



PIE Tech

POLLACHI INSTITUTE OF ENGINEERING AND TECHNOLOGY

(Approved by **AICTE** and Affiliated to **Anna University**)

sky is the limit

Department of Electrical and Electronics Engineering

Regulation 2021

II Year – IV Semester

EE3401 – TRANSMISSION AND DISTRIBUTION

1.1 STRUCTURE OF POWER SYSTEM

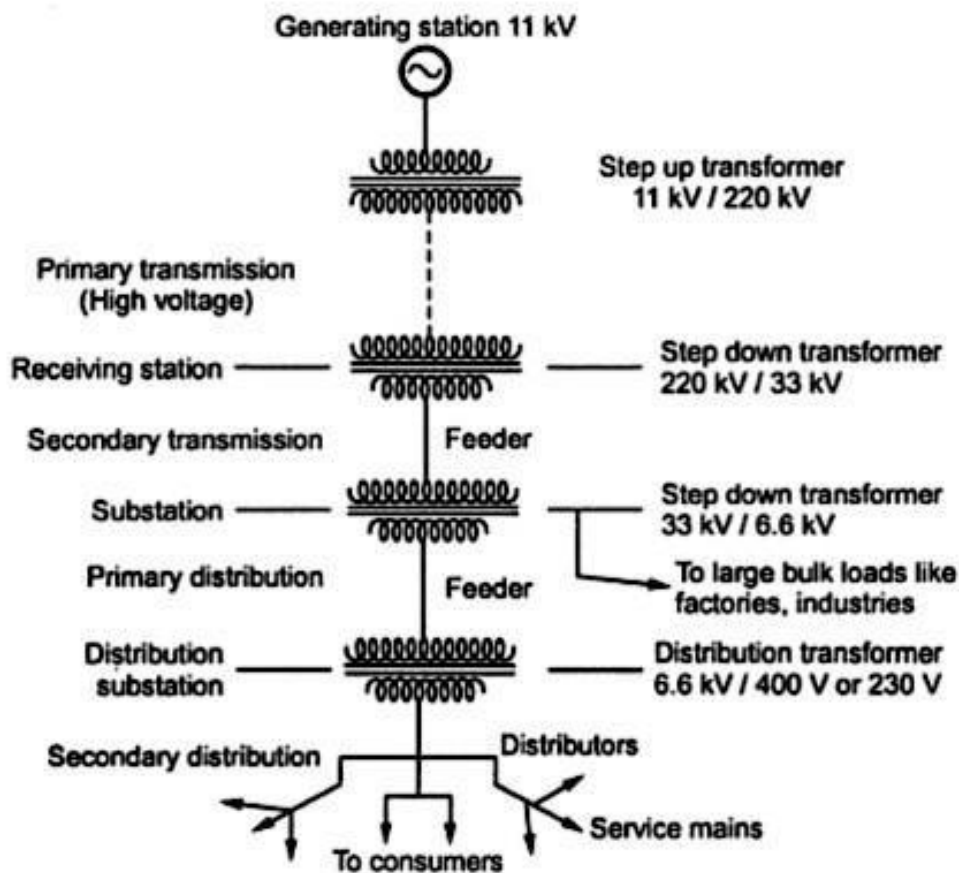


Figure 1.1 Structure of Power System

[Source: "Principles of Power System" by V.K.Mehta Page: 128]

COMPONENTS OF POWER SYSTEM

Power transformers:

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

Current transformers: (CT):

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

Potential transformers (PT):

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

Circuit breaker (CB):

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

Isolators or Isolating switches:

Isolators are employed in substations to isolate a part of the system for general maintenance. Isolator switches are operated only under no load condition. They are provided on each side of every circuit breaker Bus-bar: When number of lines operating at the same voltage levels needs to be connected electrically, bus-bars are used. Bus-bars are conductors made of copper or aluminum, with very low impedance and high current carrying capacity. Different types of bus-bar arrangements are single bus bar arrangements, single bus-bar with double bus-bar arrangements, sectionalized double bus-bar arrangement, double main and auxiliary bus-bar arrangement, breaker and a half scheme/1.5 Breaker scheme, and ring bus-bar scheme

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

1.2.1 CONSTANTS OF A TRANSMISSION LINE

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

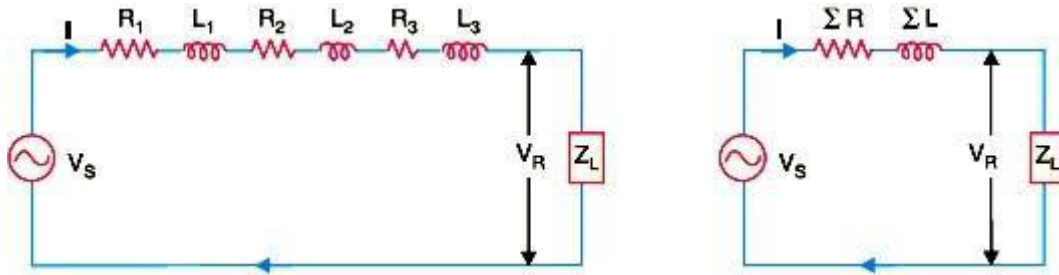


Figure 1.2.1 Resistance and Inductance

[Source: "Principles of Power System" by V.K.Mehta Page: 203]

(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.1.2.1

(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.*,

$$L = \frac{\varphi}{I} \text{ henry}$$

where φ = flux linkages in weber-turns

I = current in amperes

The inductance is also uniformly distributed along the length of the line as shown in Fig. Again for the convenience of analysis, it can be taken to be lumped as shown in Fig.1.2.1

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

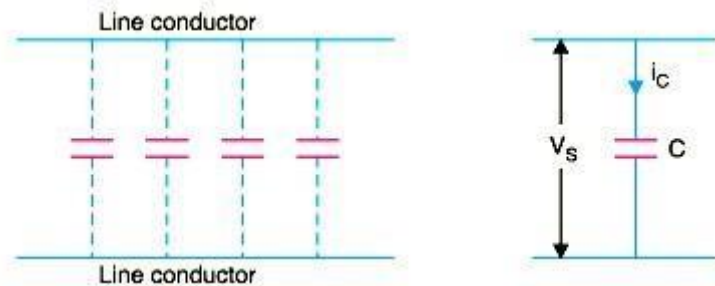


Figure 1.2.2 Capacitance

[Source: “Principles of Power System” by V.K.Mehta Page: 203]

$$C = q/v$$

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. 1.2.2]. 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.

1.2.2 RESISTANCE OF A TRANSMISSION LINE

The resistance of transmission line conductors is the most important cause of power loss in a transmission line. The resistance R of a line conductor having resistivity ρ , length l and

area of cross-section a is given by ;

$$R = \rho l/a$$

The variation of resistance of metallic conductors with temperature is practically linear over the normal range of operation. Suppose R_1 and R_2 are the resistances of a conductor at t_1 °C and t_2 °C

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

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

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

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

1.2.3 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.

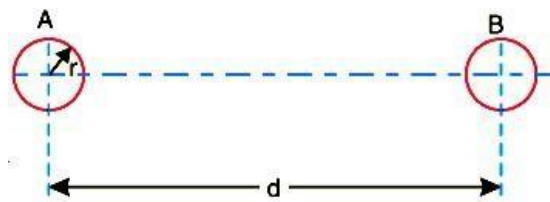


Figure 1.2.3 Single phase Line

[Source: "Principles of Power System" by V.K.Mehta Page: 208]

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

$$I_A + I_B = 0$$

In order to find the inductance of conductor A (or conductor B), we shall have to consider

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

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

Flux linkages with conductor A due to current I_B

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

Total flux linkages with conductor A is

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

Now,

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

$\therefore$

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

$\therefore$

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

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

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

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

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

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

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

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

1.2.4 INDUCTANCE OF A 3-PHASE OVERHEAD LINE

Fig. shows the three conductors A, B and C of a 3-phase line carrying currents I_A , I_B and I_C respectively. Let d_1 , d_2 and d_3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced i.e. $I_A + I_B + I_C = 0$. Consider the flux linkages with conductor A. There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of I_B and I_C .

