is the same,

$$\therefore \quad \varepsilon_1 d = \varepsilon_2 d_1 = \varepsilon_3 d_2$$

$$\text{or} \quad 5 \times 2 = 4 \times d_1 = 3 \times d_2$$

$$\therefore \quad d_1 = 2 \cdot 5 \text{ cm} \quad \text{and } d_2 = 3 \cdot 34 \text{ cm}$$

---

* $g_{max} = \dfrac{Q}{\pi \varepsilon_0 \varepsilon_1 d}$ $\quad \therefore \quad g_{max}\, d = \dfrac{Q}{\pi \varepsilon_0 \varepsilon_1}$ $\quad$ or $\quad \dfrac{g_{max}}{2} d = \dfrac{Q}{2\pi \varepsilon_0 \varepsilon_1}$

Permissible peak voltage for the cable

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

$$= \frac{40}{2}\left[2 \log_e \frac{2 \cdot 5}{2} + 2 \cdot 5 \log_e \frac{3 \cdot 34}{2 \cdot 5} + 3 \cdot 34 \log_e \frac{8}{3 \cdot 34}\right]$$

$$= 20\,[0 \cdot 4462 + 0 \cdot 7242 + 2 \cdot 92] \text{ kV}$$

$$= 20 \times 4 \cdot 0904 = 81 \cdot 808 \text{ kV}$$

∴ Safe working voltage (r.m.s.) for cable

$$= \frac{81 \cdot 808}{\sqrt{2}} = \mathbf{57 \cdot 84 \text{ kV}}$$

Ungraded cable. Permissible peak voltage for the cable

$$= \frac{g_{max}}{2}\, d \log_e \frac{D}{d} = \frac{40}{2} \times 2 \log_e \frac{8}{2} \text{ kV} = 55 \cdot 44 \text{ kV}$$

∴ Safe working voltage (r.m.s.) for the cable

$$= \frac{55 \cdot 44}{\sqrt{2}} = \mathbf{39 \cdot 2 \text{ kV}}$$

4. Compute the capacitance of 1km length of the cable. A single core cable has a conductor diameter of 1 cm and a sheath of inside diameter 1.8cm.If impregnated paper of relative permittivity 4 is used as the insulation.

Solution.

Capacitance of cable, $C = \dfrac{\varepsilon_r\, l}{41 \cdot 4 \log_{10}(D/d)} \times 10^{-9}$ F

Here $\varepsilon_r = 4$; $l = 1000$ m

$D = 1 \cdot 8$ cm ; $d = 1$ cm

Substituting these values in the above expression, we get,

$$C = \frac{4 \times 1000}{41 \cdot 4 \log_{10}(1 \cdot 8/1)} \times 10^{-9} \text{ F} = 0 \cdot 378 \times 10^{-6} \text{ F} = \mathbf{0 \cdot 378\ \mu F}$$

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 safe- guard the interest of the consumers, the government has enacted a law in this regard. The statutory limit of voltage variation is ± 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. ± 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.

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 deterio-ration 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.

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.

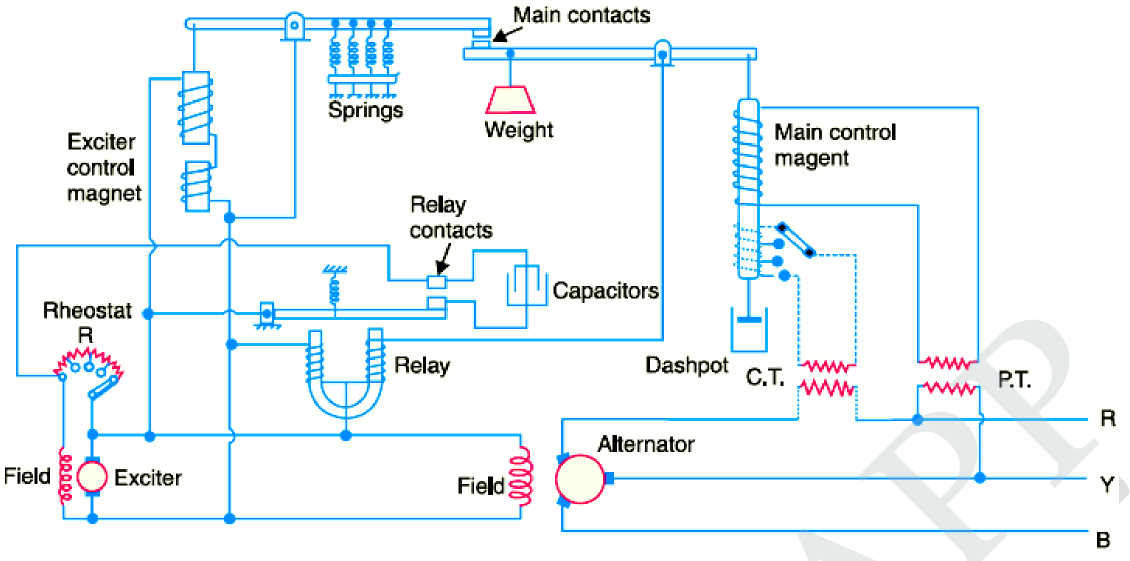
)Tirril Regulator

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. Consequently, relay contacts remain open and the exciter field rheostat is in the field circuit.

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.

This increases the exciter-voltage and hence the excitation of the alternator. The increased excitation causes the alternator voltage to rise quickly. At the same time, the excitation of the exciter magnet is increased due to the increase in exciter voltage. Therefore, the left-hand lever is pulled down, opening the main contacts, energising the relay magnet and putting the rheostat R again in the field circuit before the alternator voltage has time to increase too far. The reverse would happen should the load on the alternator decrease.

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 ± 1%.

ii)Brown-Boveri Regulator

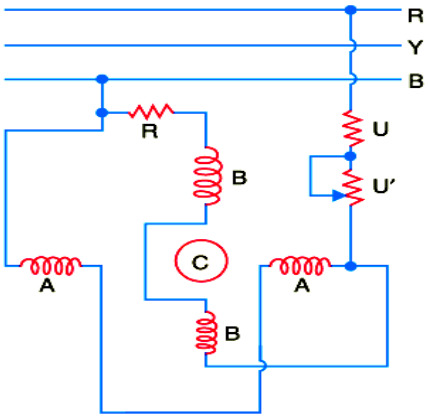
In this type of regulator, exciter field rheostat is varied continuously or in small steps instead of being first completely cut in and then completely cut out as in Tirril regulator. For this purpose, a regulating resistance is connected in series with the field circuit of the exciter. Fluctuations 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.

Construction

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 :

(i) Control system

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.

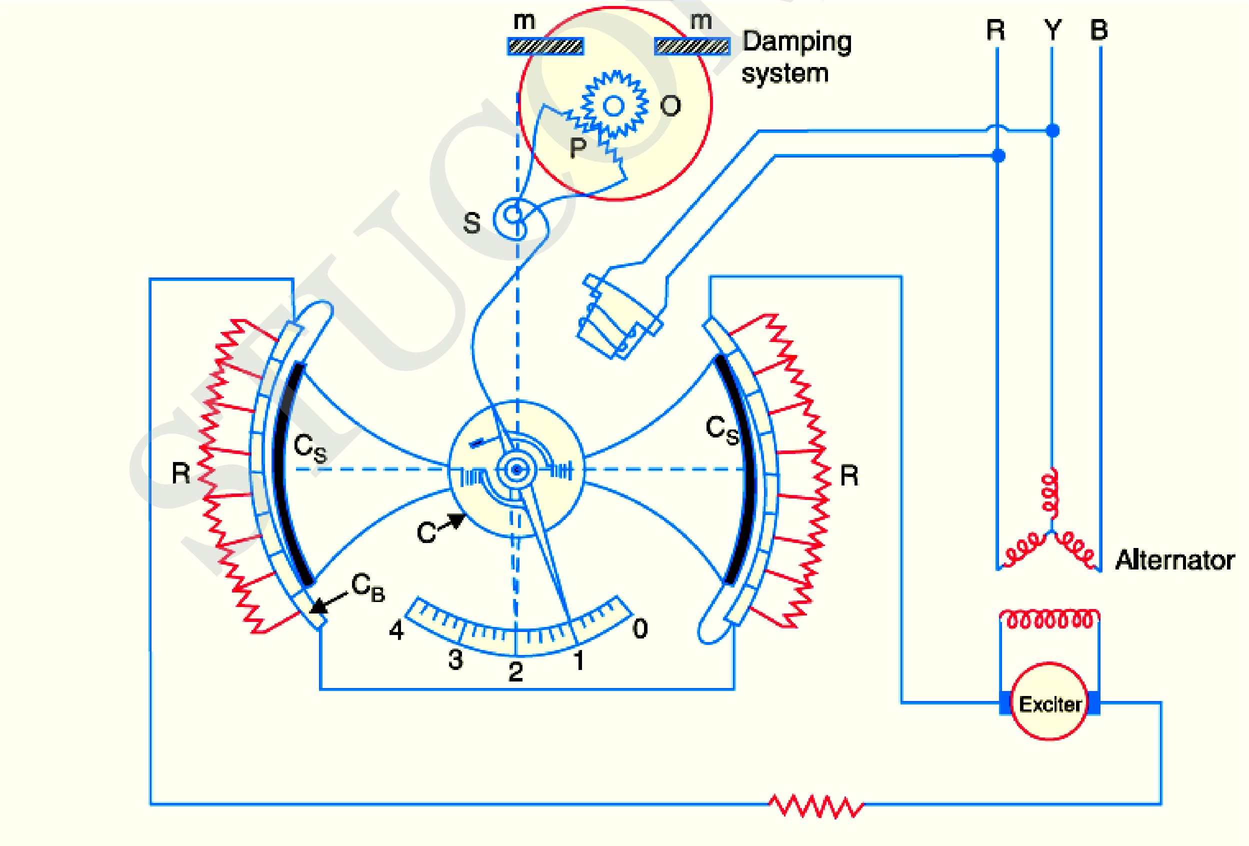


If the resistance is increased, the torque is decreased and vice-versa. Therefore, the variable resistance U′ provides a means by which the regulator may be set to operate at the desired voltage

.

(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.

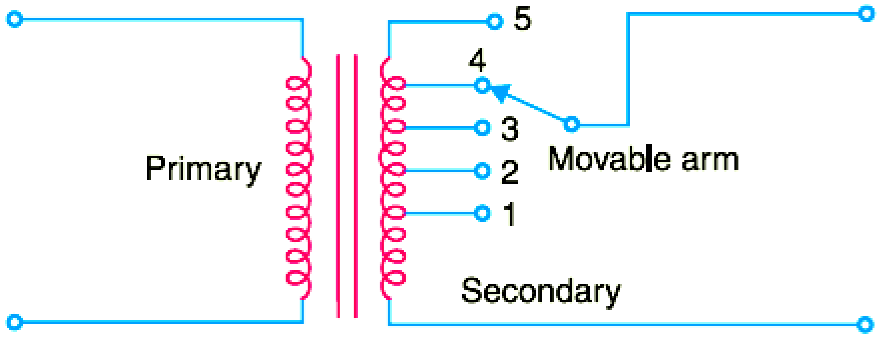
Now imagine that the terminal voltage of the alternator rises due to decrease in load on the supply system. The increase in the alternator voltage will cause an increase in electrical torque which becomes greater than the mechanical torque. This causes the drum to rotate in clockwise direction, say to 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.

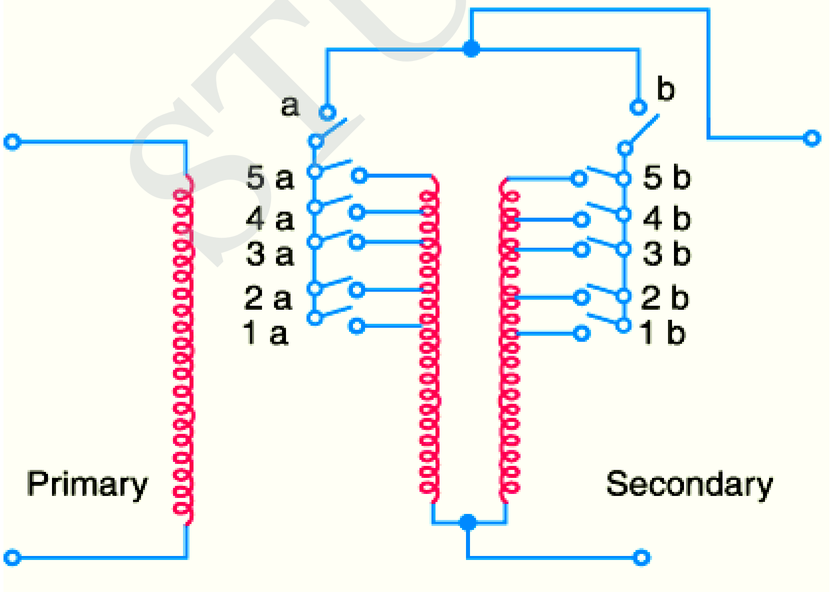
Fig. shows the arrangement where a number of tappings have been provided on the secondary. As the position of the tap is varied, the effective number of secondary turns is varied and hence the output voltage of the secondary can be changed. Thus referring to Fig.



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.

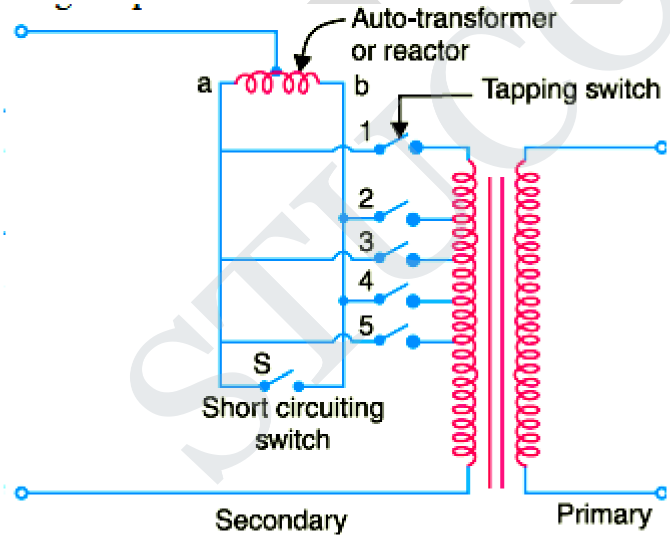
This method has the following disadvantages:

(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 tappings and the other end b is connected to switches across even tappings. A short-circuiting switch S is connected across the auto-transformer and remains in the closed position under normal operation. In the normal operation, there is *no inductive voltage drop across the auto-transformer. Referring to Fig, 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.



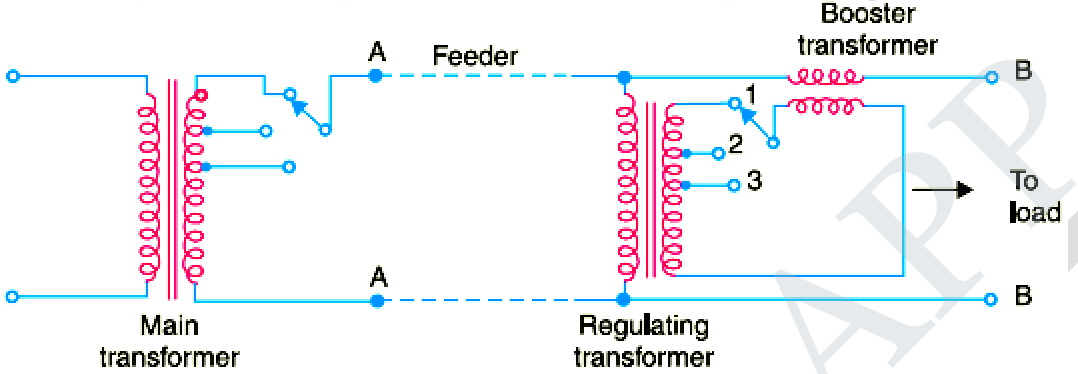
Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage. For this purpose, short-circuiting switch S is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed. In this way, tapping can be changed 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.