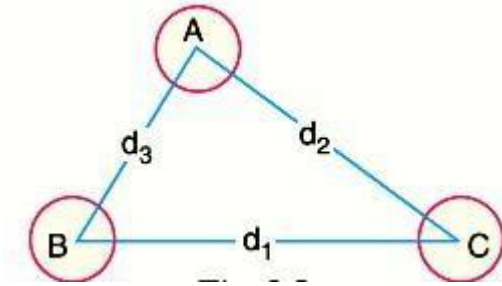


Figure 1.2.4 Three phase Line

[Source: "Principles of Power System" by V.K.Mehta Page: 208]

Flux linkages with conductor A due to its own current

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

Flux linkages with conductor A due to current IB

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

Flux linkages with conductor A due to current IC

Total flux linkages with conductor A is

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

As $I_A + I_B + I_C = 0$,

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

1.2.4.1 SYMMETRICAL SPACING

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

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

1.2.4.2 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 :

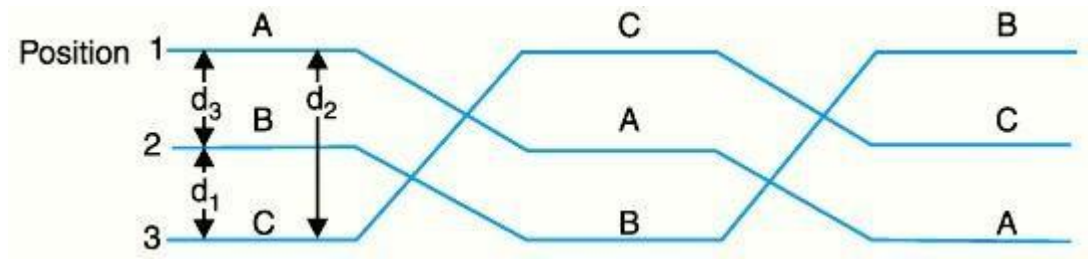


Figure 1.2.5 Unsymmetrical Spacing

[Source: "Principles of Power System" by V.K.Mehta Page: 211]

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

$$I_B = I(-0.5 - j 0.866)$$

$$I_C = I(-0.5 + j 0.866)$$

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

$$= \frac{\mu_0 I}{2\pi} \left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j 0.866 \log_e \frac{d_3}{d_2} \right]$$

∴ Inductance of conductor A is

$$\begin{aligned} L_A &= \frac{\Psi_A}{I_A} = \frac{\Psi_A}{I} \\ &= \frac{\mu_0}{2\pi} \left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j 0.866 \log_e \frac{d_3}{d_2} \right] \end{aligned}$$

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

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

Similarly inductance of conductors B and C will be :

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

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

Inducance of each line conductor

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

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

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

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.

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

Spacing of conductors, $d = 300 \text{ cm}$

Radius of conductor, $r = 1 \text{ cm}$

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

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

$$\therefore \text{Loop inductance/m} = 10^{-7} (1 + 4 \log_e d/r) \text{ H} = 10^{-7} (1 + 4 \log_e 300/1) \text{ H} \\ = 23.8 \times 10^{-7} \text{ H}$$

$$\text{Loop inductance/km} = 23.8 \times 10^{-7} \times 1000 = 2.38 \times 10^{-3} \text{ H} = 2.38 \text{ mH}$$

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

$$\therefore \text{Loop inductance/m} = 10^{-7} (100 + 4 \log_e 300/1) \text{ H} = 122.8 \times 10^{-7} \text{ H}$$

$$\text{Loop inductance/km} = 122.8 \times 10^{-7} \times 1000 = 12.28 \times 10^{-3} \text{ H} = 12.28 \text{ mH}$$

2. The three conductors of a 3-phase line are arranged at the corners of a triangle of sides 2 m, 2.5 m and 4.5 m. Calculate the inductance per km of the line when the conductors are regularly transposed. The diameter of each conductor is 1.24 cm.

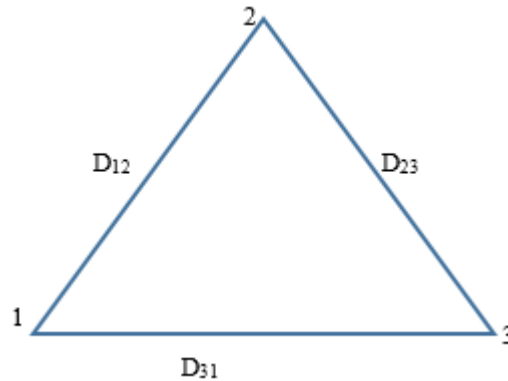


Figure 1.2.6

Fig.1.2.6 shows three conductors of a 3-phase line placed at the corners of a triangle of sides $D_{12} = 2 \text{ m}$, $D_{23} = 2.5 \text{ m}$ and $D_{31} = 4.5 \text{ m}$.

The conductor radius $r = 1.24/2 = 0.62 \text{ cm}$.

$$\begin{aligned} \text{Equivalent equilateral spacing, } D_{eq} &= (D_{12} D_{23} D_{31})^{1/3} \\ &= (2 \times 2.5 \times 4.5)^{1/3} \\ &= 2.82 \text{ m} \\ &= 282 \text{ cm} \end{aligned}$$

$$\begin{aligned} \text{Inductance/phase/m} &= 10^{-7} (0.5 + 2 \log_e D_{eq}/r) \text{ H} \\ &= 10^{-7} (0.5 + 2 \log_e 282/0.62) \text{ H} \\ &= 12.74 \times 10^{-7} \text{ H} \end{aligned}$$

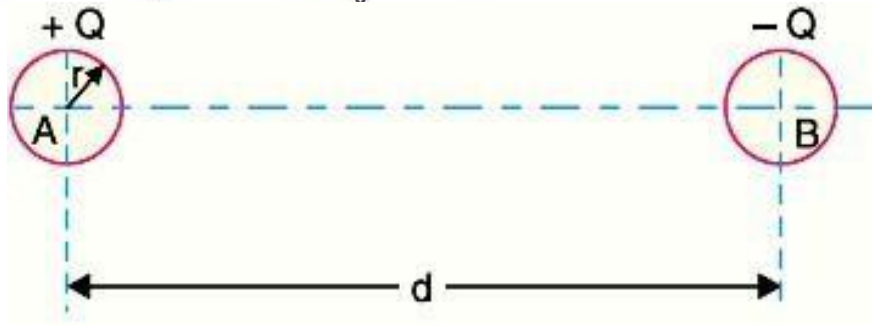
$$\begin{aligned} \text{Inductance/phase/km} &= 12.74 \times 10^{-7} \times 1000 \\ &= 1.274 \times 10^{-3} \text{ H} \\ &= \mathbf{1.274 \text{ mH}} \end{aligned}$$

1.3 CAPACITANCE OF A SINGLE PHASE TWO-WIRE LINE

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

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

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



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

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

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

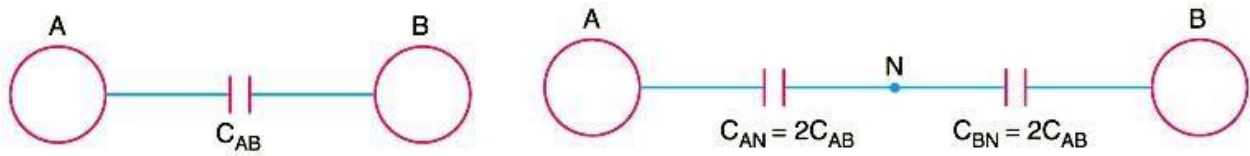
Both these potentials are w.r.t. the same neutral plane. Since the unlike charges attract each other, the potential difference between the conductors is

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

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

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

difference between the conductors. Thus the capacitance to ground or capacitance to neutral for the two-wire line is twice the line-to-line capacitance



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

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

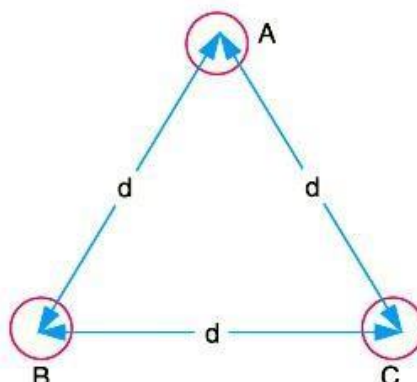
The reader may compare eq. (ii) to the one for inductance. One difference between the equations for capacitance and inductance should be noted carefully. The radius in the equation for capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula.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

1.3.1 CAPACITANCE OF A 3-PHASE OVERHEAD LINE

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

(i) Symmetrical Spacing

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



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

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

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

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

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

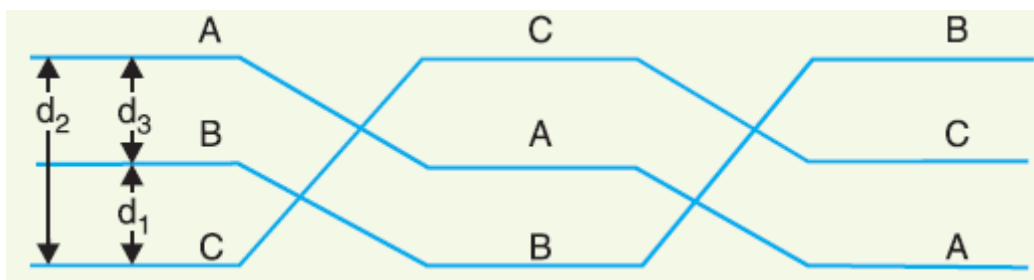
$\therefore$ Capacitance of conductor A w.r.t neutral,

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

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

(ii) Unsymmetrical spacing.

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



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

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

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

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

Average voltage on conductor A is

$$\begin{aligned} V_A &= \frac{1}{3} (V_1 + V_2 + V_3) \\ &= \frac{1}{3 \times 2\pi\epsilon_0} * \left[Q_A \log_e \frac{1}{r^3} + (Q_B + Q_C) \log_e \frac{1}{d_1 d_2 d_3} \right] \end{aligned}$$

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

$$\begin{aligned} \therefore V_A &= \frac{1}{6\pi\epsilon_0} \left[Q_A \log_e \frac{1}{r^3} - Q_A \log_e \frac{1}{d_1 d_2 d_3} \right] \\ &= \frac{Q_A}{6\pi\epsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3} \\ &= \frac{1}{3} \times \frac{Q_A}{2\pi\epsilon_0} \log_e \frac{d_1 d_2 d_3}{r^3} \\ &= \frac{Q_A}{2\pi\epsilon_0} \log_e \left(\frac{d_1 d_2 d_3}{r^3} \right)^{1/3} \\ &= \frac{Q_A}{2\pi\epsilon_0} \log_e \frac{(d_1 d_2 d_3)^{1/3}}{r} \end{aligned}$$

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

Problems :

1. Determine the capacitance and the charging current per km when the transmission line of example 2.2 is operating at 132 kV.

Solution: The radius of conductor = 0.4 cm.

The mutual GMD of conductors, $D_m = 2.015$ metres.

$$\therefore \text{Capacitance per phase per metre} = \frac{2\pi\epsilon_0}{\ln \frac{2.015}{0.4}} \times 10^2 \text{ F/metre}$$

$$= \frac{10^{-9}}{18 \times \ln \frac{2.015}{0.4}} = 8.928 \text{ pF/metre}$$

$$= 8.928 \times 10^{-12} \times 10^3 \text{ F/km}$$

$$= 8.928 \times 10^{-9} \text{ F/km}$$

$$\begin{aligned} \text{The charging current} &= \frac{132 \times 1000}{\sqrt{3}} \times 8.928 \times 10^{-9} \times 314 \\ &= 0.2136 \text{ amp/km. } \textbf{Ans.} \end{aligned}$$

2. Determine the capacitance and the charging current per km when the transmission line of example 2.5 operates at 220 kV, dia of conductor = 2.5 cm.

Solution:

Mutual GMD = 6.61 metres

$$D_{s_1} = \sqrt{1.25 \times 10^{-2} \times 10.965} = 0.3702 \text{ metre} = D_{s_3}$$

$$D_{s_2} = \sqrt{1.25 \times 10^{-2} \times 9} = 0.3354 \text{ metre}$$

$$\therefore D_s = \sqrt[3]{D_{s_1} D_{s_2} D_{s_3}} = \sqrt[3]{0.045965899} = 0.3582 \text{ metre}$$

$$\therefore \text{Capacitance per km} = \frac{10^{-6}}{18 \ln \frac{6.61}{0.3582}} = 0.019056 \text{ } \mu\text{F/km}$$

$$\begin{aligned} \therefore \text{Charging current per km} &= \frac{220 \times 1000}{\sqrt{3}} \times 314 \times 0.01905 \times 10^{-6} \\ &= 0.76 \text{ amp/km. } \textbf{Ans.} \end{aligned}$$

3. Determine the capacitance and charging current per km of the line of example

2.7 if the line operates at 220 kV, dia = 4.5 cms.

Solution:

$$D_s = \sqrt{2.25 \times 10^{-2} \times 0.4} = 0.094868 \text{ metre}$$

$$\therefore \text{ Capacitance per km} = \frac{10^{-6}}{18 \ln \frac{8.19}{0.094868}} = 0.01246 \text{ } \mu\text{F}$$

$$\begin{aligned} \text{The charging current per km} &= \frac{220 \times 1000}{\sqrt{3}} \times 314 \times 0.01246 \times 10^{-6} \\ &= 0.497 \text{ amp. } \quad \text{Ans.} \end{aligned}$$

1.4 CONCEPT OF SELF-GMD AND MUTUAL-GMD

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

(i) Self-GMD (D_s)

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

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

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

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

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

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

(b) For a single circuit 3- ϕ line, the mutual-GMD is equal to the equivalent equilateral spacing i.e.,

$$(d_1 d_2 d_3)^{1/3}$$

1.5 SKIN EFFECT

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

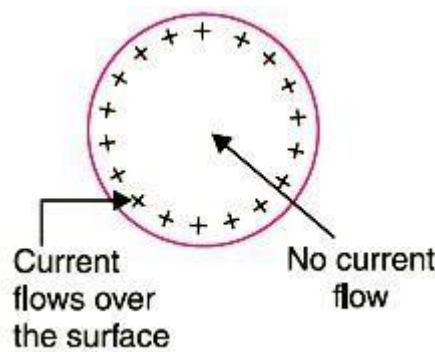


Figure 1.1 Structure of Power System

[Source: "Principles of Power System" by V.K.Mehta Page: 204]

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.

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

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. is large and its cost forms a major proportion of the total cost of complete installation.

3. Steel cored aluminium

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

Steel-cored aluminium conductor consists of central core of galvanized steel wires surrounded by a number of aluminium strands. Usually, diameter of both steel and aluminium wires is the same. The X-section of the two metals are generally in the ratio

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

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.

4. Galvanised steel

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

5. Cadmium copper

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

2.1 CLASSIFICATION OF OVERHEAD TRANSMISSION LINES

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

(i) Short transmission lines.

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

(ii) Medium transmission lines.

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

(iii) Long transmission lines.

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

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

2.2 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.

$$\% \text{ VOLTAGE REGULATION} = \frac{\text{Output voltage} - \text{Input voltage}}{\text{Input voltage}} \times 100$$

2.2.1 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

$$\% \text{ VOLTAGE REGULATION} = (\text{Output voltage} / \text{Input voltage}) * 100$$

2.3 PERFORMANCE OF SINGLE PHASE SHORT TRANSMISSION LINES

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

Let

I = load current

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

X_L = loop reactance

V_R = receiving end voltage

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

V_S = sending end voltage

$\cos \phi_S$ = sending end power factor

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

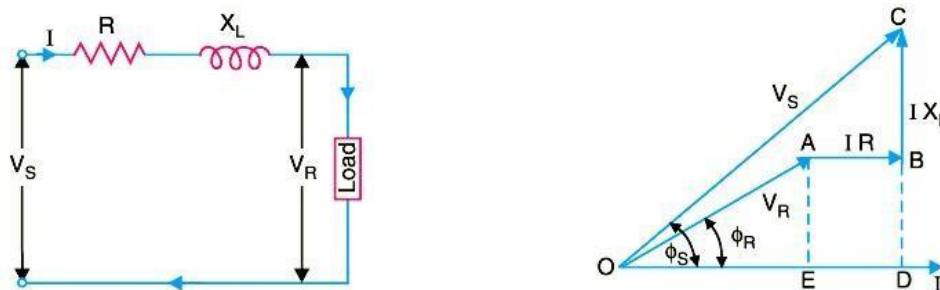


Figure 2.3 Equivalent Circuit of Short Line

[Source: "Principles of Power System" by V.K.Mehta Page: 230]

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

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

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

$$\begin{aligned}
 OC &= OF = OA + AF = OA + AG + GF \\
 &= OA + AG + BH \\
 V_s &= V_R + I_R \cos \phi_R + I X_L \sin \phi_R
 \end{aligned}$$

2.3.1 THREE-PHASE SHORT TRANSMISSION LINES

For reasons associated with economy, transmission of electric power is done by 3-phase system. This system may be regarded as consisting of three single phase units, each wire transmitting one-third of the total power. As a matter of convenience, we generally analyse 3- phase system by considering one phase only. Therefore, expression for regulation, efficiency etc. derived for a single phase line can also be applied to a 3-phase

system. Since only one phase is considered, phase values of 3-phase system should be taken. Thus, V_S and V_R are the phase voltages, whereas R and X_L are the resistance and inductive reactance per phase respectively