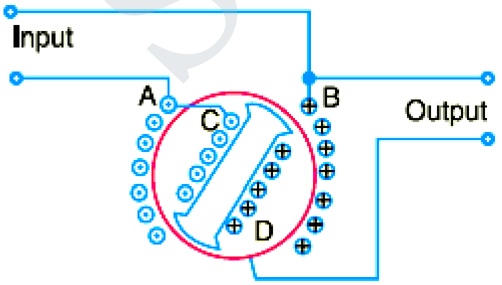
The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled. The primary of this transformer is supplied from a regulating transformer *fitted with on-load tap-changing gear. The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.

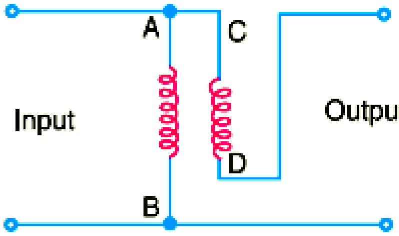


The voltage at AA is maintained constant by tap-changing gear in the main transformer. However, there may be considerable voltage drop between AA and BB due to fairly long feeder and tapping of loads. The voltage at BB is controlled by the use of regulating transformer and booster transformer. By changing 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.

6.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.

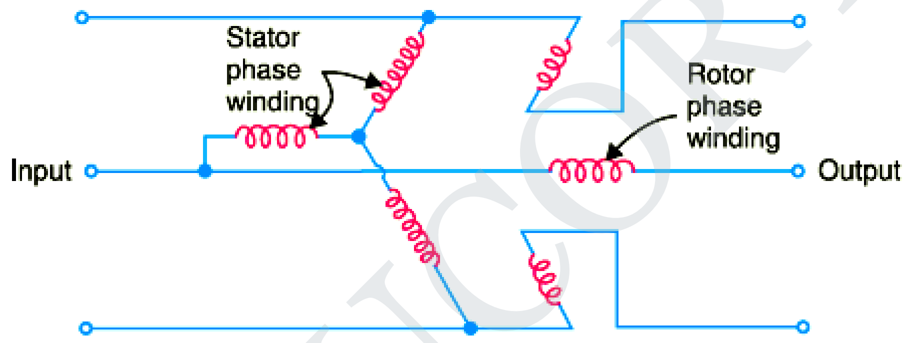
A single phase induction regulator is illustrated in Fig. In construction, it is similar to a single phase induction motor except that the rotor is not allowed to rotate continuously but can be adjusted in any position either manually or by a small motor. The primary winding A B is wound on the *stator 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.

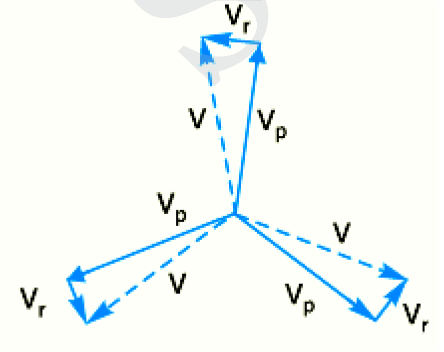
Owing to their greater flexibility, single phase regulators are frequently used for voltage control of distribution primary feeders.

(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 has of rotor winding. As the rotor is turned, the magnitude of the rotating flux is not changed; hence the rotor e.m.f. per phase remains constant. However, the variation of the position of the rotor will affect the phase of the rotor e.m.f. w.r.t. the applied voltage as shown in Fig.



The input primary voltage per phase is Vp and the boost introduced by the regulator is Vr . The output voltage V is the vector sum of Vp and Vr . Three phase p induction regulators are used to regulate the voltage of feeders and in connection with high voltage oil testing transformers.

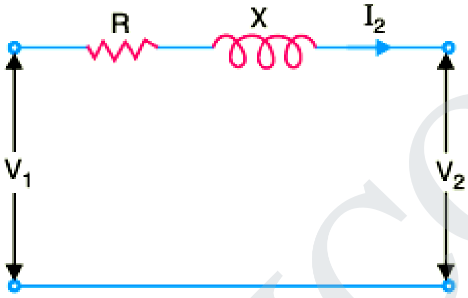
6.Voltage Control by Synchronous Condenser

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.

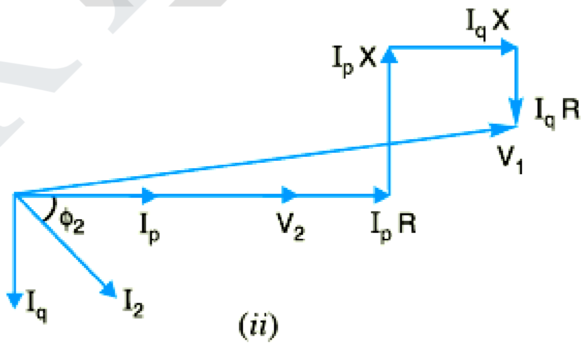
For simplicity, consider a short transmission line where the effects of capacitance are neglected. Therefore, the line has only resistance and inductance. Let V_1 and V_2 be the per phase sending end and receiving end voltages respectively. Let I_2 be the load current at a lagging power factor of cos φ_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 2 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



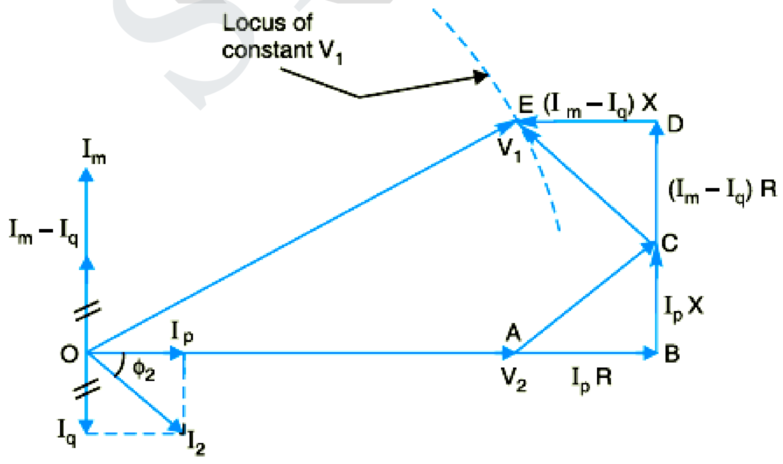
(i)



(ii)

(ii) With synchronous condenser

Now suppose that a synchronous condenser taking a leading current * *I is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. Note that since I and I are in direct opposition and that I must be greater than I , the four drops due to these two currents simplify to :



$(I_m - I_q)\, R$ in phase with I_m

and $(I_m - I_q)\, X$ in quadrature leading with I_m

From the vector diagram, the relation between V_1 and V_2 is given by ;

$$OE^2 = (OA + AB - DE)^2 + (BC + CD)^2$$

or

$$V_1^2 = [V_2 + I_p R - (I_m - I_q)\, X]^2 + [I_p X + (I_m - I_q)\, R]^2$$

From this equation, the value of I_m can be calculated to obtain any desired ratio of V_1 / V_2 for a m

UNIT V DISTRIBUTION SYSTEMS

Distribution Systems – General Aspects – Kelvin's Law – AC and DC distributions - Techniques of Voltage Control and Power factor improvement – Distribution Loss –Types of Substations -Methods of Grounding – Trends in Transmission and Distribution: EHVAC, HVDC and FACTS (Qualitative treatment only).

Distribution System

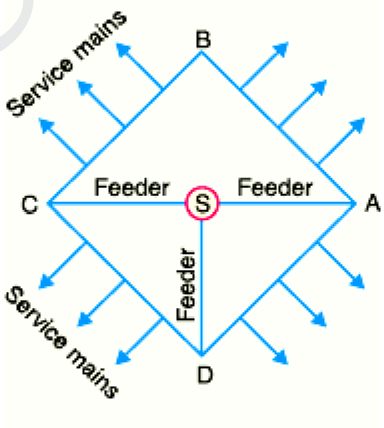
That part of power system which distributes electric power for local use is known as **distribution system.**

In general, the distribution system is the electrical system between the sub-station fed by the transmission system and the consumers meters. It generally consists of *feeders*, *distributors* and the*service mains*. Fig. 12.1 shows the single line diagram of a typical low tension distribution system.

(*i*) *Feeders*. A feeder is a conductor which connects the sub-station (or localised generating station) to the area where power is to be distributed. Generally, no tappings are taken from the feeder so that current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.

(*ii*) *Distributor*. A distributor is a conductor from which tappings are taken for supply to the consumers. In Fig. 12.1, *A B*, *BC*, *CD* and *DA* are the distributors. The current through a distributor is not constant because tappings are taken at various places along its length. While designing a distributor, voltage drop along its length is the main consideration since the statutory limit of voltage variations is ± 6% of rated value at the consumers' terminals.

(*iii*) *Service mains*. A service mains is generally a small cable which connects the distributor to the consumers' terminals.



Kelvins Law:

The most economical area of conductor is that for which the total annual cost of transmission line is minimum. This is called as kelvins law after Lord Kelvin who first stated in 1881.

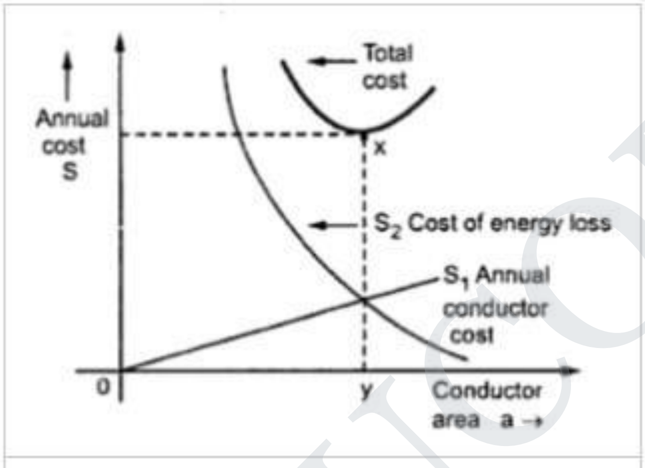
The transmission line cost forms major part in the annual charges of a power system.
The cost is due to

1. Depreciation
2. Repair and maintenance
3. Loss of energy in the line due to its resistance
4. The cost towards the production of the lost energy is considered

- If we decreases the area of the conductor in order to reduce the capital cost, the line losses increase.
- Similarly, if we increase the conductor cross-section to save the cost towards copper loss in the line, the weight of copper increases and hence the capital cost will be more.

Because of the above reasons, it is difficult to find the economical size of the conductor. But it becomes easy with the help of kelvin's law.

In this post we will understand about the kelvin's law and limitations of the kelvin's law.



Assume
A = Cross section of conductor

C = total initial cost towards conductor

C is directly proportional to A

$C \propto A$

$C = PA$

where P is a constant.

Let r be the annual rate of interest and depreciation.
The annual fixed cost $C_1 = C_r = PA_r$

Since line losses are inversely proportional to the area of the conductor
The annual cost on lost energy,

$C_2 = Q/A$ where Q is a constant.

Total annual cost $C = C_1 + C_2$

$= PA_r + Q/A$

For C to be minimum,

$C/dA = 0$

$Pr - Q/A^2 = 0$

$Pr = Q/A^2$

$Pr.A^2 = Q$

$A^2 = Q/Pr$

$A = \sqrt{(Q/Pr)}$

The equation shows that
"The economical cross-section of the conductor is that for which the annual charge on the conductor equals the annual charge for the loss of energy in the conductor".
This is known as Kelvin's law.

Limitations of Kelvin's Law
This law has many problems and limits as we are selecting the cross-section from an economical point of view.

1. 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.
2. Kelvin's law did not consider many physical factors like voltage regulation, corona loss, temperature rise etc.
3. The assumption that annual cost on account of interest and depreciation on the capital outlay is not 100% true.
4. The conductor size determined by this law may not be always practicable one.
5. The rates of interest and depreciation may vary from time to time.
6. The diameter of the conductor may be so small as to cause high corona loss.
7. The conductor may be too weak to stamp from mechanical point of view.
8. Cost of insulation in cables is assumed to be independent of the cross-section of the conductor which is only an approx. assumption.

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 con struction 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

AC DISTRIBUTION

Now-a-days electrical energy is generated, transmitted and distributed in the form of alternating cur-rent. 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.

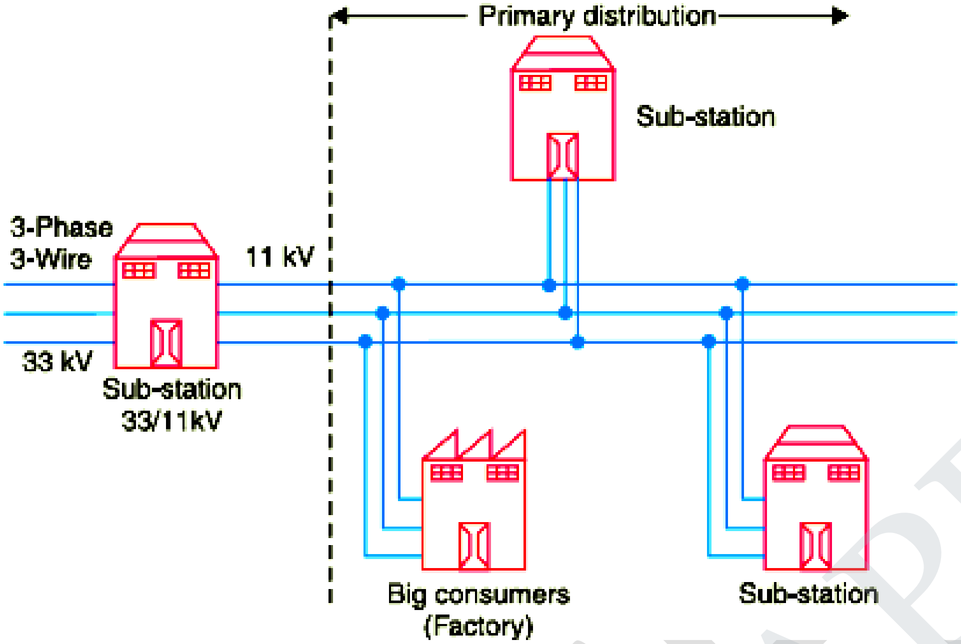
There is no definite line between transmission and distribution according to voltage or bulk capacity. However, in general, the a.c. distribution system is the electrical system between the step- down substation fed by the transmission system and the consumers' meters. The a.c. distribution system is classified into

primary distribution system and
Secondary distribution system.

i) Primary distribution system.

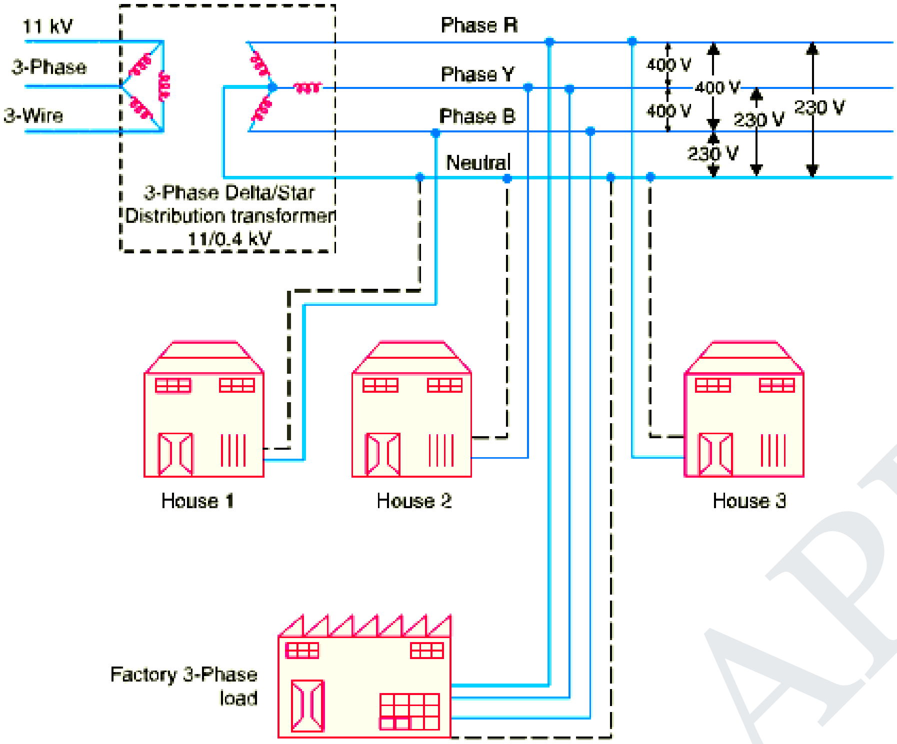
It is that part of a.c. distribution system which operates at voltages somewhat higher than general utilization and handles large blocks of electrical energy than the average low-voltage consumer uses. The voltage used for primary distribution depends upon the amount of power to be conveyed and the distance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



ii) Secondary distribution system

It is that part of a.c. distribution system.Thesecondarydistributionemploys400/230V, 3- phase, 4wire 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 400Vandpowerisdeliveredby 3-phase,4- wire a.c.system. The voltage between any two phasesis400Vandbetween any phase and neutralize 230V.The single phase domestic loads are connected between any one phase and the neutral, where as3-phase400Vmotor loadsareconnectedacross3- phase lines directly.