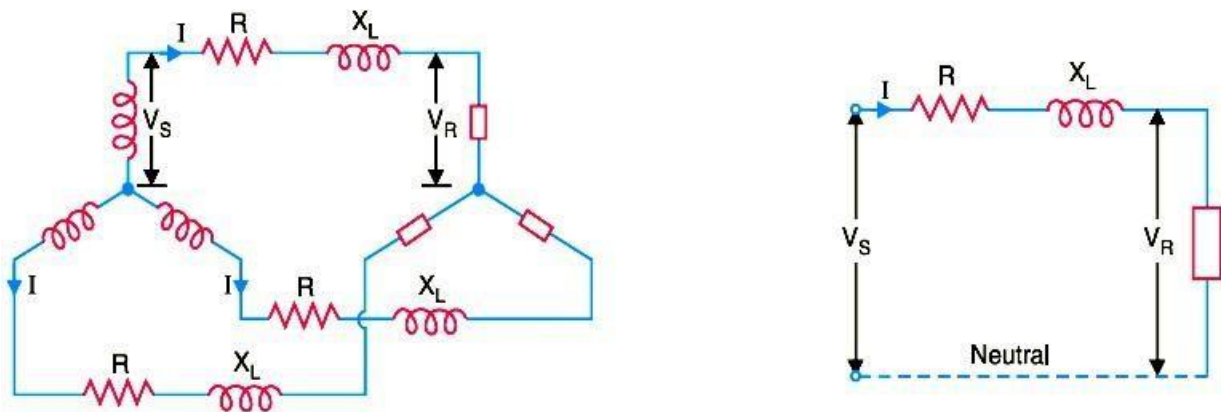


Figure 2.3 Equivalent Circuit of Three Phase Short Line

[Source: "Principles of Power System" by V.K.Mehta Page: 232]

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

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

1. Effect on regulation.

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

The following conclusions can be drawn from the above expressions :

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

2. Effect on transmission efficiency.

The power delivered to the load depends upon the power factor. It is clear that in each

(iv) For a given V_R and I , the voltage regulation of the line decreases with the decrease in p.f. for leading loads.

case, for a given amount of power to be transmitted (P) and receiving end voltage Power Factor Meter (V_R), the load current I is inversely proportional to the load p.f. $\cos\phi_R$.

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

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

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

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

Consequently, with the decrease in load p.f., the load current and hence the line losses are increased. This leads to the conclusion that transmission efficiency of a line decreases with the decrease in load Power Factor Regulator p.f. and vice-versa,

2.4 MEDIUM TRANSMISSION LINES

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

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

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

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

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

i)End Condenser Method

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

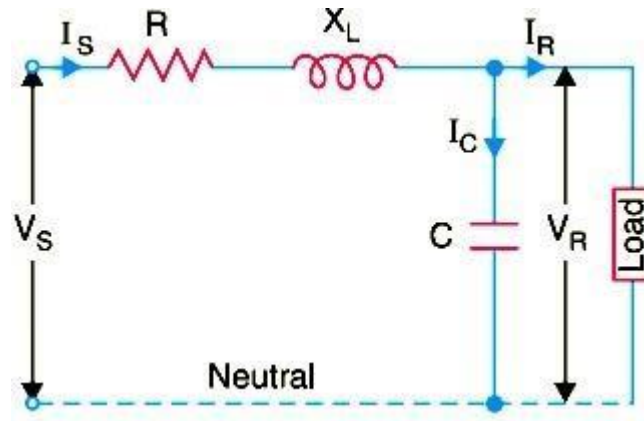


Figure 2.4.1 Equivalent Circuit End Condenser Method

[Source: "Principles of Power System" by V.K.Mehta Page: 253]

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

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

V_S = sending end voltage per phase

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

we have,

$$V_R = V_R + j 0$$

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

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

The sending end current I_S is the phasor sum of load current

I_R and capacitive current I_C i.e.,

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

$$\text{Voltage drop/phase} = I_S Z = I_S (R + j X_L)$$

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

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

ii) Nominal T Method

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

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

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

V_S = sending end voltage/phase

V_1 = voltage across capacitor C

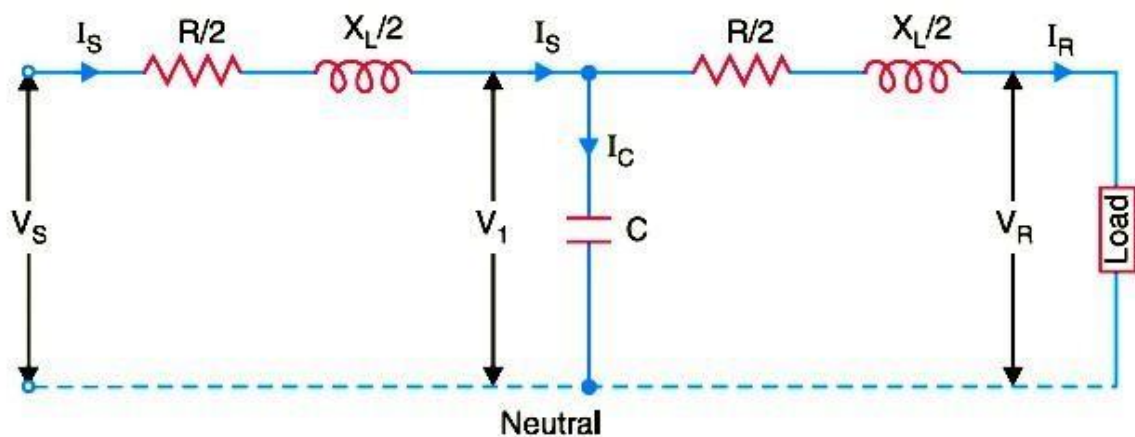


Figure 2.4.2 Equivalent Circuit Nominal - T Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

The phasor diagram for the circuit is shown in Fig.2.4.3, 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, $\vec{I}_R = I_R (\cos \phi_R - j \sin \phi_R)$

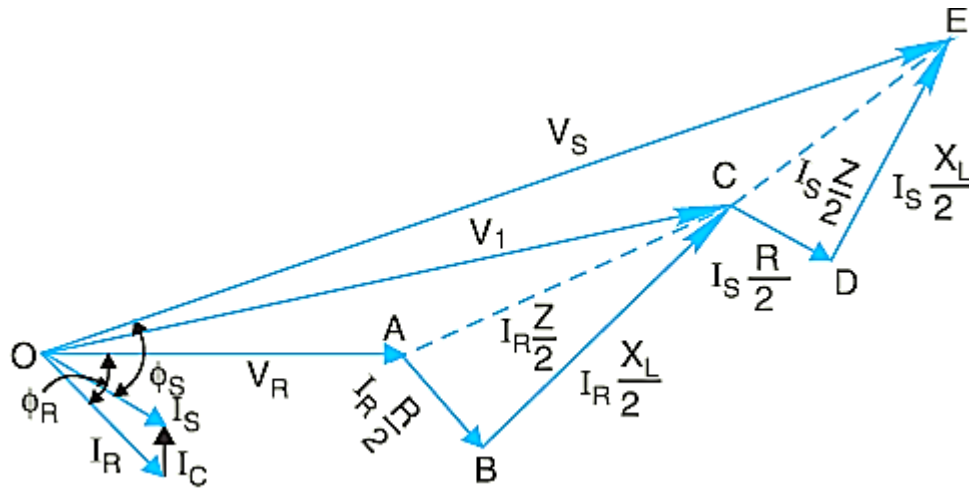


Figure 2.4.3 Phasor Diagram Nominal - T Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

$$\begin{aligned} \text{Voltage across } C, \quad \vec{V}_1 &= \vec{V}_R + \vec{I}_R \vec{Z} / 2 \\ &= V_R + I_R (\cos \phi_R - j \sin \phi_R) \left(\frac{R}{2} + j \frac{X_L}{2} \right) \end{aligned}$$

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

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

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

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.