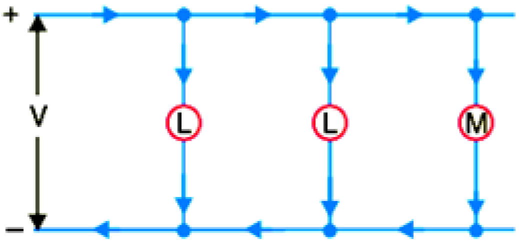
4 D.C. DISTRIBUTION

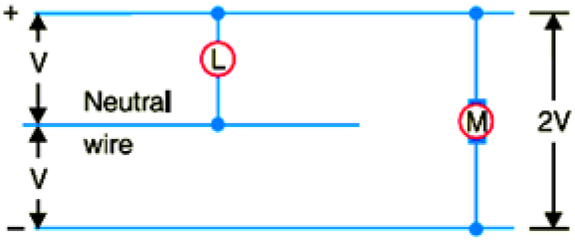
It is a common knowledge that electric power is almost exclusively generated, transmitted and distributed as a.c. However, for certain applications, d.c. supply is absolutely necessary. For instance, d.c. supply is required for the operation of variable speed machinery (d.c. motors), for electro-chemical 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.

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.





(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.

5 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.

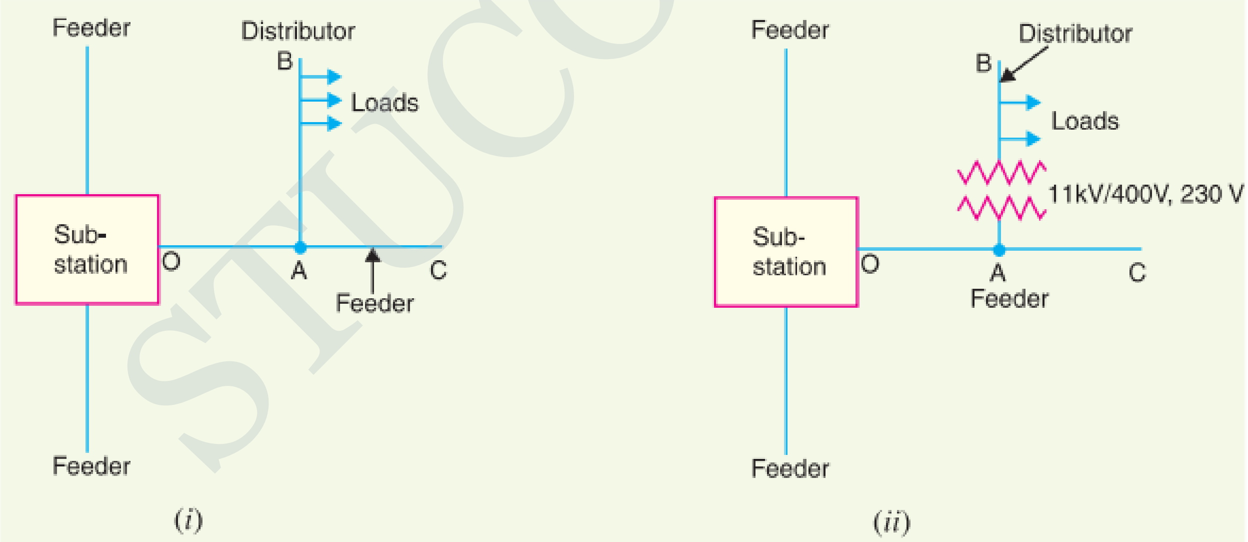
An overhead system causes electromagnetic interference with the telephone lines. The power line currents are superimposed on speech currents, resulting in the potential of the communication channel being raised to an undesirable level. However, there is no such interference with the underground system.

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.

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 :

Radial System. In this system, separate feeders radiate from a single substation and feed the distributors at one end only. Fig. (i) 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.



(*i*)

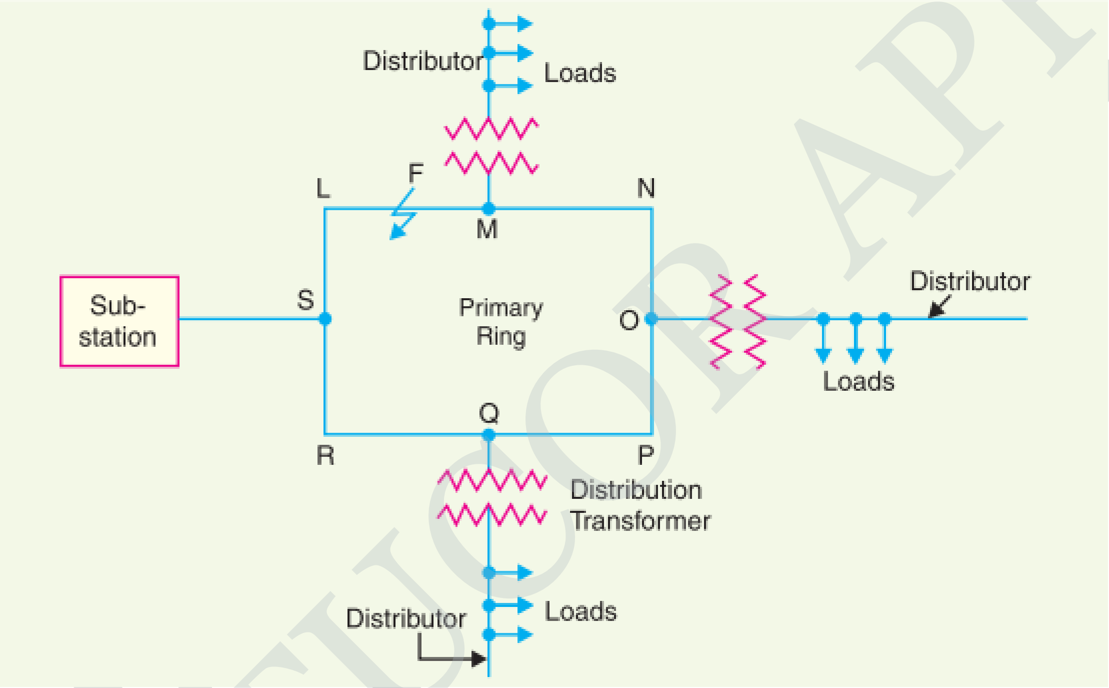
(*ii*)

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

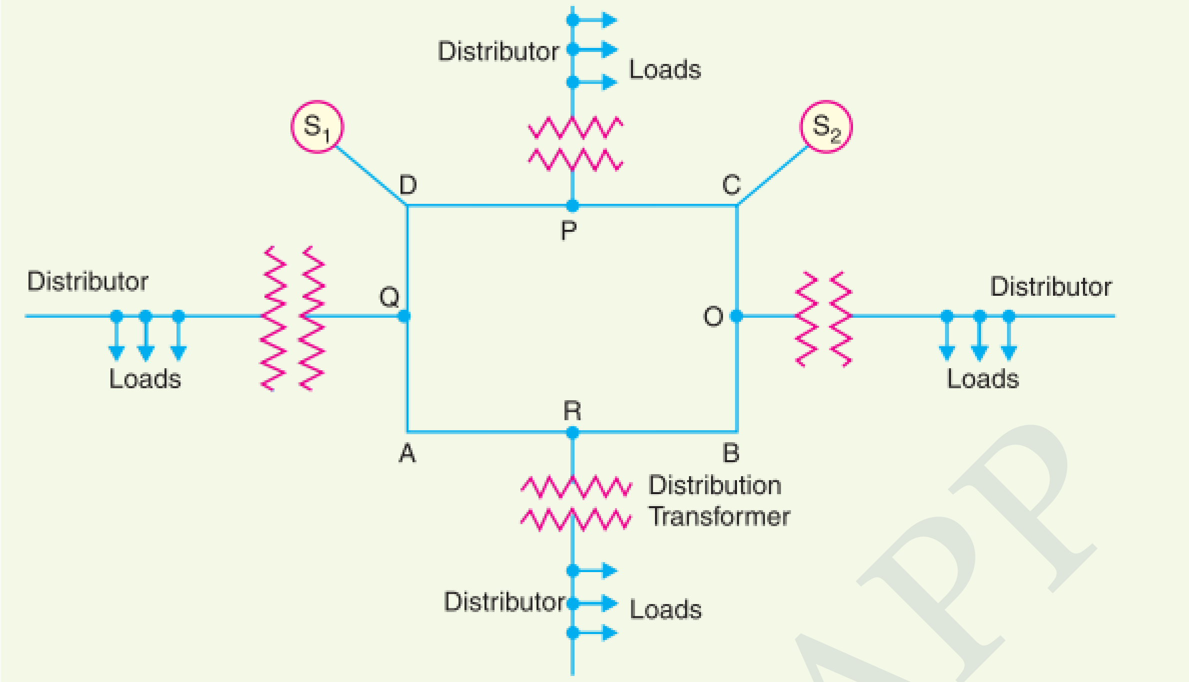
from
the substation
(*c*) The consumers at the distant end of the distributor would be subjected to serious voltage fluctuations when the load on the distributor changes.
Due to these limitations, this system is used for short distances only.

(*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. 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 :



nterconnected system.

When the feeder ring is energised by two or more than two generating stations or substations, it is called inter-connected system. Fig. shows the single line diagram of interconnected system where the closed feeder ring *ABCD* is supplied by two substations *S*1 and *S*2 at points *D* and *C* respectively. Distributors are connected to points *O*, *P*, *Q* and *R* of the feeder ring through distribution transformers. 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.



7 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 ± 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 con-tinuously 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.

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.

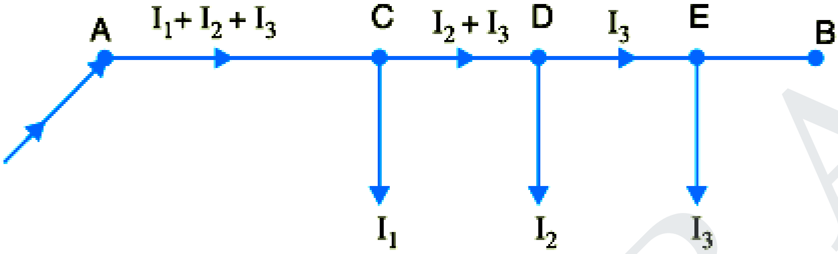


Fig. shows the single line diagram of a d.c. distributor A B fed at the end A also known as singly fed distributor) and loads I_1 , I_2 and I_3 tapped off at points C, D and E respectively.

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

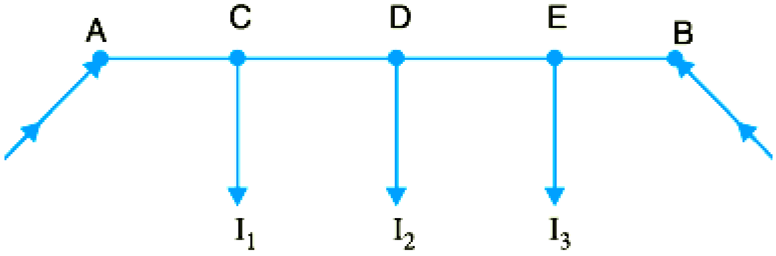
(a) The current in the various sections of the distributor away from feeding point goes on decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.

(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

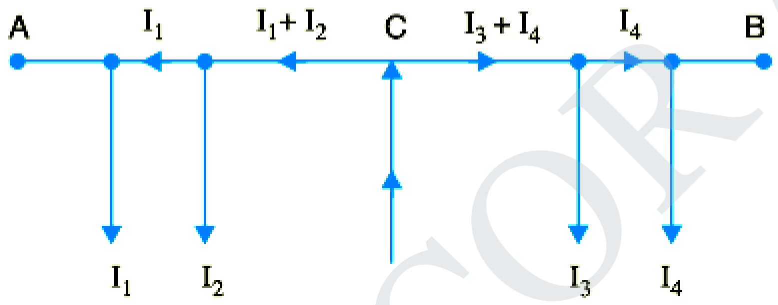
(a) If a fault occurs on any feeding point of the distributor, the continuity of supply is maintained from the other feeding point.

(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.

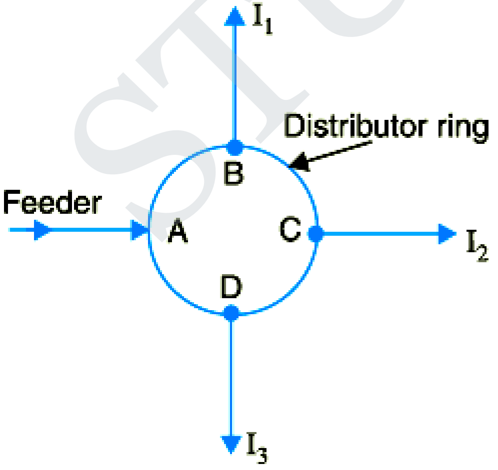
(iii) Distributor fed at the centre.

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.



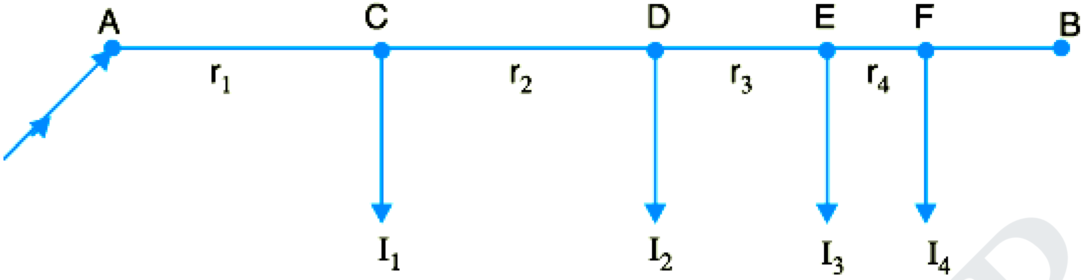
(iv)Ring mains.

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.



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

Fig. shows the single line diagram of a 2-wire d.c. distributor A B 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 A C, 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 $= r_4 I_4$

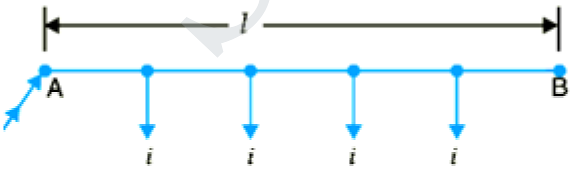
$\therefore$ Total voltage drop in the distributor

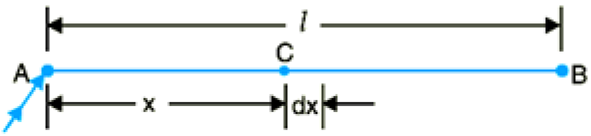
$$= r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$$

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

UNIFORMLY LOADED DISTRIBUTOR FED AT ONE END

Fig shows the single line diagram of a 2-wire d.c. distributor A B 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

$= i\,l - i\,x$ amperes $= i\,(l - x)$ amperes

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

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

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

∴ Voltage drop over the distributor AB

$$= i\,r\left(l \times l - \frac{l^2}{2}\right)$$

$$= \tfrac{1}{2}\,i\,r\,l^2 = \tfrac{1}{2}\,(i\,l)\,(r\,l)$$

$$= \tfrac{1}{2}\,I\,R$$

where

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

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

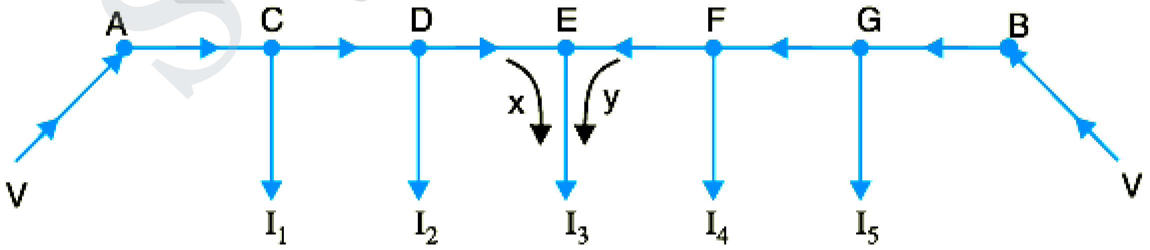
Thus, in a uniformly loaded distributor fed at one end, the total voltage drop is equal to that produced by the whole of the load assumed to be concentrated at the middle point.