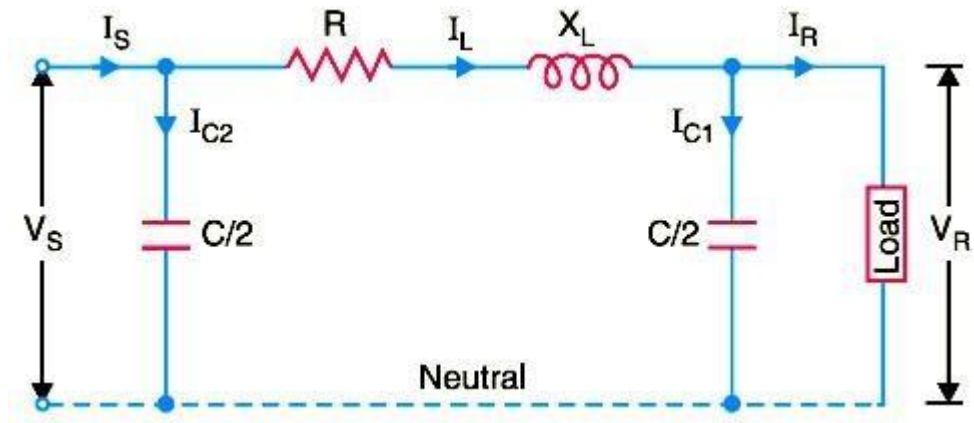


Figure 2.4.4 Equivalent Circuit Nominal - π Method

[Source: "Principles of Power System" by V.K.Mehta Page: 246]

Let

I_R = load current per phase

R = resistance per phase

X_L = inductive reactance per phase

C = capacitance per phase

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

V_S = sending end voltage per phase

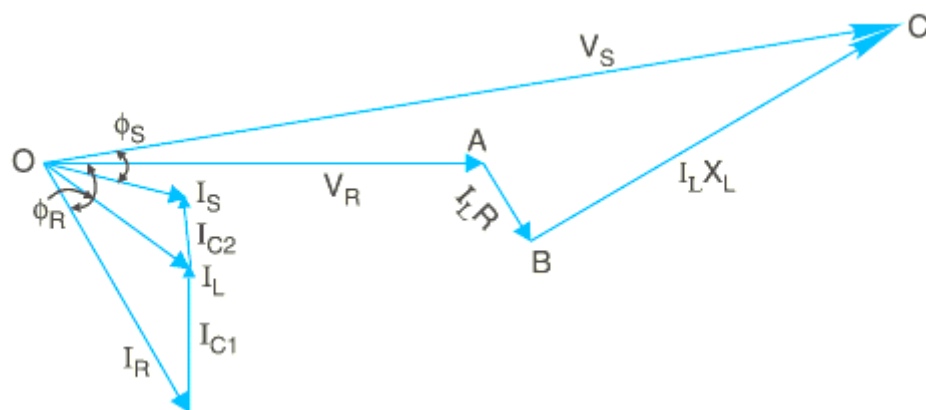


Figure 2.4.5 Phasor Diagram Nominal - π Method

[Source: "Principles of Power System" by V.K.Mehta Page: 243]

The phasor diagram for the circuit is shown in Fig 2.4.5 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, $\vec{I}_L = \vec{I}_R + \vec{I}_{C1}$

Sending end voltage, $\vec{V}_S = \vec{V}_R + \vec{I}_L \vec{Z} = \vec{V}_R + \vec{I}_L (R + jX_L)$

Charging current at the sending end is

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

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

Problem 1

Determine the efficiency and regulation of a 3-phase, 100 km, 50 Hz transmission line delivering 20 MW at a p.f. of 0.8 lagging and 66 kV to a balanced load. The conductors are of copper, each having resistance 0.1 ohm per km, 1.5 cm outside dia, spaced equilaterally 2 metres between centres. Neglect leakance and use (i) nominal- T , and (ii) nominal- π method.

Solution:

Total resistance of line $100 \times 0.1 = 10$ ohms.

$$\begin{aligned} \text{The inductance of the line} &= 2 \times 10^{-7} \times 100 \times 1000 \ln\left(\frac{200}{0.75}\right) \\ &= 11.17 \times 10^{-2} \text{ H} \end{aligned}$$

$$\therefore \text{Inductive reactance} = 314 \times 11.17 \times 10^{-2} = 35.1 \text{ ohm}$$

$$\begin{aligned} \text{The capacitance/phase} &= \frac{2\pi \times 8.854 \times 10^{-12}}{\ln\left(\frac{200}{0.75}\right)} \times 100 \times 1000 \\ &= 9.954 \times 10^{-7} \\ &= 0.9954 \mu\text{F}. \end{aligned}$$

Nominal-T method: The nominal- T circuit for the problem is given below:

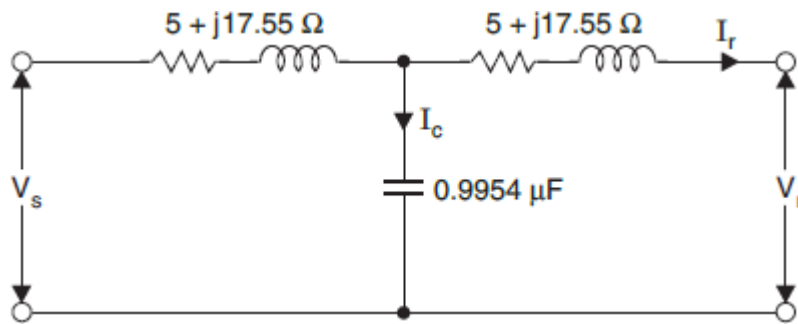


Figure 2.4.6 Nominal - T Method

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 73]

$$I_r = \frac{20 \times 1000}{\sqrt{3} \times 66 \times 0.8} = 218.68 \text{ amps}$$

$$V_r = \frac{66 \times 1000}{\sqrt{3}} = 38104 \text{ volts}$$

Taking I_r as the reference, the voltage across the condenser will be

$$\begin{aligned} V_c &= (38104 \times 0.8 + 218.68 \times 5) + j(38104 \times 0.6 + 218.68 \times 17.55) \\ &= 31576 + j26700 \end{aligned}$$

The current
$$I_c = j\omega CV_c = j314(31576 + j26700) \times 0.9954 \times 10^{-6}$$

$$= j9.87 - 8.34$$

$$\begin{aligned} \therefore I_s &= 218.68 + j9.87 - 8.34 = 210.34 + j9.87 \\ &= 210.57 \text{ amps} \end{aligned}$$

$$\begin{aligned} \therefore V_s &= V_c + I_s \frac{Z}{2} \\ &= 31576 + j26700 + (210.34 + j9.87)(5 + j17.53) \\ &= 31576 + 1051 - 173 + j26700 + j3691 + j49.35 \\ &= 32454 + j30440 \end{aligned}$$

$$\therefore |V_s| = 44495 \text{ volts}$$

The no load receiving end voltage will be

$$\frac{|V_s|(-j3199)}{5 + j17.55 - j3199} = \frac{44495(-j3199)}{5 - j3181} = 44746 \text{ volts}$$

$$\therefore \% \text{ regulation} = \frac{44746 - 38104}{38104} \times 100 = 17.4\%. \quad \text{Ans.}$$

To determine η we evaluate transmission line losses as follows:

$$3[218.68^2 \times 5 + 210.57^2 \times 5] = 1382409 \text{ watts} = 1.3824 \text{ MW}$$

$$\therefore \% \eta = \frac{20}{20 + 1.3824} \times 100 = 93.5\%. \quad \text{Ans.}$$

Nominal- π method: The nominal- π circuit for the problem is as follows:

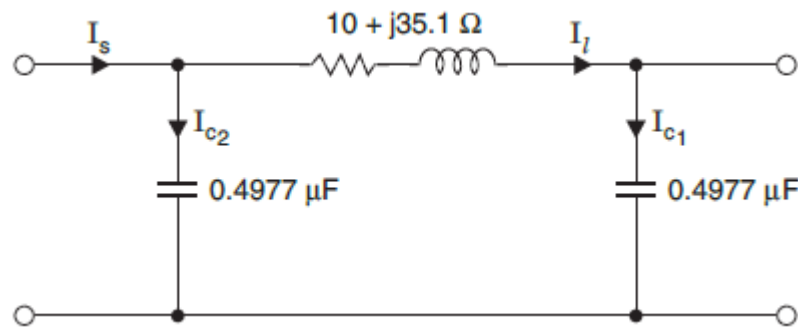


Figure 2.4.7 Nominal - π Method

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 74]

For nominal- π it is preferable to take receiving end voltage as the reference phasor. The current $I_r = 218.68 (0.8 - j0.6)$.

$$\text{Current } I_{c1} = j\omega CV_r = j314 \times 0.4977 \times 10^{-6} \times 38104 = j5.95 \text{ amp}$$

$$I_l = I_r + I_{c1} = 174.94 - j131.20 + j5.95 = 174.94 - j125.25$$

$$\begin{aligned} \therefore V_s &= V_r + I_l Z = 38104 + (174.94 - j125.25) (10 + j35.1) \\ &= 38104 + 1749.4 - j1252.5 + j6140 + 4396 \\ &= 44249 + j4886 \text{ volts} \end{aligned}$$

$$|V_s| = 44518 \text{ volts}$$

The no load receiving end voltage will be

$$\begin{aligned} \frac{44518 (-j6398)}{10 + j35.1 - j6398} &= 44762 \text{ volts} \\ \% \text{ voltage regulation} &= \frac{44762 - 38104}{38104} \times 100 \\ &= 17.47\% \end{aligned}$$

The line current $I_l = 215.15$

$$\therefore \text{Loss} = 3 \times 215.15^2 \times 10 = 1.388 \text{ MW}$$

$$\begin{aligned} \therefore \% \eta &= \frac{20}{21.388} \times 100 \\ &= 93.5\%. \text{ Ans.} \end{aligned}$$

2.5 LONG TRANSMISSION LINES

It is well known that line constants of the transmission line are uniformly distributed over the entire length of the line. However, reasonable accuracy can be obtained in line calculations for short and medium lines by considering these constants as lumped. If such an assumption of lumped constants is applied to long transmission lines (having length excess of about 150 km), it is found that serious errors are introduced in the performance calculations. Therefore, in order to obtain fair degree of accuracy in the performance calculations of long lines, the line constants are considered as uniformly distributed throughout the length of the line. Rigorous mathematical treatment is required for the solution of such lines. Fig.2.5.1 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.