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,

$$I_3 = x + y$$

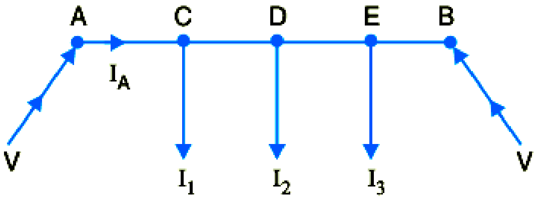
Therefore, we arrive at a very important conclusion that at the point of minimum potential, current comes from both ends of the distributor.

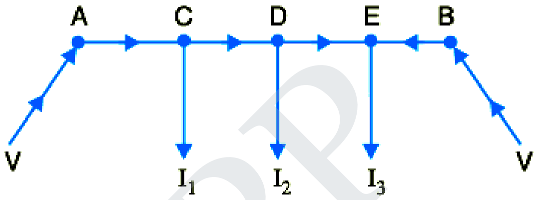
Point of minimum potential.

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 *Ia* . Then current distribution in the various sections of the distributor can be worked out as shown in Fig.

$$I_{AC} = I_A ; \qquad I_{CD} = I_A - I_1$$

$$I_{DE} = I_A - I_1 - I_2 ; \qquad I_{EB} = I_A - I_1 - I_2 - I_3$$





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

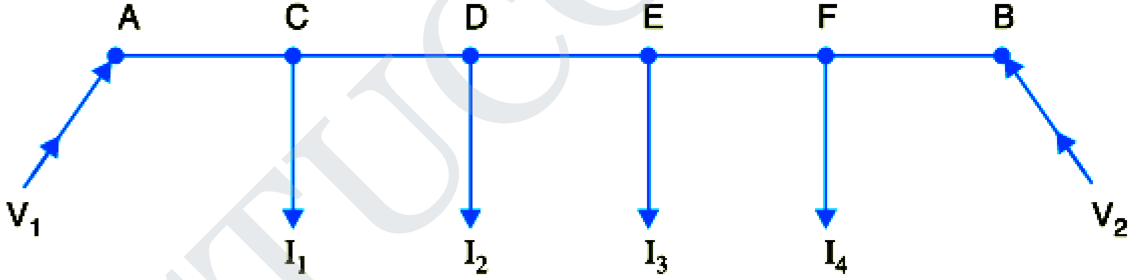
$$\text{or} \quad V - V = I_A R_{AC} + (I_A - I_1) R_{CD} + (I_A - I_1 - I_2) R_{DE} + (I_A - I_1 - I_2 - I_3) R_{EB}$$

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

$V_1 - V_2$ = Voltage drop over A B



UNIFORMLY LOADED DISTRIBUTOR FED AT BOTH ENDS

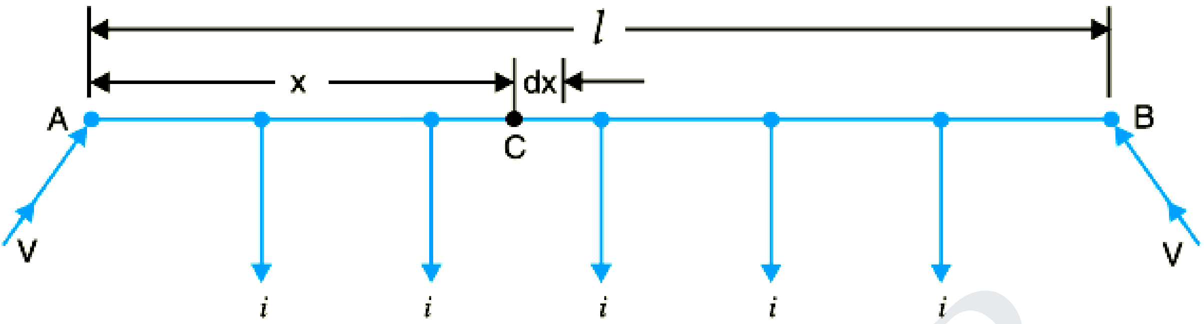
We shall now determine the voltage drop in a uniformly loaded distributor fed at both ends. There can be two cases *viz*. the distributor fed at both ends with (*i*) equal voltages (*ii*) unequal voltages. The two cases shall be discussed separately.

(*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. 13.24. 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

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

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

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

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

$$\therefore \quad \text{Max. voltage drop} = \frac{i\,r}{2}\left(l\,x - x^2\right)$$

$$= \frac{i\,r}{2}\left(l \times \frac{l}{2} - \frac{l^2}{4}\right) \qquad [\text{Putting } x = l/2]$$

$$= \frac{1}{8} i\,r\,l^2 = \frac{1}{8}(i\,l)(r\,l) = \frac{1}{8} I\,R$$

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

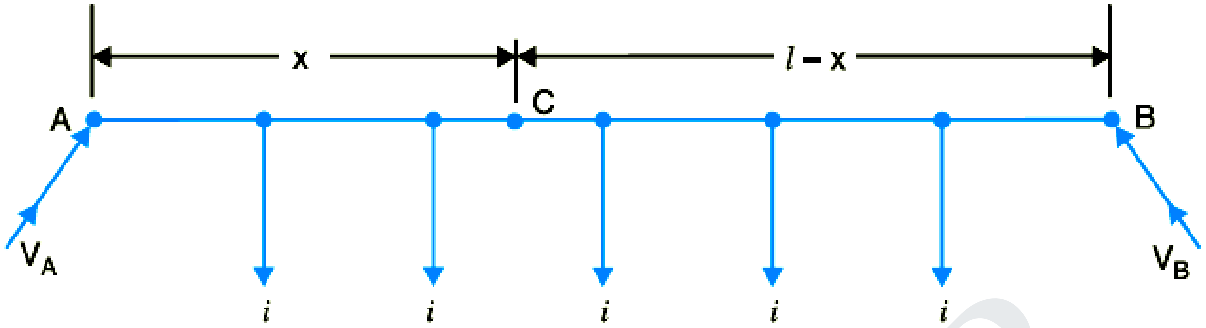
$r\,l$ = *R*, the total resistance of the distributor

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

(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).

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

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

$$= V_A - \frac{i\,r\,x^2}{2} \qquad \ldots(i)$$

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

$$= V_B - \frac{i\,r\,(l-x)^2}{2} \qquad \ldots(ii)$$

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.

METHODS OF VOLTAGE CONTROL:

Practically each equipment used in power system are rated for a certain voltage with a ermissible band of voltage variations. Voltage at various buses must, therefore, be controlled within a specified regulation figure.

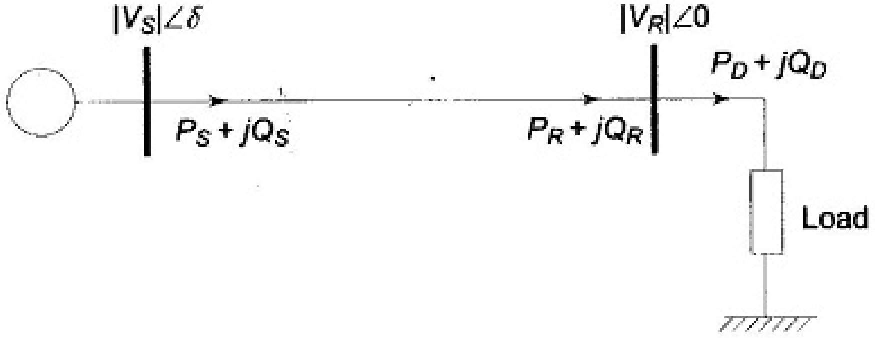


Fig. . A two-bus system

Practical loads are generally lagging in nature and are such that the VAR demand may exceed. It is necessary the receiving-end voltage must change from the specified value $|V^{S}R|$ to some value |VR| to meet the demanded VARs.

Under light load conditions, the charging capacitance of the line may cause the VAR demand to become negative resulting in the receiving-end voltage exceeding the sending-end voltage. In order to regulate the line voltage under varying demands of VARs, the two methods discussed below are employed.

1. Reactive Power Injection

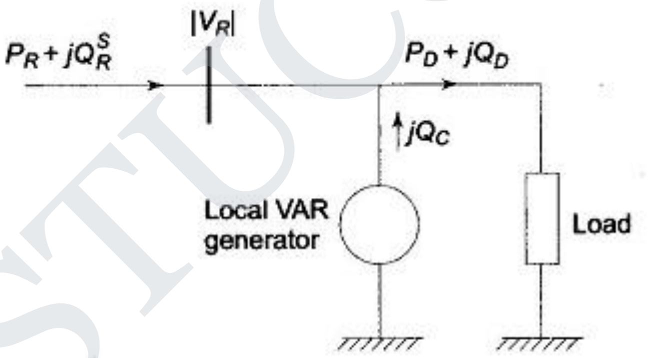


Fig. Use of local VAR generator at the load bus

It follows from the above discussion that in order to keep the receiving-end voltage at a specified value|, a fixed amount of VARs must be drawn from the line. To accomplish this under conditions of a varying VAR demand, a local VAR generator (controlled reactive power source/compensating equipment) must be used as shown in Fig.

The VAR balance equation at the receiving-end is now Fluctuations in QD are absorbed by the local VAR generator Qc such that the VARs drawn from the line remain fixed at QSR The receiving-end voltage would thus remain fixed at |VSR| (this of course assumes a fixed sending-end voltage |VS|. Local VAR compensation can, in fact, be made automatic by using the signal from the VAR meter installed at the receiving-end of the line. Two types of VAR generators are employed in practice—static type and rotating type. These are discussed below.

i. Static VAR generator

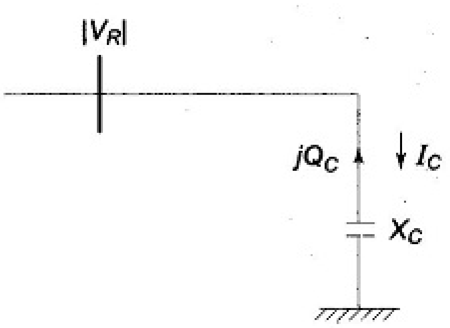


Fig. Static capacitor bank

It is nothing but a bank of three-phase static capacitors and/or inductors. Capacitor and inductor banks can be switched on in steps. However, stepless (smooth) VAR control can now be achieved using SCR (Silicon Controlled Rectifier) circuitry. Since Qc is proportional to the square of terminal voltage, for a given capacitor bank, their effectiveness tends to decrease as the voltage sags under full load conditions.

If the system voltage contains appreciable harmonics, the fifth being the most troublesome, the capacitors may be overloaded considerably. Capacitors act as short circuit when switched on.

Under heavy load conditions, when positive VARs are needed, capacitor banks are employed; while under light load conditions, when negative VARs are needed, inductor banks are switched on.

ii. Rotating VAR generator

It is nothing but a synchronous motor running at no-load and having excitation adjustable over a wide range. It feeds positive VARs into the line under overexcited conditions and feeds negative VARs when underexcited. A machine thus running is called a synchronous condenser.

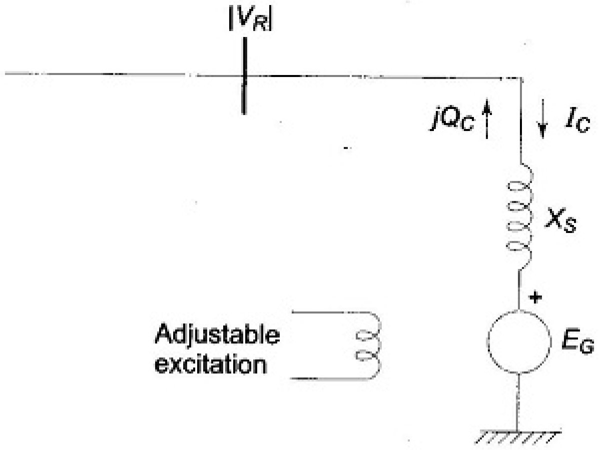


Fig. Rotating VAR generation

AR injection at a given excitation is less sensitive to changes in bus voltage. As |VR| decreases and (|EG| — |VR|) increases with consequent smaller reduction in Qc compared to the case of static capacitors.

Continue reading at http://www.eeguide.com/methods-of-voltage-control/

2. TAP-CHANGING TRANSFORMER

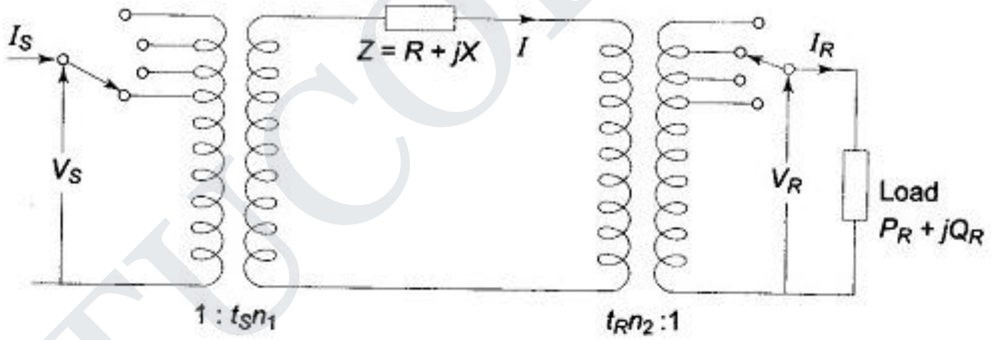
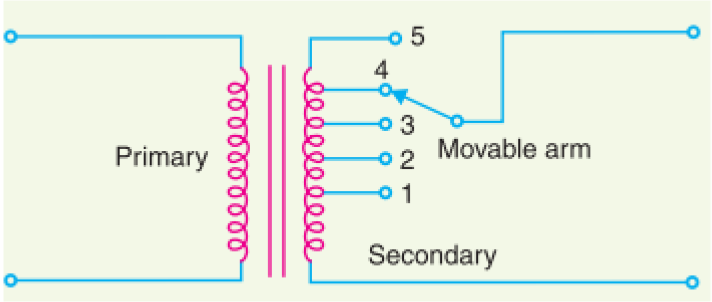


Fig. Transmission line with tap changing transformer at each end

The VAR injection method discussed above lacks the flexibility and economy of voltage control by transformer tap changing. The transformer tap changing is obviously limited to a narrow range of voltage control. If the voltage correction needed exceeds this range, tap changing is used in conjunction with the VAR injection method. Receiving-end voltage which tends to sag owing to VARs demanded by the load, can be raised by simultaneously changing the taps of sending-and receiving-end transformers. Such tap changes must be made **'on-load'** and can be done either manually or automatically, the transformer being called a Tap Changing Under Load (TCUL) transformer.

Off – Load Tap Changing Transformer –method, the voltage is controlled by changing the turn ratio of the transformer. The transformer is disconnected from the supply before changing the tap. The tap changing of the transformer mostly done manually.



POWER FACTOR IMPROVEMENT

Causes of low Power factor

1. Single phase and three phase induction Motors(Usually, Induction motor works at poor power factor i.e. at:
   Full load, Pf = 0.8 -0.9
   Small load, Pf = 0.2 -0.3
   No Load, Pf may come to Zero (0).
2. Varying Load in Power System(As we know that load on power system is varying. During low load period, supply voltage is increased which increase the magnetizing current which cause the decreased power factor)
3. Industrial heating furnaces
4. Electrical discharge lamps (High intensity discharge lighting) Arc lamps (operate a very low power factor)
5. Transformers
6. Harmonic Currents

Disadvantages of Low Power Factor

1. Large Line Losses (Copper Losses)
2. Large kVA rating and Size of Electrical Equipments
3. Poor Voltage Regulation and Large Voltage Drop
4. Low Efficiency
5. Penalty from Electric Power Supply Company on Low Power factor
6. Greater Conductor Size and Cost will be increased

Methods for Power Factor Improvement

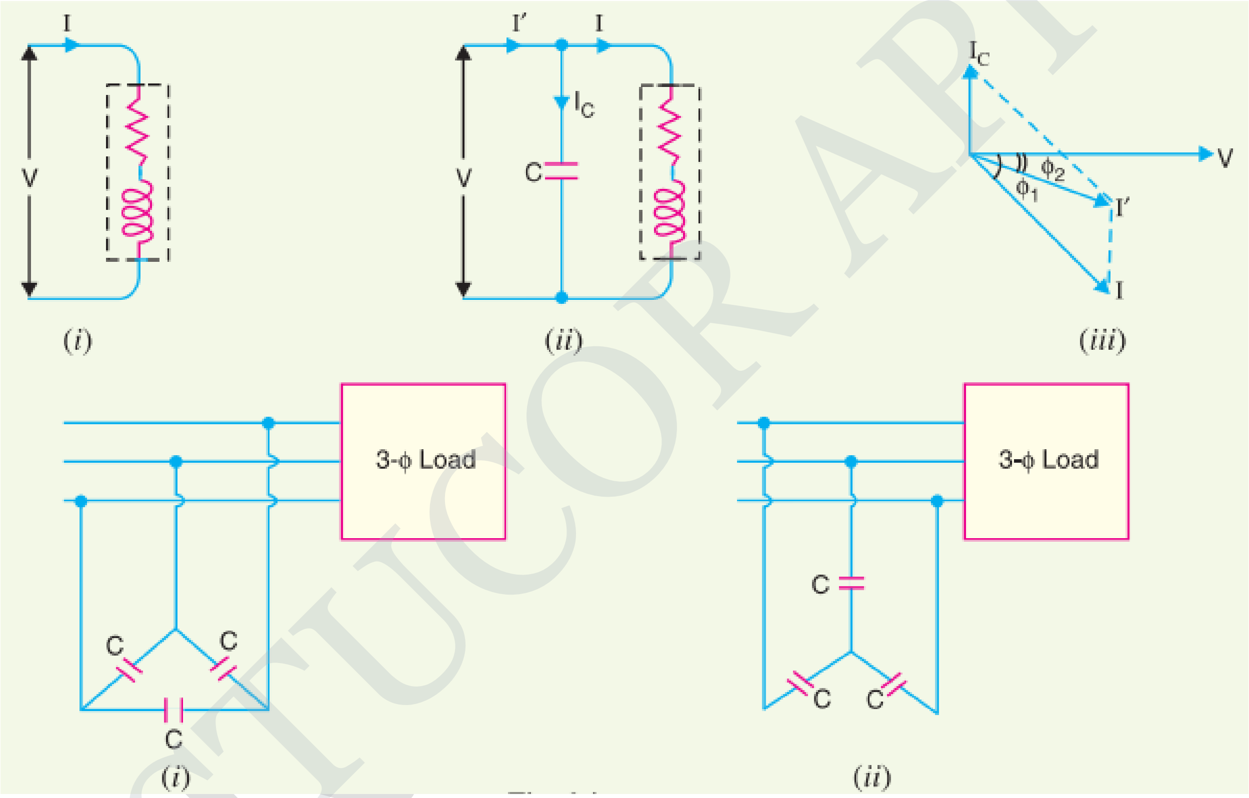
The following devices and equipment are used for Power Factor Improvement.

- Static Capacitor

- Synchronous Condenser
- Phase Advancer

Static Capacitor

- For Power factor improvement purpose, Static capacitors are connected in parallel with those devices which work on low power factor.
- These static capacitors provides leading current which neutralize the lagging inductive component of load current (i.e. leading component neutralize or eliminate the lagging component of load current) thus power factor of the load circuit is improved.
- These capacitors are installed in Vicinity of large inductive load e.g Induction motors and transformers etc, and improve the load circuit power factor to improve the system or devises efficiency.



Advantages:

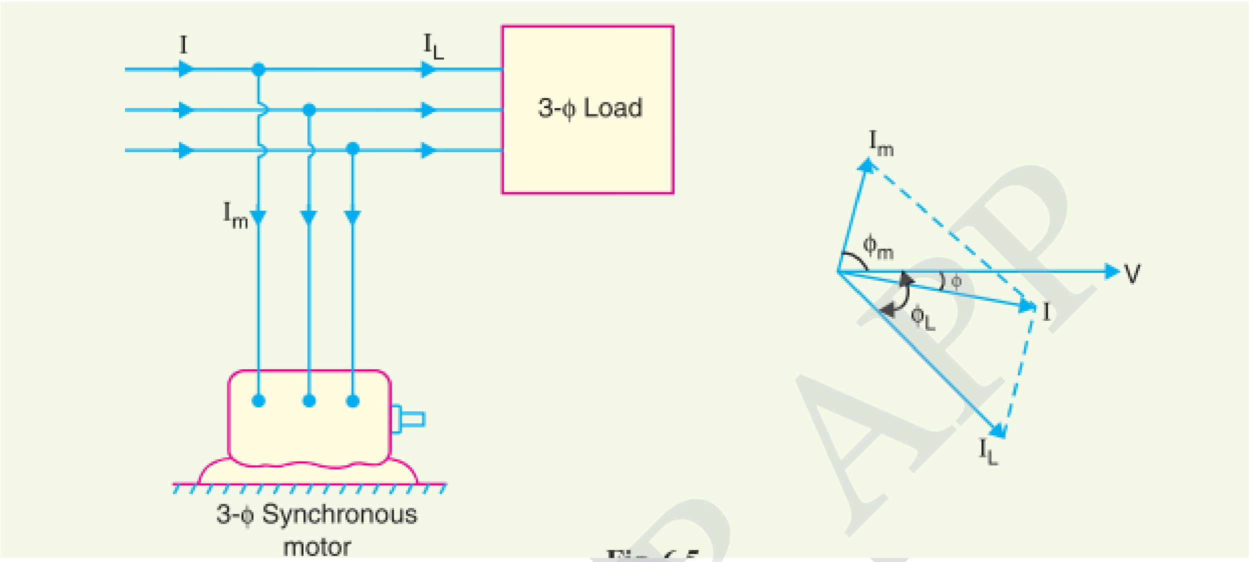
- Losses are low in static capacitors
- There is no moving part, therefore need low maintenance
- It can work in normal conditions (i.e. ordinary atmospheric conditions)
- Do not require a foundation for installation
- They are lightweight so it is can be easy to installed

Disadvantages:

- The age of static capacitor bank is less (8 – 10 years)

- With changing load, we have to ON or OFF the capacitor bank, which causes switching surges on the system
- If the rated voltage increases, then it causes damage it
- Once the capacitors spoiled, then repairing is costly

Synchronous Condenser



- When a Synchronous motor operates at No-Load and over-exited then it's called a synchronous Condenser. Whenever a Synchronous motor is over-exited then it provides leading current and works like a capacitor.
- When a synchronous condenser is connected across supply voltage (in parallel) then it draws leading current and partially eliminates the re-active component and this way, power factor is improved. Generally, synchronous condenser is used to improve the power factor in large industries.

Advantages:

- Long life (almost 25 years)
- High Reliability
- Step-less adjustment of power factor.
- No generation of harmonics of maintenance
- The faults can be removed easily
- It's not affected by harmonics.
- Require Low maintenance (only periodic bearing greasing is necessary)

Disadvantages:

- It is expensive (maintenance cost is also high) and therefore mostly used by large power users.

- An auxiliary device has to be used for this operation because synchronous motor has no self starting torque
- It produces noise

Phase Advancer

- Phase advancer is a simple AC exciter which is connected on the main shaft of the motor and operates with the motor's rotor circuit for power factor improvement. Phase advancer is used to improve the power factor of induction motor in industries.
- As the stator windings of induction motor takes lagging current 90° out of phase with Voltage, therefore the power factor of induction motor is low.
- If the exciting ampere-turns are excited by external AC source, then there would be no effect of exciting current on stator windings. Therefore the power factor of induction motor will be improved. This process is done by Phase advancer.

Advantages:

- Lagging kVAR (Reactive component of Power or reactive power) drawn by the motor is sufficiently reduced because the exciting ampere turns are supplied at slip frequency (fs).
- The phase advancer can be easily used where the use of synchronous motors is Unacceptable

Disadvantage:

- Using Phase advancer is not economical for motors below 200 H.P. (about 150kW)

Advantages of Power factor improvement and Correction

Following are the merits and benefits of improved Power factor;

- Increase in efficiency of system and devices
- Low Voltage Drop
- Reduction in size of a conductor and cable which reduces cost of the Cooper
- An Increase in available power
- Line Losses (Copper Losses) I2R is reduced
- Appropriate Size of Electrical Machines (Transformer, Generators etc)
- Eliminate the penalty of low power factor from the Electric Supply Company
- Low kWh (Kilo Watt per hour)
- Saving in the power bill
- Better usage of power system, lines and generators etc
- Saving in energy as well as rating and the cost of the electrical devices and equipment is reduced

Distribution losses

This difference in the generated and distributed units is known as Transmission and Distribution loss. Transmission and Distribution loss are the amounts that are not paid for by users.

T&D Losses = (Energy Input to feeder(Kwh) – Billed Energy to Consumer(Kwh)) / Energy Input kwh x 100

There are two types of Transmission and Distribution Losses:

1. Technical Losses
2. Non Technical Losses (Commercial Losses)

1. Technical Losses

The technical losses are due to energy dissipated in the conductors, equipment used for transmission line, transformer, subtransmission line and distribution line and magnetic losses in transformers.

Technical losses are normally **22.5%**, and directly depend on the network characteristics and the mode of operation.

The major amount of losses in a power system is in primary and secondary distribution lines. While transmission and sub-transmission lines account for only about 30% of the total losses. Therefore the primary and secondary distribution systems must be properly planned to ensure within limits.

- The unexpected load increase was reflected in the increase of technical losses above the normal level
- Losses are inherent to the distribution of electricity and cannot be eliminated.

There are two Type of Technical Losses.

1. Permanent / Fixed Technical losses

- Fixed losses do not vary according to current. These losses take the form of heat and noise and occur as long as a transformer is energized
- Between 1/4 and 1/3 of technical losses on distribution networks are fixed losses. Fixed losses on a network can be influenced in the ways set out below
- Corona Losses
- Leakage Current Losses
- Dielectric Losses
- Open-circuit Losses
- Losses caused by continuous load of measuring elements
- Losses caused by continuous load of control elements

2. Variable Technical losses

Variable losses vary with the amount of electricity distributed and are, more precisely, proportional to the square of the current. Consequently, a 1% increase in current leads to an increase in losses of more than 1%.

- Between 2/3 and 3/4 of technical (or physical) losses on distribution networks are variable Losses.
- By increasing the cross sectional area of lines and cables for a given load, losses will fall. This leads to a direct trade-off between cost of losses and cost of capital expenditure. It has been suggested that optimal average utilization rate on a distribution network that considers the cost of losses in its design could be as low as 30 per cent.
- Joule losses in lines in each voltage level
- Impedance losses
- Losses caused by contact resistance.

Main Reasons for Technical Losses

1. Lengthy Distribution lines

In practically **11 KV** and **415 volts lines**, in rural areas are extended over long distances to feed loads scattered over large areas. Thus the primary and secondary distributions lines in rural areas are largely radial laid usually extend over long distances.

This results in high line resistance and therefore high I^2R losses in the line.

- Haphazard growths of sub-transmission and distribution system in to new areas.
- Large scale rural electrification through long 11kV and LT lines.

2. Inadequate Size of Conductors of Distribution lines

The size of the conductors **should be selected on the basis of KVA x KM capacity of standard conductor for a required voltage regulation**, but rural loads are usually scattered and generally fed by radial feeders. The conductor size of these feeders should be adequate.

3. Installation of Distribution transformers away from load centers

Distribution Transformers are not located at Load center on the Secondary Distribution System.

In most of case Distribution Transformers are not located centrally with respect to consumers. Consequently, the farthest consumers obtain an extremity low voltage even though a good voltage levels maintained at the transformers secondary.

This again leads to higher line losses. (The reason for the line losses increasing as a result of decreased voltage at the consumers end therefore in order to reduce the voltage drop in the line to the farthest consumers, the distribution transformer should be located at the load center to keep voltage drop within permissible limits.)

4. Low Power Factor of Primary and secondary distribution system

In most LT distribution circuits normally the Power Factor ranges from 0.65 to 0.75. A low Power Factor contributes towards high distribution losses.

For a given load, if the Power Factor is low, the current drawn in high And the losses proportional to square of the current will be more. Thus, line losses owing to the poor PF can be reduced by improving the Power Factor.

This can be done by application of shunt capacitors.

- Shunt capacitors can be connected either in secondary side (11 KV side) of the 33/11 KV power transformers or at various point of Distribution Line.
- The optimum rating of capacitor banks for a distribution system is 2/3rd of the average KVAR requirement of that distribution system.
- The vantage point is at 2/3rd the length of the main distributor from the transformer.
- A more appropriate manner of improving this PF of the distribution system and thereby reduce the line losses is to connect capacitors across the terminals of the consumers having inductive loads.
- By connecting the capacitors across individual loads, the line loss is reduced from 4 to 9% depending upon the extent of PF improvement.

5. Bad Workmanship

Bad Workmanship contributes significantly role towards increasing distribution losses.

Joints are a source of power loss. Therefore the number of joints should be kept to a minimum. Proper jointing techniques should be used to ensure firm connections.

Replacement of deteriorated wires and services should also be made timely to avoid any cause of leaking and loss of power.

6. Feeder Phase Current and Load Balancing>

One of the easiest loss savings of the distribution system is balancing current along three-phase circuits.

Feeder phase balancing also tends to balance voltage drop among phases giving three-phase customers less voltage unbalance. Amperage magnitude at the substation doesn't guarantee load is balanced throughout the feeder length.

Feeder phase unbalance may vary during the day and with different seasons. Feeders are usually considered "balanced" when phase current magnitudes are within 10.Similarly, balancing load among distribution feeders will also lower losses assuming similar conductor resistance. This may require installing additional switches between feeders to allow for appropriate load transfer.

7. Load Factor Effect on Losses

Power consumption of customer varies throughout the day and over seasons.

Residential customers generally draw their highest power demand in the evening hours. Same commercial customer load generally peak in the early afternoon. Because current level (hence, load) is the primary driver in distribution power losses, keeping power consumption more level throughout the day will lower peak power loss and overall energy losses.

Load variation is Called load factor and It varies from 0 to 1.

Load Factor = Average load in a specified time period / peak load during that time period.

For example, for 30 days month (720 hours) peak Load of the feeder is 10 MW. If the feeder supplied a total energy of 5,000 MWH, the load factor for that month is (5,000 MWh)/ (10MW x 720) =0.69.

Lower power and energy losses are reduced by raising the load factor, which, evens out feeder demand variation throughout the feeder.

The load factor has been increase by offering customers "time-of-use" rates. Companies use pricing power to influence consumers to shift electric-intensive activities during off-peak times (such as, electric water and space heating, air conditioning, irrigating, and pool filter pumping).

With financial incentives, some electric customers are also allowing utilities to interrupt large electric loads remotely through radio frequency or power line carrier during periods of peak use. Utilities can try to design in higher load factors by running the same feeders through residential and commercial areas.

8. Transformer Sizing and Selection

Distribution transformers use **copper conductor windings** to induce a magnetic field into a grain-oriented silicon steel core. **Therefore, transformers have both load losses and no-load core losses.**

Transformer copper losses vary with load based on the resistive power loss equation (P loss = I^2R). For some utilities, economic transformer loading means loading distribution transformers to capacity-or slightly above capacity for a short time-in an effort to minimize capital costs and still maintain long transformer life.

However, since peak generation is usually the most expensive, **total cost of ownership (TCO)** studies should take into account the cost of peak transformer losses. Increasing distribution transformer capacity during peak by one size will often result in lower total peak power dissipation-more so if it is overloaded.

Transformer no-load excitation loss (iron loss) occurs from a changing magnetic field in the transformer core whenever it is energized. Core loss varies slightly with voltage but is essentially considered constant. Fixed iron loss depends on transformer core design and steel lamination molecular structure. Improved manufacturing of steel cores and introducing amorphous metals (such as metallic glass) have reduced core losses.