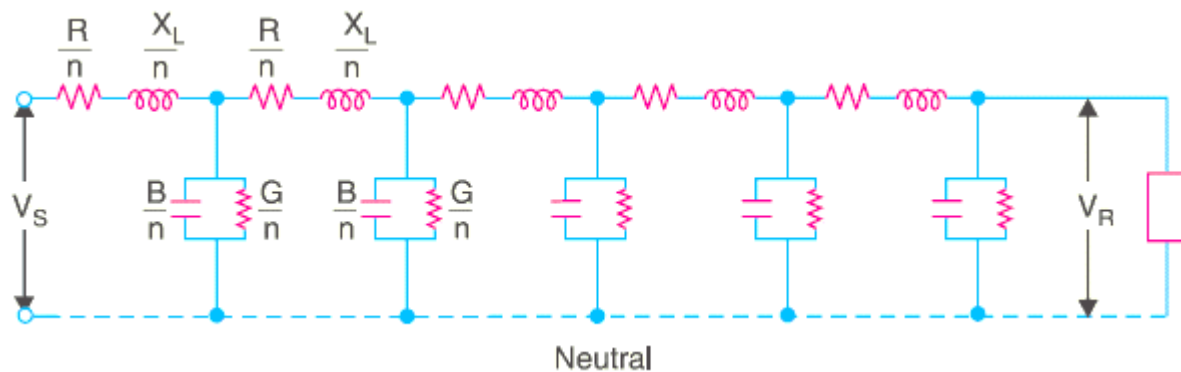


Figure 2.5.1 Long Transmission Line - Rigorous Method

[Source: "Principles of Power System" by V.K.Mehta Page: 251]

The following points may be noted :

- (i) The line constants are uniformly distributed over the entire length of line as is actually the case.
- (ii) The resistance and inductive reactance are the series elements.
- (iii) The leakage susceptance (B) and leakage conductance (G) are shunt elements. The leakage susceptance is due to the fact that capacitance exists between line and neutral. The leakage conductance takes into account the energy losses occurring through leakage over the 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.

2.5.1 ANALYSIS OF LONG TRANSMISSION LINE (RIGOROUS METHOD)

Fig.2.5.2 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, $dV = I z dx$

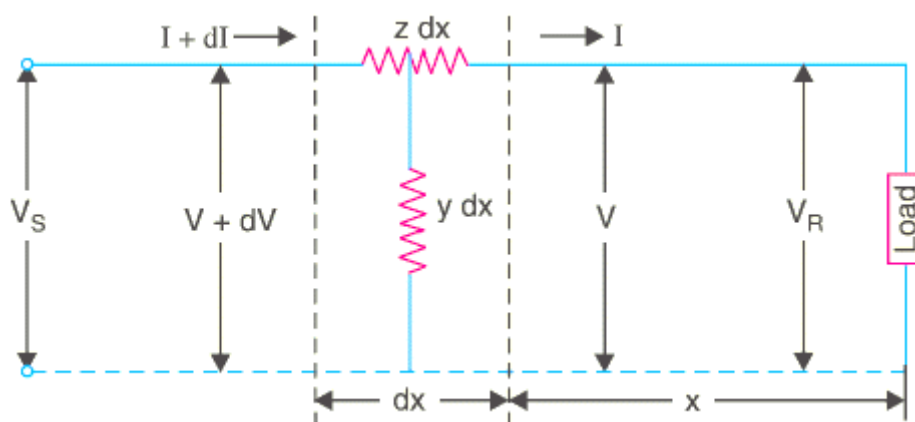


Figure 2.5.2 Equivalent Circuit Rigorous Method

[Source: "Principles of Power System" by V.K.Mehta Page: 252]

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.,

Current through shunt admittance of element,

$$dI = V y dx$$

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

$$\frac{d^2 V}{dx^2} = z \frac{dI}{dx}$$

$$\frac{d^2 V}{dx^2} = yzV$$

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

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

$$\frac{dV}{dx} = Iz$$

$$Iz = k_1 \sqrt{yz} \sinh(x \sqrt{yz}) + k_2 \sqrt{yz} \cosh(x \sqrt{yz})$$

$$I = \sqrt{\frac{y}{z}} \left[k_1 \sinh(x \sqrt{yz}) + k_2 \cosh(x \sqrt{yz}) \right]$$

From the above equations 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 : At $x = 0$, $V = V_R$ and $I = I_R$

Putting these values we have,

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

$$V_R = k_1$$

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

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

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

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

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

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

2.6 POWER CIRCLE DIAGRAM

Receiving End Power Circle Diagram:

Consider equation in general circuit constants

$$V_s = AV_r + BI_r$$

In phasor diagram except for I_r all other phasors represent voltages. We are interested in studying the power diagram, that too receiving end power diagram. The voltage phasor diagram must be multiplied by suitable value of current. If we multiply equation by V_r/B we get as,

$$\frac{V_s V_r}{B} = \frac{AV_r^2}{B} + V_r I_r$$

We find that the last term in the expression represents the volt-amperes at the receiving end; this is what is required. Since V_r is taken as the reference, the effect of multiplying the equation by V_r/B will be to change the magnitude of all the phasors in Fig. 2.6.1 by $|V_r|/|B|$ and rotate them clockwise through an angle $\angle(0 - \beta^\circ)$ i.e., $-\beta^\circ$. Now when origin is shifted to n and phasor BI_r is to be rotated through $-\beta^\circ$, this phasor will subtend an angle $-\phi_r$ with the horizontal axis. V_r^2/B will subtend an angle $-\beta$ with the horizontal axis. Now with respect to V_r^2/B other phasors AV_r^2/B and $V_s V_r/B$ are drawn as shown in Fig.2.6.1.

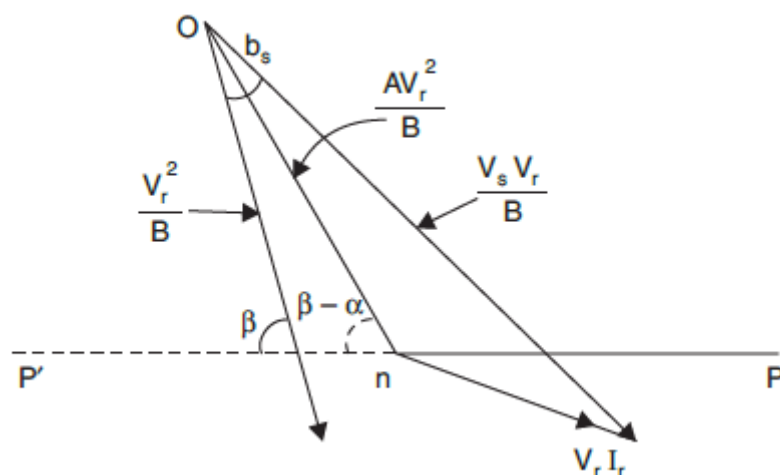


Figure 2.6.1 Phasor diagram

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 239]

Normally in a 3-phase system, 3-phase power is specified and $L-L$ voltage is given. The power circle diagram that we have obtained we started with phase quantities. We could make use of 3-phase quantities also and in that case the power will be 3-phase power and voltage line to line. The procedure we are going to describe is say on per phase basis.

- (a) Let P be the 3-phase power and V_L the line to line voltage at the receiving end, then

$$P_r = \frac{P}{3} \text{ and } V_r = \frac{V_L}{\sqrt{3}}$$

- (b) Calculate

$$\frac{|A||V_r^2|}{|B|}$$

- (c) Now looking at the relative values of P_r and $A V_r^2 / B$ choose a suitable scale.
- (d) Draw a horizontal line and fix a point n on this line. From this point draw a line subtending an angle ϕ_r as shown in Fig.6.1.2 Then after reducing P_r to scale cut the horizontal line at l by an amount equal to P_r . Draw a vertical line such that it cuts the slanted line (at angle ϕ_r) at m . Thus the operating point m is obtained.
- (e) Now from the point n , draw a line no equal to $A V_r^2 / B$ (reduced to scale) at angle $(\beta - \alpha)$ in the third quadrant.
- (f) Measure the length Om . Convert this to MVA or kVA depending upon the scale chosen. Then

$$Om \times \text{scale} = \frac{|V_s||V_r|}{|B|}$$

The capacity of the phase modifier in all cases will be mm' . The VAr's requirements of the load are fixed and are equal to ml . Therefore, the division of VAr's in the three situations is as follows:

- (i) When m' is above m . The capacity of the phase modifier is mm' . The VAr's transmitted over the line are $m'l$, i.e., in order to have sending end voltage corresponding to this operating point, transmission line has to transmit not only the VAr's required by the load but it has to supply VAr's to the synchronous phase modifier equal to mm' i.e., the phase modifier takes the lagging VAr's from the system which means it is under-excited.

(ii) When m' lies between m and l . In order to meet the VAr's requirements of the load mm' is supplied by the phase modifier and $m'l$ have to be transmitted over the line. The phase modifier is over-excited.

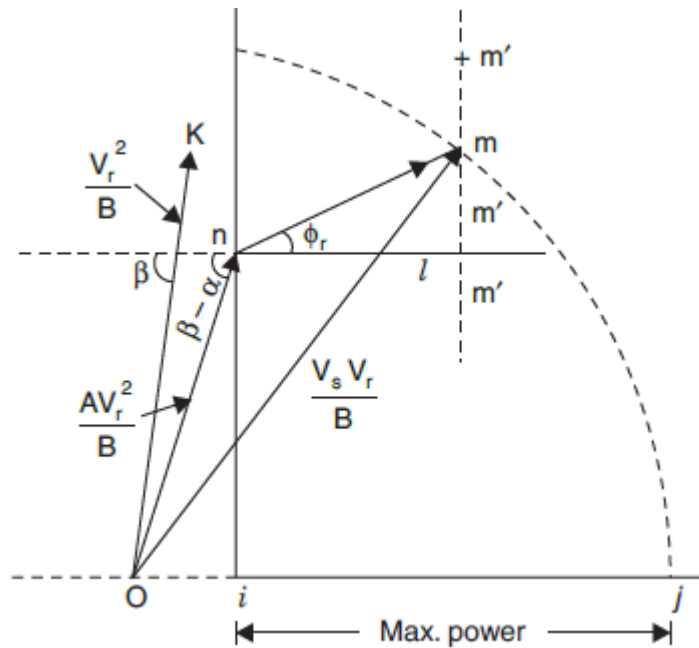


Figure 2.6.2 Power Circle diagram

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 242]

(iii) When m' lies below the horizontal axis. The capacity of the phase modifier is mm' . Here the phase modifier not only supplied VAr's to the load but it supplies lm' VAr's to the transmission line also to get this operating point. The phase modifier is over-excited.

The power factor of the load is fixed and is given by $\cos \phi_r$. The power factor of the transmission line at the receiving end will depend upon the position of the operating point m' with respect to the horizontal axis. The power factor angle in all cases is the angle between the line nm' and the horizontal axis. If the point m' lies above the horizontal axis the power factor is lagging and if it lies below the horizontal axis it is leading.

To find out the load angle or torque angle δ_s , draw a horizontal line passing through O and then from O draw a line subtending an angle β . This line corresponds to $|V_r^2|/|B|$. Cut this line to scale equal to $|V_r^2|/|B|$. The angle between Ok and Om' gives the torque angle for regulated systems and for unregulated systems the angle between Ok and Om is the torque angle δ_s .

2.7 CORONA

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

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

2.7.1 Theory of corona formation

Some ionisation is always present in air due to cosmic rays, ultraviolet radiations and radioactivity. Therefore, under normal conditions, the air around the conductors contains some ionised particles and neutral molecules. When p.d. is applied between the conductors, potential gradient is set up in the air which will have maximum value at the conductor surfaces. Under the influence of potential gradient, the existing free electrons acquire greater velocities. The greater the applied voltage, the greater the potential gradient and more is the velocity of free electrons. When the potential gradient at the conductor surface reaches about 30 kV per cm (max. value), the velocity acquired by the free electrons is sufficient to strike a neutral molecule with enough force to dislodge one or more electrons from it. This produces another ion and one or more free electrons, which in turn are accelerated until they collide with other neutral molecules, thus producing other ions. Thus, the process of ionisation is cumulative. The result of this ionisation is that either corona is formed or spark takes place between the conductors.

2.7.2 Factors Affecting Corona

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

(i) Atmosphere

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

(ii) Conductor size.

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

(iii) Spacing between conductors.

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

(iv) Line voltage.

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

2.7.3 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.

2.7.4 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.

3.1 SAG IN OVERHEAD LINES

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



Figure 3.1 Sag in Overhead lines

[Source: "Principles of Power System" by V.K.Mehta Page: 187]

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

3.2 CALCULATION OF SAG

In an overhead line, the sag should be so adjusted that tension in the conductors is within safe limits. The tension is governed by conductor weight, effects of wind, ice loading and temperature variations. It is a standard practice to keep conductor tension less than 50% of its ultimate tensile strength i.e., minimum factor of safety in respect of conductor tension should be

We shall now calculate sag and tension of a conductor when

- (i) supports are at equal levels and
- (ii) supports are at unequal levels.

(i) When supports are at equal levels .Consider a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.8.2. It can be proved that lowest point will be at a conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.3.2.1 It can be proved that lowest point will be at the mid-span.

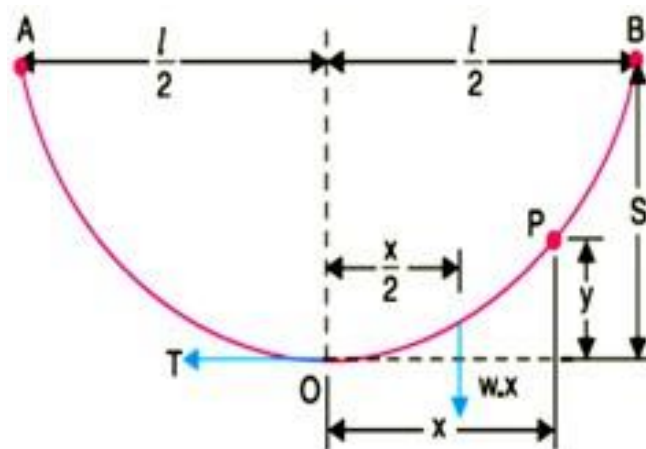


Figure 3.2.1 Supports are at Equal Levels

[Source: "Principles of Power System" by V.K.Mehta Page: 187]

conductor between two equilevel supports A and B with O as the lowest point as shown in Fig.3.2.1. It can be proved that lowest point will be at the mid-span.

Let

l = Length of span

w = Weight per unit length of conductor

T = Tension in the conductor.

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

(a) The weight $w x$ of conductor acting at a distance $x/2$ from O.

$$\text{Moment of force due to weight} = w x \times x/2$$

(b) The tension T acting at O .

$$\text{Moment of force due to tension} = T y$$

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

$$T y = w x \times \frac{x}{2}$$

$$y = \frac{w x^2}{2 T}$$

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 $y = S$, Sag

$$S = \frac{w(l/2)^2}{2T}$$

$$= \frac{w l^2}{8 T}$$

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

suspended between supports at unequal levels. Fig. 3.2.2 shows a conductor suspended between two supports A and B which are at different levels. The lowest point on the conductor is O.

Let

l = Span length

h = Difference in levels between two supports

x_1 = Distance of support at lower level (i.e., A) from O

x_2 = Distance of support at higher level (i.e. B) from O

T = Tension in the conductor

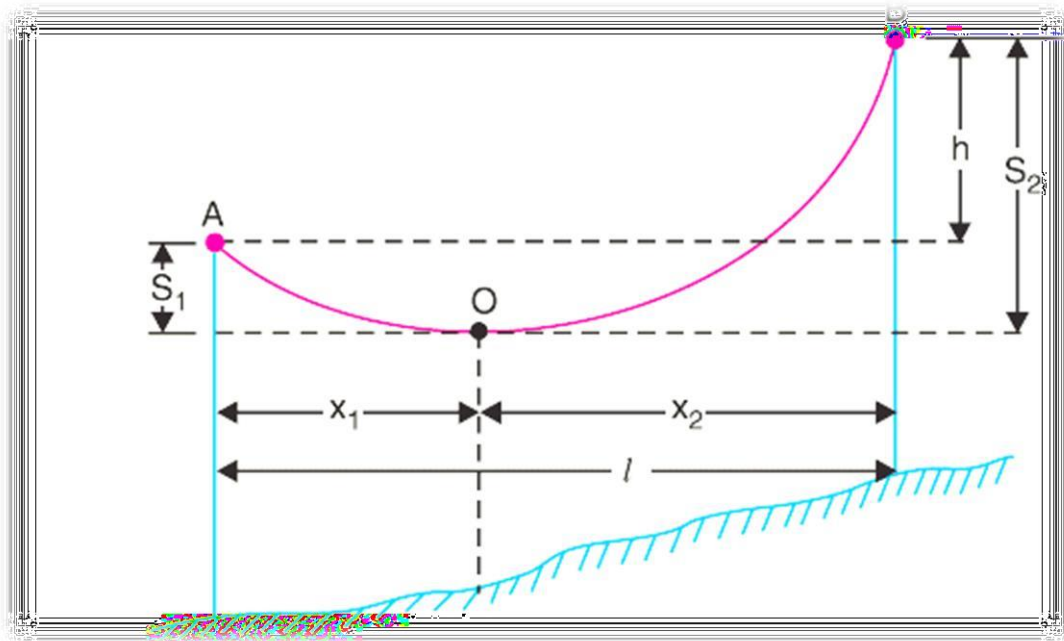


Figure 3.2.2 Supports are at UnEqual Levels

[Source: "Principles of Power System" by V.K.Mehta Page: 188]