9. Balancing 3 phase loads

Balancing 3-phase loads periodically throughout a network can reduce losses significantly. It can be done relatively easily on overhead networks and consequently offers considerable scope for cost effective loss reduction, given suitable incentives.

10. Switching off transformers

One method of **reducing fixed losses** is to switch off transformers in periods of low demand. If two transformers of a certain size are required at a substation during peak periods, only one might be required during times of low demand so that the other transformer might be switched off in order to reduce fixed losses.

This will produce some **offsetting increase in variable losses** and might affect security and quality of supply as well as the operational condition of the transformer itself. However, these trade-offs will not be explored and optimized unless the cost of losses are taken into account.

11. Other Reasons for Technical Losses

- Unequal load distribution among three phases in L.T system causing high neutral currents.
- leaking and loss of power
- Over loading of lines.
- Abnormal operating conditions at which power and distribution transformers are operated
- Low voltages at consumer terminals causing higher drawl of currents by inductive loads.
- Poor quality of equipment used in agricultural pumping in rural areas, cooler air-conditioners and industrial loads in urban areas.

Substation - introduction

The assembly of apparatus used to change some characteristic (e.g. voltage, a.c. to d.c., frequency, p.f. etc.) of electric supply is called a sub-station. Sub-stations are important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations. It is, therefore, essential to exercise utmost care while designing and building a sub-station. The following are the important points which must be kept in view while laying out a sub-station :

(i) It should be located at a proper site. As far as possible, it should be located at the centre of gravity of load.

(ii) It should provide safe and reliable arrangement. For safety, consideration must be given to the maintenance of regulation clearances, facilities for carrying out repairs and maintenance, abnormal occurrences such as possibility of explosion or fire etc. For reliability, consideration must be given for good design and construction, the provision of suitable protective gear etc.

(iii) It should be easily operated and maintained.

(iv) It should involve minimum capital cost.

1Classification of Sub-Stations

There are several ways of classifying sub-stations. However, the two most important ways of classifying them are according to (1) service requirement and (2) constructional features.

According to service requirement

A sub-station may be called upon to change voltage level or improve power factor or convert a.c. power into d.c. power etc. According to the service requirement, sub-stations may be classified into :

i)Transformer sub-stations.

Those sub-stations which change the voltage level of electric supply are called transformer sub-stations. These sub-stations receive power at some voltage and deliver it at some other voltage. Obviously, transformer will be the main component in such sub- stations. Most of the sub-stations in the power system are of this type.

(ii) Switching sub-stations

These sub-stations do not change the voltage level i.e. incoming and outgoing lines have the same voltage. However, they simply perform the switching operations of power lines.

(iii) Power factor correction sub-stations.

Those sub-stations which improve the power factor of the system are called power factor correction sub-stations. Such sub-stations are generally located at the receiving end of transmission lines. These sub-stations generally use synchronous condensers as the power factor improvement equipment.

(iv) Frequency changer sub-stations

Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilisation.

(v) Converting sub-stations

Those sub-stations which change a.c. power into d.c. power are called converting sub-stations. These sub-stations receive a.c. power and convert it into d.c power with suitable apparatus to supply for such purposes as traction, electroplating, electric welding etc.

(vi) Industrial sub-stations

Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

2. According to constructional features

A sub-station has many components (e.g. circuit breakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous and reliable service. According to constructional features, the sub-stations are classified as :

(i) Indoor sub-station
(ii Outdoor sub-station
(iii) Underground sub-station
(iv) Pole-mounted sub-station
\

(i) Indoor sub-stations

For voltages upto 11 kV, the equipment of the sub-station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages upto 66 kV.

(ii) Outdoor sub-stations

For voltages beyond 66 kV, equipment is invariably installed out- door. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor.

(iii) Underground sub-stations

In thickly populated areas, the space available for equipment and building is limited and the cost of land is high. Under such situations, the sub-station is created underground.

(iv) Pole-mounted sub-stations

This is an outdoor sub-station with equipment installed over- head on H-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such sub- stations. For complete discussion on pole-mounted sub-station,

METHODS OF GROUNDING

Neutral Grounding

The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element is called neutral grounding. It provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (e.g. a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig.

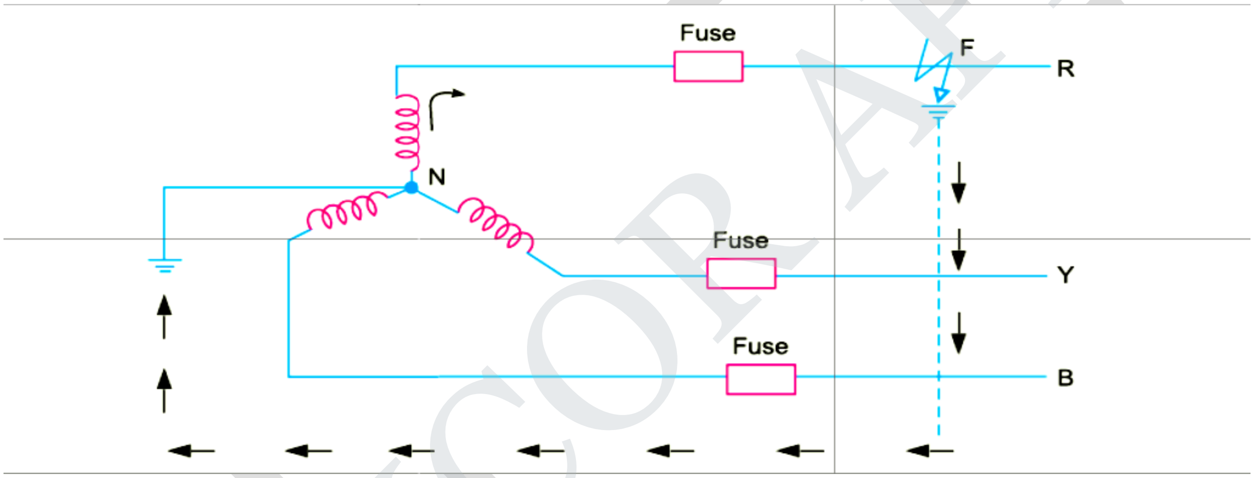


Fig. shows a 3-phase, star-connected system with neutral earthed. Suppose a single line to ground fault occurs in line R at point F. This will cause the current to flow through ground path as shown in Fig. Note that current flows from R phase to earth, then to neutral point N and back to R-phase. Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in R-phase and isolate the faulty line R. This will protect the system from the harmful effects of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system i.e. it will remain nearly constant.

Advantages of Neutral Grounding

The following are the advantages of neutral grounding

(i) Voltages of the healthy phases do not exceed line to ground voltages i.e. they remain nearly constant.

(ii) The high voltages due to arcing grounds are eliminated.

(iii) The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.

(iv) The over voltages due to lightning are discharged to earth.

(v) It provides greater safety to personnel and equipment.

(vi) It provides improved service reliability.
(vii) Operating and maintenance expenditures are reduced

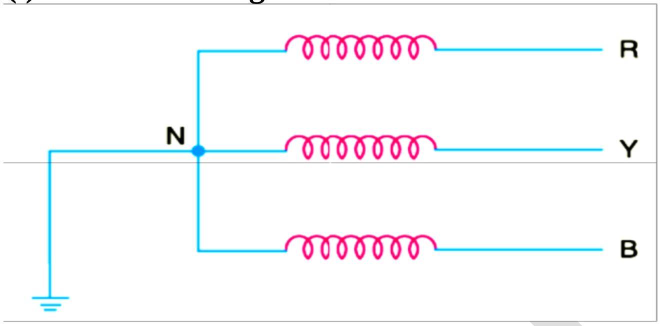
Methods of Neutral Grounding

The methods commonly used for grounding the neutral point of a 3-phase system are :

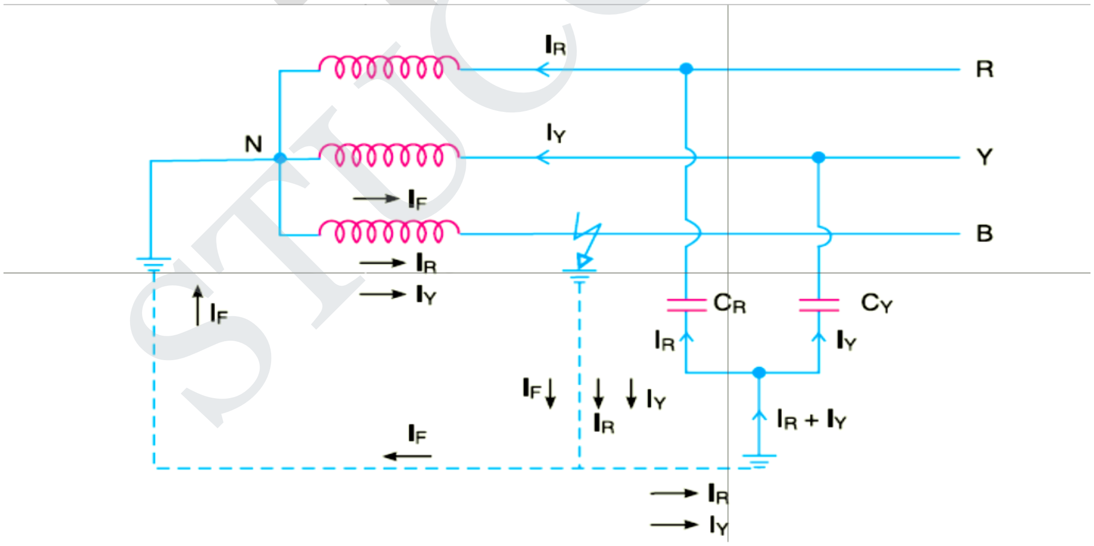
(i) Solid or effective grounding
(ii) Resistance grounding (iii)
Reactance grounding (iv)
Peterson-coil grounding

The choice of the method of grounding depends upon many factors including the size of the system, system voltage and the scheme of protection to be used.

(i)Solid Grounding



When the neutral point of a 3-phase system (e.g. 3- phase generator, 3-phase transformer directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called solid grounding or effective grounding. Fig. shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions. Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.



Advantages

The solid grounding of neutral point has the following advantages:

(i) The neutral is effectively held at earth potential.

(ii)When earth fault occurs on any phase, the resultant capacitive current IC is in phase opposition to the fault current IF . The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur. Consider a line to ground fault in line B as shown in Fig. The capacitive currents flowing in the healthy phases R and Y are IR and IY respectively. The resultant capacitive current IC is the phasor sum of IR and IY . In addition to these capacitive currents, the power source also supplies the fault current IF . This fault current will go from fault point to earth, then to neutral point N and back to the fault point through the faulty phase. The path of IC is capacitive and that of IF is *inductive. The two currents are in phase opposition and completely cancel each other. Therefore, no arcing ground phenomenon or over-voltage conditions can occur.

(iii)When there is an earth fault on any phase of the system, the phase to earth voltage of the faulty phase becomes zero. However, the phase to earth voltages of the remaining two healthy phases remain at normal phase voltage because the potential of the neutral is fixed at earth potential. This permits to insulate the equipment for phase voltage. Therefore, there is a saving in the cost of equipment.

(iv) It becomes easier to protect the system from earth faults which frequently occur on the system. When there is an earth fault on any phase of the system, large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth fault relay.

Disadvantages

The following are the disadvantages of solid grounding :

(i) Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.

(ii) The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.

(iii) The increased earth fault current results in greater interference in the neighboring communication lines.

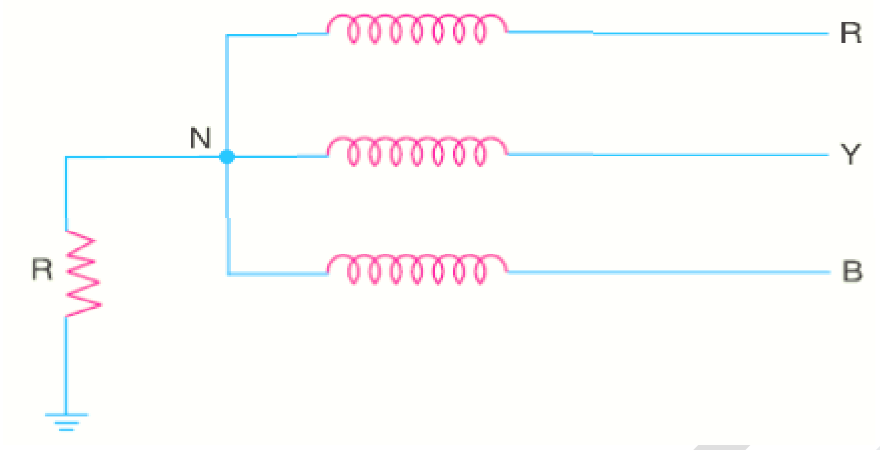
Applications

Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages up to 33 kV with total power capacity not exceeding 5000 kVA.

(ii)Resistance Grounding

In order to limit the magnitude of earth fault current, it is a common practice to connectthe neutral point of a 3-phase system to earth through a resistor. This is called resistance grounding. When the neutral point of a 3-phase system (e.g. 3-phase generator, 3- phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called resistance grounding. F ig.shows the grounding of neutral point through a resistor R . The value of R should neither be very low nor very high. If the value of earthing resistance R is very low, the earth fault current will be large and the system becomes similar to the solid grounding system

On the other hand, if the earthing resistance R is very high, the system conditions become similar to ungrounded neutral system. The value of R is so chosen such that the earth fault urrent is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.



Advantages

The following are the advantages of resistance earthing:

i)The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.

ii)It improves the stability of the system.

Disadvantages

The following are the disadvantages of resistance grounding :

(i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.

(ii)This system is costlier than the solidly grounded system.

(iii)A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications

It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

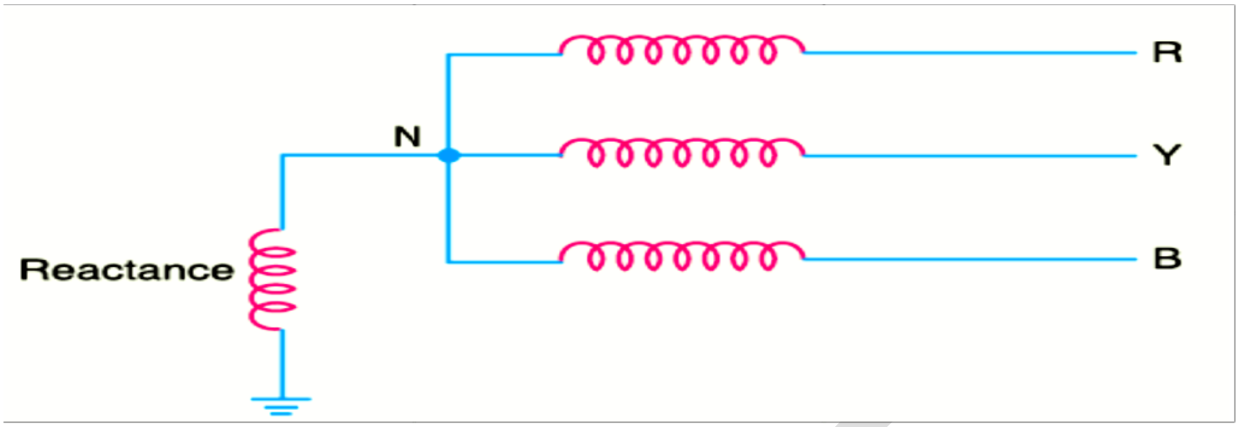
(iii)Reactance Grounding

In this system, a reactance is inserted between the neutral and ground as shown in Fig. Thepurpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can to changed to obtain the conditions similar to that of solid grounding.This method is not used these days because of the following

Disadvantages

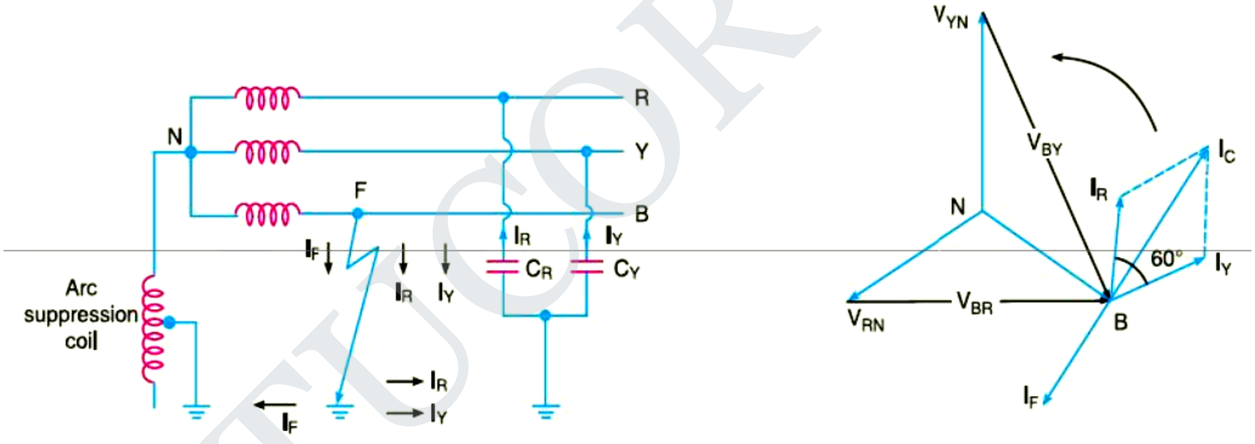
(i) In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.

(ii)High transient voltages appear under fault conditions.



(Iv)Arc Suspension Grounding (Or Resonant Grounding)

If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current I_F flowing through L will be in phase opposition to the capacitive current IC of the system. If L is so adjusted that $I_L = I_c$ then resultant current in the fault will be zero. This condition is known as resonant grounding. When the value of L of arc suppression coil is such that the fault current I_F exactly balances the capacitive current I_c, it is called resonant grounding.



(i) (ii)

- For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors CR and CY

$$\therefore \quad I_R = I_Y = \frac{\sqrt{3} V_{ph}}{X_C}$$

$$\therefore \quad I_C = \sqrt{3}\, I_R = \sqrt{3} \times \frac{\sqrt{3} V_{ph}}{X_C} = \frac{3 V_{ph}}{X_C}$$

Here, X_C is the line to ground capacitive reactance.

Fault current, $$I_F = \frac{V_{ph}}{X_L}$$

Here, X_L is the inductive reactance of the arc suppression coil.

For resonant grounding, $I_L = I_C$.

or $$\frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$$

or $$X_L = \frac{X_C}{3}$$

or $$\omega L = \frac{1}{3\omega C}$$

$$\therefore \quad L = \frac{1}{3\omega^2 C} \qquad \ldots(i)$$

Advantages

The Peterson coil grounding has the following advantages:

(i) The Peterson coil is completely effective in preventing any damage by an arcing ground.

(ii) The Peterson coil has the advantages of ungrounded neutral system.

Disadvantages

The Peterson coil grounding has the following disadvantages :

(i) Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance L of Peterson coil requires readjustment.

(ii) The lines should be transposed.

Trends in Transmission and Distribution

Necessity of EHVAC

With the increase in transmission voltage, for same amount of power to be transmitted current in the line decreases which reduces I 2R losses. This will lead to increase in transmission efficiency. With decrease in transmission current, size of conductor required reduces which decreases the volume of conductor. The transmission capacity is proportional to square of operating voltages. Thus the transmission capacity of line increases with increase in voltage.

With increase in level of transmission voltage, the installation cost of the transmission line per km decreases. It is economical with EHV transmission to interconnect the power systems on a large scale. The no. of circuits and the land requirement for transmission decreases with the use of higher transmission voltages.

The major advantages are:

- Redution in the current. θ

- Reduction in the losses.
- Reduction in volume of conductor material required.
- Decrease in voltage drop & improvement of voltage regulation.
- Increase in Transmission Efficiency.
- Increased power handling capacity. θThe no. of circuits & the land requirement reduces as transmission voltage increases.
- The total line cost per MW per km decreases considerably with the increase in line voltage.

The major disadvantages are:

- Corona loss & radio interference
- Line supports θErection difficulties θInsulation needs
- The cost of transformers, switchgear equipments & protective equipments increases with increase in transmission line voltage.
- The EHV lines generates electrostatic effects which are harmful to human beings & animals

HVDC

The system which uses the direct current for the transmission of the power such type of system is called HVDC (High Voltage Direct Current) system. The HVDC system is less expensive and has minimum losses. It transmits the power between the unsynchronized AC system.

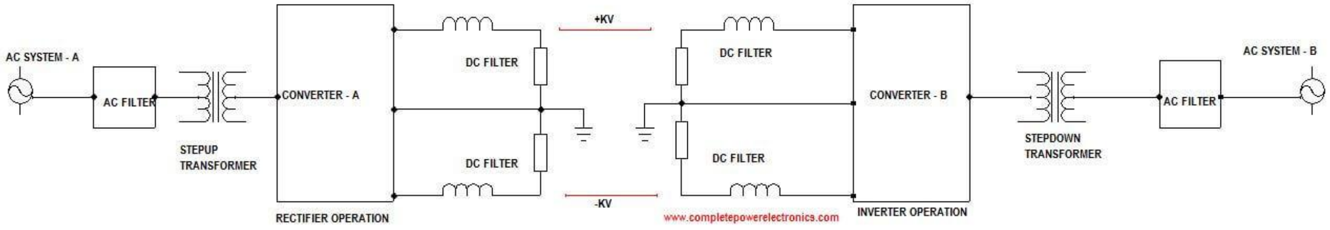
For large power transmission over long distances, the HVDC proves to be economical and efficient over High Voltage AC [HVAC] transmission system.

Component of an HVDC Transmission System

The HVDC system has the following main components.

- Converter Station
- Converter Unit
- Converter Transformers
- Filters
- Reactive Power Source
- Smoothing Reactor
- HVDC System Pole

The block diagram of HVDC transmission system is shown below.



Converter Station

The terminal substations which convert an AC to DC are called rectifier terminal while the terminal substations which convert DC to AC are called inverter terminal. Every terminal is designed to work in both the rectifier and inverter mode. Therefore, each terminal is called converter terminal, or rectifier terminal. A two-terminal HVDC system has only two terminals and one HVDC line.

Converter Unit

The conversion from AC to DC and vice versa is done in HVDC converter stations by using three-phase bridge converters. This bridge circuit is also called Graetz circuit. In HVDC transmission a 12-pulse bridge converter is used. The converter obtains by connecting two or 6-pulse bridge in series.

Converter Transformer

The converter transformer converts the AC networks to DC networks or vice versa. They have two sets of three phase windings. The AC side winding is connected to the AC bus bar, and the valve side winding is connected to valve bridge.These windings are connected in star for one transformer and delta to another.

Filters

The AC and DC harmonics are generated in HVDC converters. The AC harmonics are injected into the AC system, and the DC harmonics are injected into DC lines.

Reactive Power Source

Reactive power is required for the operations of the converters. The AC harmonic filters provide reactive power partly. The additional supply may also be obtained from shunt capacitors synchronous phase modifiers and static var systems. The choice depends on the speed of control desired.

Smoothing Reactor

Smoothing reactor is an oil filled oil cooled reactor having a large inductance. It is connected in series with the converter before the DC filter. It can be located either on the line side or on the neutral side.

HVDC System Pole

The HVDC system pole is the part of an HVDC system consisting of all the equipment in the HVDC substation. It also interconnects the transmission lines which during normal operating condition exhibit a common direct polarity with respect to earth. Thus the word pole refers to the path of DC which has the same polarity with respect to earth. The total pole includes substation pole and transmission line pole.

HVDC Advantages, Disadvantages Over HVAC Transmission System

HVDC Advantages:

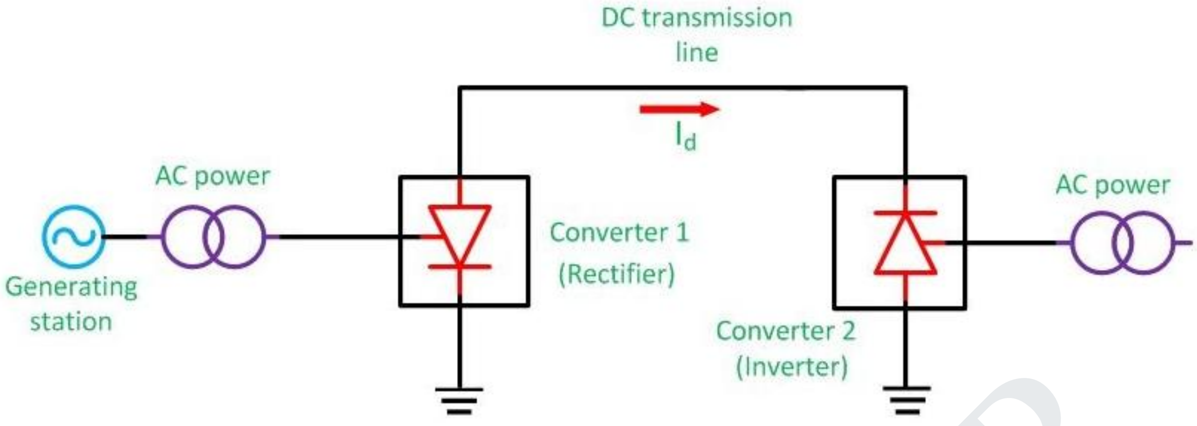
1. Cost of transmission is less, since only two conductors are used for transmission.
2. There is no reactive power. So transmission losses are reduced.
3. Due to high voltage transmission, for the same power current is less. So I^2R loss is very less.
4. Because of DC transmission, there is no skin effect. So thin conductors can be used. In case of HVAC transmission, the thick conductors must be used to eliminate skin effect.
5. Two AC systems having different frequencies can be interconnected using HVDC transmission lines. This is not possible in HVAC transmission system.
6. Installation cost is less. Due to only two conductors and smaller towers required for HVDC.
7. HVDC uses electronic converters. So Protections, fault clearance can be implemented faster than HVAC. Therefore DC transmission system have improved transient stability.
8. In case of faults, power levels on HVDC system can be controlled electronically (i.e., very fast).
9. Since HVDC requires no charging current and the reactive power, it is preferred in power transmission through cables.
10. Unlike HVDC transmission system, HVAC induces body currents in the vicinity of the conductors.
11. HVDC transmission does not have any dielectric loss heating problems in the insulation of conductors.
12. HVDC has minimum audible noise as well as minimum radio, TV interference.
13. Due to bipolar transmission the voltage levels are balanced with respect to an earth.
14. DC cables used for transmission are cheaper than AC cables.
15. In HVDC, line charging and electric resonance do not present which leads to high-efficiency.

Disadvantages of HVDC Transmission:

1. High cost converting and inverting equipments are required for HVDC transmission. So it is uneconomical for low power supply over short distances.
2. Converters control is quite complex.
3. Additional filters are required at various stages of HVDC transmission system. So its lead to high installation cost.

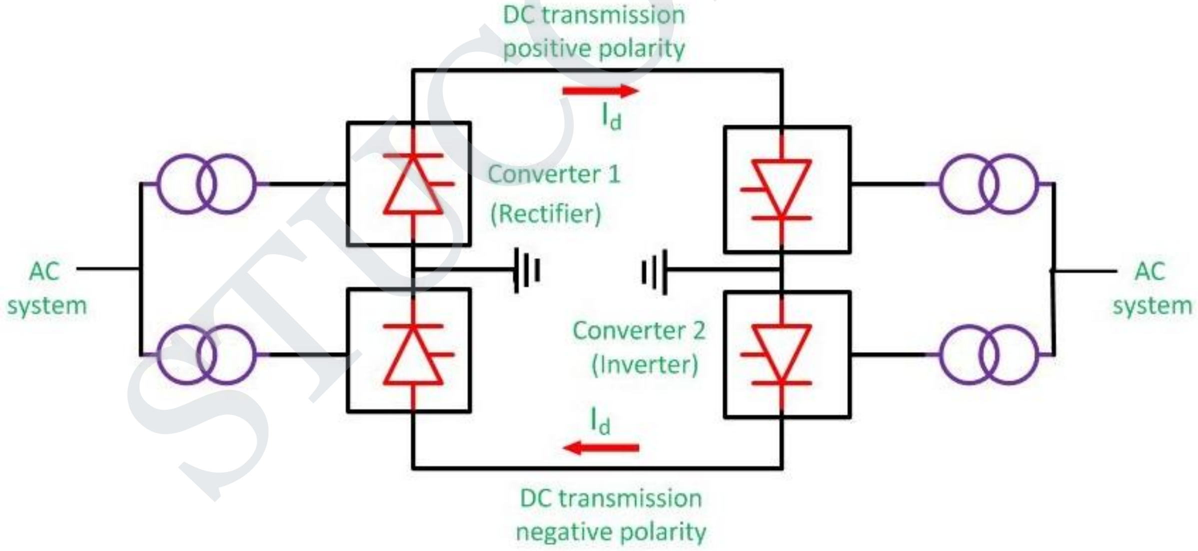
Types of HVDC Links

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.



Monopolar link

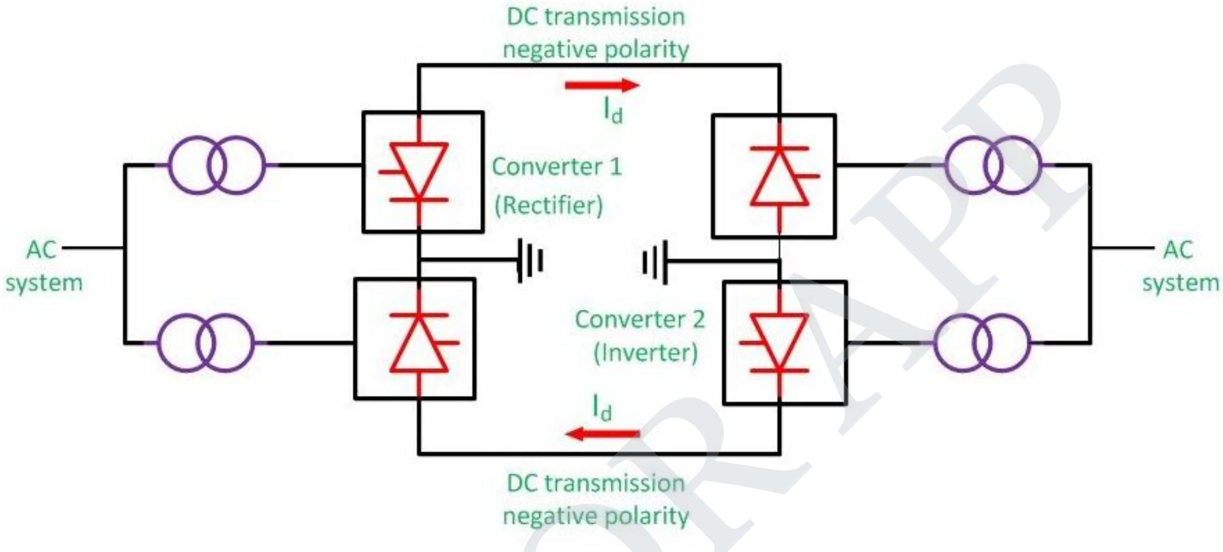
2. Bipolar link – The Bipolar link has two conductors one is positive, and the other one is negative to the earth. The link has converter station at each end. The midpoints of the converter stations are earthed through electrodes. The voltage of the earthed electrodes is just half the voltage of the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



Bipolar link

The most significant advantage of the bipolar link is that if any of their links stop operating, the link is converted into Monopolar mode because of the ground return system. The half of the system continues supplies the power. Such types of links are commonly used in the HVDC systems.

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.



Homopolar link

The homopolar system is not used presently.

FACTS

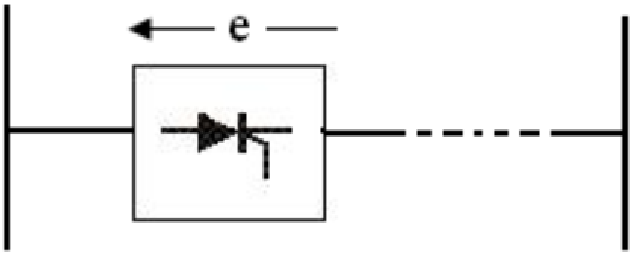
A Flexible Alternating Current Transmission System (FACTS) is a system composed of static equipment used for the AC transmission of electrical energy and it is meant to enhance controllability and increase power transfer capability of the network and it is generally a power electronics-based system.

A FACT is defined by the IEEE as “a power electronics based system other static equipment that provide control of one or more AC transmission system parameters to enhance controllability and increase power transfer capability”.

FACTS controllers are classified as

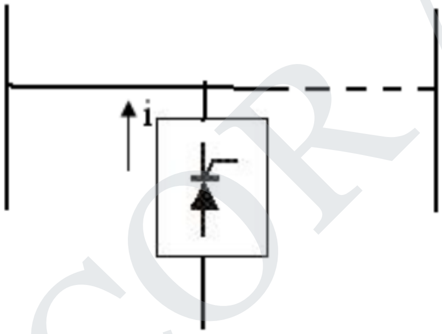
1. Series Controllers
2. Shunt Controllers
3. Combined Series-Series Controllers
4. Combined Series-Shunt Controllers

Series Controllers:



- It could be a variable impedance (capacitor, reactor, etc) or a power electronic based variable source of main frequency, subsynchonous and harmonic frequencies to serve the desired need.
- Inject a voltage in series with the line.
- If the voltage is in phase quadrature with the current, controller supplies or consumes reactive power.
- Any other phase, involves control of both active and reactive power.

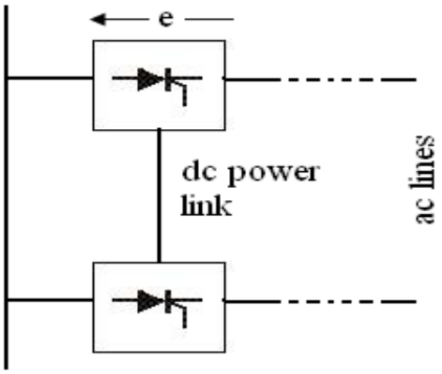
Shunt Controllers



- It could be a variable impedance (capacitor, reactor, etc) or a power electronic based variable
  source or combination of both.
- Inject a current in the system.
- If the current is in phase quadrature with the voltage, controller supplies or consumes reactive power.
- Any other phase, involves control of bothactive and reactive power.

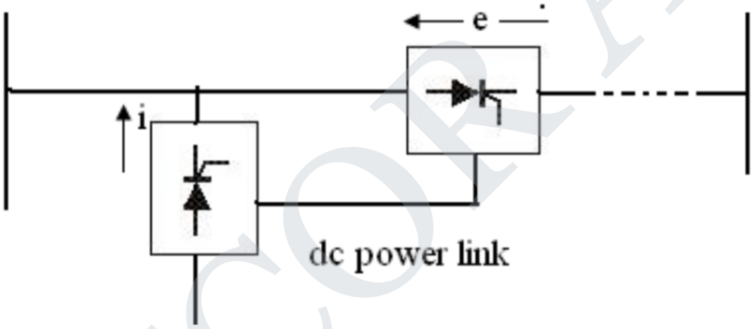
Combined Series-Series Controllers:

- It could be a combination of separate series controllers or unified controller.
- Series controllers supply reactive power for each line and real power among lines via power link.
- Interline power flow controller balance real and reactive power flow in the lines.
- It could be a combination of separate series & shunt controllers or unified power flow controller.



Combined Series-Shunt Controllers:

- It could be a combination of separate series & shunt controllers or unified power flow controller.
- Inject current into the system with the shunt controller and voltage in series with the line with series controller.
- When the controllers are unified, exchange real power between series and shunt controllers via power link.



Problems

1. Compute the minimum consumer voltage of a 2 wire D.C street mains AB, 600m long if fed from both ends at 220V. Loads of 20A,40A,50A, and 30A are tapped at distances of 100m,250m,400m and 500m from the end A respectively. If the area of X-section of distributor conductor is 1 square centimeter. Take $\rho=1.7\times10^{-6}\Omega$-cm.

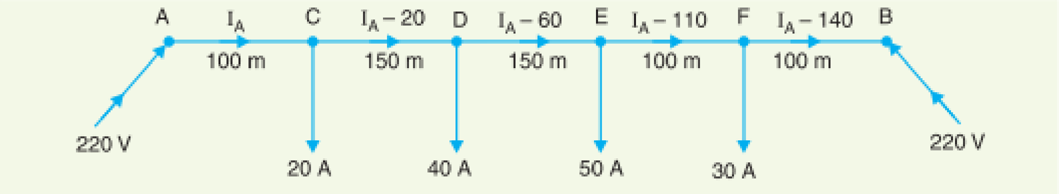


Fig. 13.17

Resistance of 1 m length of distributor

$$= 2 \times \frac{1 \cdot 7 \times 10^{-6} \times 100}{1} = 3 \cdot 4 \times 10^{-4}\ \Omega$$

$$\begin{aligned}
\text{Resistance of section } AC, R_{AC} &= (3 \cdot 4 \times 10^{-4}) \times 100 = 0 \cdot 034\ \Omega \\
\text{Resistance of section } CD, R_{CD} &= (3 \cdot 4 \times 10^{-4}) \times 150 = 0 \cdot 051\ \Omega \\
\text{Resistance of section } DE, R_{DE} &= (3 \cdot 4 \times 10^{-4}) \times 150 = 0 \cdot 051\ \Omega \\
\text{Resistance of section } EF, R_{EF} &= (3 \cdot 4 \times 10^{-4}) \times 100 = 0 \cdot 034\ \Omega \\
\text{Resistance of section } FB, R_{FB} &= (3 \cdot 4 \times 10^{-4}) \times 100 = 0 \cdot 034\ \Omega \\
\text{Voltage at } B &= \text{Voltage at } A - \text{Drop over length } AB \\
\text{or} \quad V_B &= V_A - [I_A R_{AC} + (I_A - 20) R_{CD} + (I_A - 60) R_{DE} \\
&\qquad + (I_A - 110) R_{EF} + (I_A - 140) R_{FB}] \\
\text{or} \quad 220 &= 220 - [0 \cdot 034 I_A + 0 \cdot 051 (I_A - 20) + 0 \cdot 051 (I_A - 60) \\
&\qquad + 0 \cdot 034 (I_A - 110) + 0 \cdot 034 (I_A - 140)] \\
&= 220 - [0 \cdot 204 I_A - 12 \cdot 58] \\
\text{or} \quad 0 \cdot 204 I_A &= 12 \cdot 58 \\
\therefore \quad I_A &= 12 \cdot 58 / 0 \cdot 204 = 61 \cdot 7 \text{ A}
\end{aligned}$$

The *actual distribution of currents in the various sections of the distributor is shown in Fig. 13.18. It is clear that currents are coming to load point *E* from both sides *i.e.* from point *D* and point *F*. Hence, *E* is the point of minimum potential.

∴ Minimum consumer voltage,

$$V_E = V_A - [I_{AC} R_{AC} + I_{CD} R_{CD} + I_{DE} R_{DE}]$$

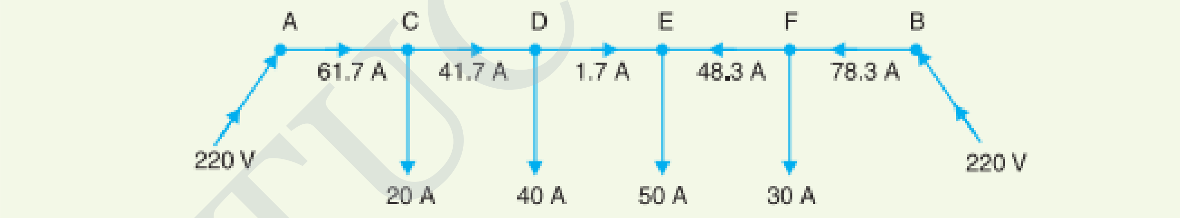


Fig. 13.18

$$\begin{aligned}
&= 220 - [61 \cdot 7 \times 0 \cdot 034 + 41 \cdot 7 \times 0 \cdot 051 + 1 \cdot 7 \times 0 \cdot 051] \\
&= 220 - 4 \cdot 31 = \mathbf{215 \cdot 69\ V}
\end{aligned}$$

A 2-wire d.c. distributor cable AB is 2 km long and supplies loads of 100A, 150A,200A and 50A situated 500 m, 1000 m, 1600 m and 2000 m from the feeding point A. Each conductor has a resistance of 0·01 Ω per 1000 m. Calculate the p.d. at each load point if a p.d. of 300 V is maintained at point A.

Solution. Fig. 13.6 shows the single line diagram of the distributor with its tapped currents.

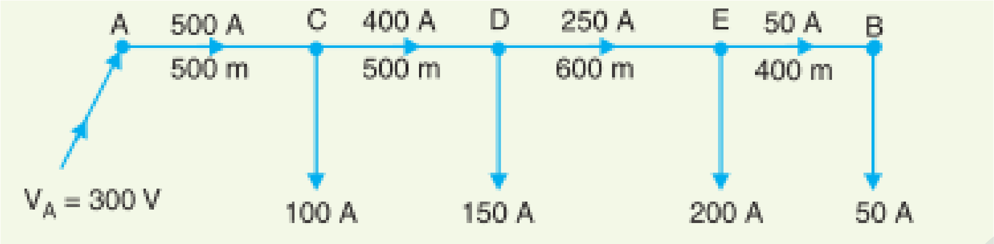
Resistance per 1000 m of distributor = 2 · 0·01 = 0·02&

Resistance of section *AC*, R_{AC} = 0·02 · 500/1000 = 0·01 &

Resistance of section*CD*, R_{CD} = 0·02 · 500/1000 = 0·01 &

Resistance of section DE, $R_{DE} = 0{\cdot}02 \cdot 600/1000 = 0{\cdot}012$ &
Resistance of section EB, $R_{EB} = 0{\cdot}02 \cdot 400/1000 = 0{\cdot}008$ &
Referring to Fig. 13.6, the currents in the various sections of the distributor are :

$I_{EB} = 50$ A ;	$I_{DE} = 50 + 200 = 250$ A
$I_{CD} = 250 + 150 = 400$ A	; $I_{AC} = 400 + 100 = 500$ A



P.D. at load point C, V_C = Voltage at A – Voltage drop in $AC = V_A - I_{AC} R_{AC}$

$= 300 - 500 \cdot 0{\cdot}01 =$ **295 V**

P.D. at load point D, $V_D = V_C - I_{CD} R_{CD}$

$= 295 - 400 \cdot 0{\cdot}01 =$ **291 V**

P.D. at load point E, $V_E = V_D - I_{DE} R_{DE}$
$= 291 - 250 \cdot 0{\cdot}012 =$ **288 V**

P.D. at load point B, $V_B = V_E - I_{EB} R_{EB}$
$= 288 - 50 \cdot 0{\cdot}008 =$ **287·6 V**

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.

Example 13.5. *A 2-wire d.c. distributor 200 metres long is uniformly loaded with 2A/metre. Resistance of single wire is 0·3 Ω/km. If the distributor is fed at one end, calculate :*

(*i*) *the voltage drop upto a distance of 150 m from the feeding point*

(*ii*) *the maximum voltage drop*

Solution.

Current loading, $i = 2$ A/m

Resistance of distributor per metre run,

$$r = 2 \times 0{\cdot}3/1000 = 0{\cdot}0006\,\Omega$$

Length of distributor, $l = 200$ m

(*i*) Voltage drop upto a distance x metres from feeding point

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

Here, $x = 150$ m

$$\therefore \quad \text{Desired voltage drop} = 2 \times 0{\cdot}0006\left(200 \times 150 - \frac{150 \times 150}{2}\right) = \mathbf{22{\cdot}5\ V}$$

(*ii*) Total current entering the distributor,

$$I = i \times l = 2 \times 200 = 400\ \text{A}$$

Total resistance of the distributor,

$$R = r \times l = 0{\cdot}0006 \times 200 = 0{\cdot}12\,\Omega$$

∴ Total drop over the distributor

$$= \frac{1}{2}\,I\,R = \frac{1}{2} \times 400 \times 0{\cdot}12 = \mathbf{24\ V}$$

Example 13.23. *A 2-wire d.c. distributor ABCDEA in the form of a ring main is fed at point A at 220 V and is loaded as under :*

10A at B ; 20A at C ; 30A at D and 10 A at E.

The resistances of various sections (go and return) are : AB = 0·1 Ω ; BC = 0·05 Ω ; CD = 0·01 Ω ; DE = 0·025 Ω and EA = 0·075 Ω. Determine :

(i) the point of minimum potential

(ii) current in each section of distributor

Solution. Fig. 13.37 (*i*) shows the ring main distributor. Let us suppose that current *I* flows in section *AB* of the distributor. Then currents in the various sections of the distributor are as shown in Fig. 13.37 (*i*).

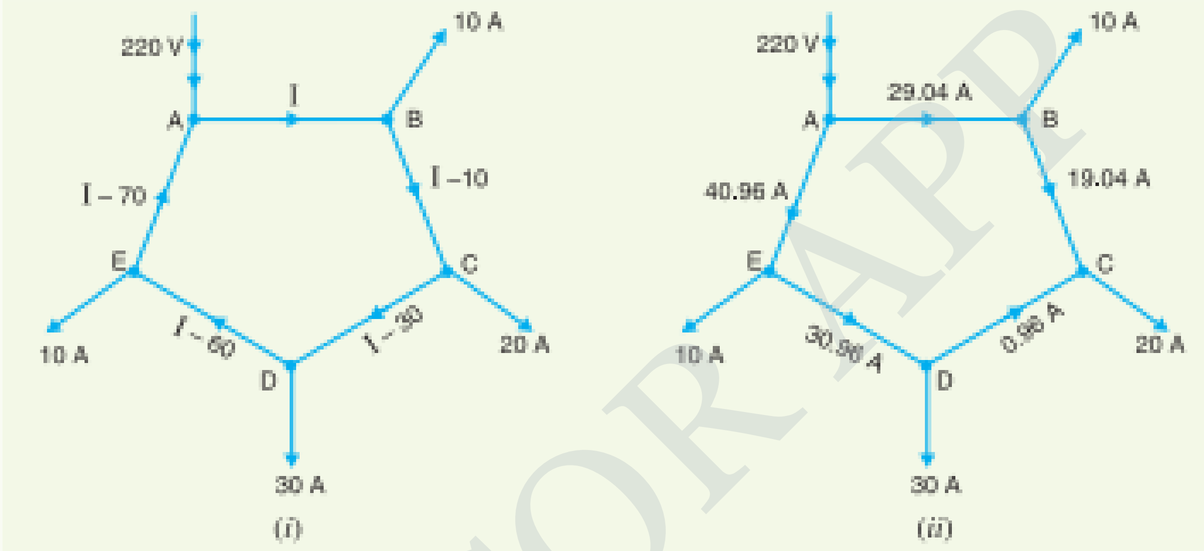


Fig. 13.37

(*i*) According to Kirchhoff's voltage law, the voltage drop in the closed loop *ABCDEA* is zero *i.e.*

$$I_{AB}\,R_{AB} + I_{BC}\,R_{BC} + I_{CD}\,R_{CD} + I_{DE}\,R_{DE} + I_{EA}\,R_{EA} = 0$$

or $$0{\cdot}1I + 0{\cdot}05\,(I - 10) + 0{\cdot}01\,(I - 30) + 0{\cdot}025\,(I - 60) + 0{\cdot}075\,(I - 70) = 0$$

or $$0{\cdot}26\,I = 7{\cdot}55$$

$\therefore$ $$I = 7{\cdot}55/0{\cdot}26 = 29{\cdot}04\text{ A}$$

The actual distribution of currents is as shown in Fig. 13.37 (*ii*) from where it is clear that *C* is the point of minimum potential.

$\therefore$ ***C* is the point of minimum potential.**

(*ii*) Current in section *AB* = I = **29·04 A** *from A to B*

Current in section *BC* = $I - 10 = 29{\cdot}04 - 10$ = **19·04 A** *from B to C*

Current in section *CD* = $I - 30 = 29{\cdot}04 - 30 = -\,0{\cdot}96$ A = **0·96 A** *from D to C*

Current in section *DE* = $I - 60 = 29{\cdot}04 - 60 = -\,30{\cdot}96$ A = **30·96 A** *from E to D*

Current in section *EA* = $I - 70 = 29{\cdot}04 - 70 = -\,40{\cdot}96$ A = **40·96 A** *from A to E*