$$S_1 = \frac{Wx_1^2}{2T}$$

$$S_2 = \frac{Wx_2^2}{2T}$$

$$x_1 + x_2 = l$$

$$S_2 - S_1 = \frac{W(x_2^2 - x_1^2)}{2T}$$

$$S_2 - S_1 = \frac{W(x_1 + x_2)(x_2 - x_1)}{2T}$$

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

$$S_2 - S_1 = h$$

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

$$x_2 - x_1 = \frac{2Th}{Wl}$$

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

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

3.2.1 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.3.2.3.

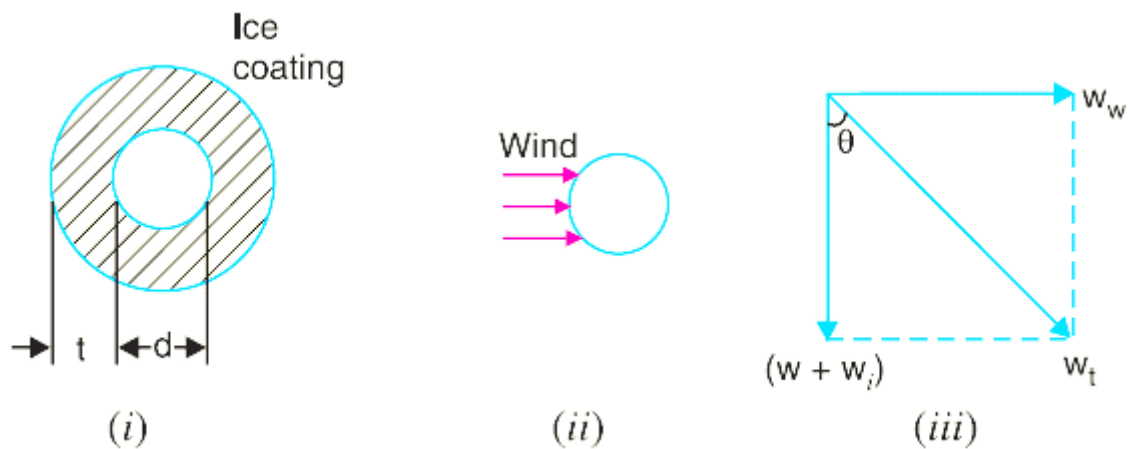


Figure 3.2.3 Effect of Wind and Ice Loading

[Source: "Principles of Power System" by V.K.Mehta Page: 189]

Total weight of conductor per unit length is,

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

w = weight of conductor per unit length

= conductor material density $\times$ volume per unit length

w_i = weight of ice per unit length

= density of ice $\times$ 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 $\times$ 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 sag is calculated by using the above formula.

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

Problem 1

A 132 kV transmission line has the following data : Wt. of conductor = 680 kg/km ;

Length of span = 260 m ; Ultimate strength = 3100 kg ; Safety factor = 2

Calculate the height above ground at which the conductor should be supported. Ground clearance required is 10 metres.

Solution:

Wt. of conductor/metre run, $w = 680/1000 = 0.68$ kg

Working tension, $T = \frac{\text{Ultimate strength}}{\text{Safety factor}} = \frac{3100}{2} = 1550$ kg

Span length, $l = 260$ m

$$\therefore \text{Sag} = \frac{w l^2}{8T} = \frac{0.68 \times (260)^2}{8 \times 1550} = 3.7 \text{ m}$$

Problem 2

A transmission line has a span of 150 m between level supports. The conductor has a cross-sectional area of 2 cm². The tension in the conductor is 2000 kg. If the specific gravity of the conductor material is 9.9 gm/cm³ and wind pressure is 1.5 kg/m length, calculate the sag. What is the vertical sag?

Solution:

Span length, $l = 150$ m; Working tension, $T = 2000$ kg

Wind force/m length of conductor, $w_w = 1.5$ kg

Wt. of conductor/m length, $w = \text{Sp. Gravity} \times \text{Volume of 1 m conductor}$
 $= 9.9 \times 2 \times 100 = 1980 \text{ gm} = 1.98 \text{ kg}$

Total weight of 1 m length of conductor is

$$w_t = \sqrt{w^2 + w_w^2} = \sqrt{(1.98)^2 + (1.5)^2} = 2.48 \text{ kg}$$

$$\begin{aligned} \text{Sag, } S &= \frac{w_t l^2}{8T} = \frac{2.48 \times (150)^2}{8 \times 2000} \\ &= 3.48 \text{ m} \end{aligned}$$

This is the value of slant sag in a direction making an angle θ with the vertical.

Referring to Fig. 8.27, the value of θ is given by ;

$$\begin{aligned} \tan \theta &= w_w/w = 1.5/1.98 = 0.76 \\ \theta &= \tan^{-1} 0.76 = 37.23^\circ \end{aligned}$$

$$\begin{aligned} \text{Vertical sag} &= S \cos \theta \\ &= 3.48 \times \cos 37.23^\circ \\ &= 2.77 \text{ m} \end{aligned}$$

Problem 3

A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1.96 cm and weighs 0.865 kg/m. Its ultimate strength is 8060 kg. If the conductor has ice coating of radial thickness 1.27 cm and is subjected to a wind pressure of 3.9 gm/cm² of projected area, calculate sag for a safety factor of 2. Weight of 1 c.c. of ice is 0.91 gm.

Solution:

Span length, $l = 275$ m ; Wt. of conductor/m length, $w = 0.865$ kg

Conductor diameter, $d = 1.96$ cm ; Ice coating thickness, $t = 1.27$ cm

Working tension, $T = 8060/2 = 4030$ kg

Volume of ice per metre (i.e., 100 cm) length of conductor

$$\begin{aligned} &= \pi t (d + t) \times 100 \text{ cm}^3 \\ &= \pi \times 1.27 \times (1.96 + 1.27) \times 100 = 1288 \text{ cm}^3 \end{aligned}$$

Weight of ice per metre length of conductor is

$$w_i = 0.91 \times 1288 = 1172 \text{ gm} = 1.172 \text{ kg}$$

Wind force/m length of conductor is

$$\begin{aligned} w_w &= [\text{Pressure}] \times [(d + 2t) \times 100] \\ &= [3.9] \times (1.96 + 2 \times 1.27) \times 100 \text{ gm} \\ &= 1755 \text{ gm} \\ &= 1.755 \text{ kg} \end{aligned}$$

Total weight of conductor per metre length of conductor is

$$\begin{aligned} w_i &= \sqrt{(w + w_i)^2 + (w_w)^2} \\ w_i &= \sqrt{(0.865 + 1.172)^2 + (1.755)^2} \\ &= 2.688 \text{ kg} \end{aligned}$$

Sag ,

$$\begin{aligned} S &= \frac{w_t l^2}{8T} \\ &= \frac{2.688 \times (275)^2}{8 \times 4030} \\ &= 6.8 \text{ m} \end{aligned}$$

Problem 4

The towers of height 30 m and 90 m respectively support a transmission line conductor at water crossing. The horizontal distance between the towers is 500 m. If the tension in the conductor is 1600 kg, find the minimum clearance of the conductor and water and clearance mid-way between the supports. Weight of conductor is 1.5 kg/m. Bases of the towers can be considered to be at water level.

Solution:

Fig. 3.2.4 shows the conductor suspended between two supports A and B at different levels with O as the lowest point on the conductor.

Here, $l = 500 \text{ m}$; $w = 1.5 \text{ kg}$; $T = 1600 \text{ kg}$.

Difference in levels between supports, $h = 90 - 30 = 60 \text{ m}$. Let the lowest point O of the conductor be at a distance x_1 from the support at lower level (i.e., support A) and at a distance x_2 from the support at higher level (i.e., support B).

Obviously, $x_1 + x_2 = 500 \text{ m}$

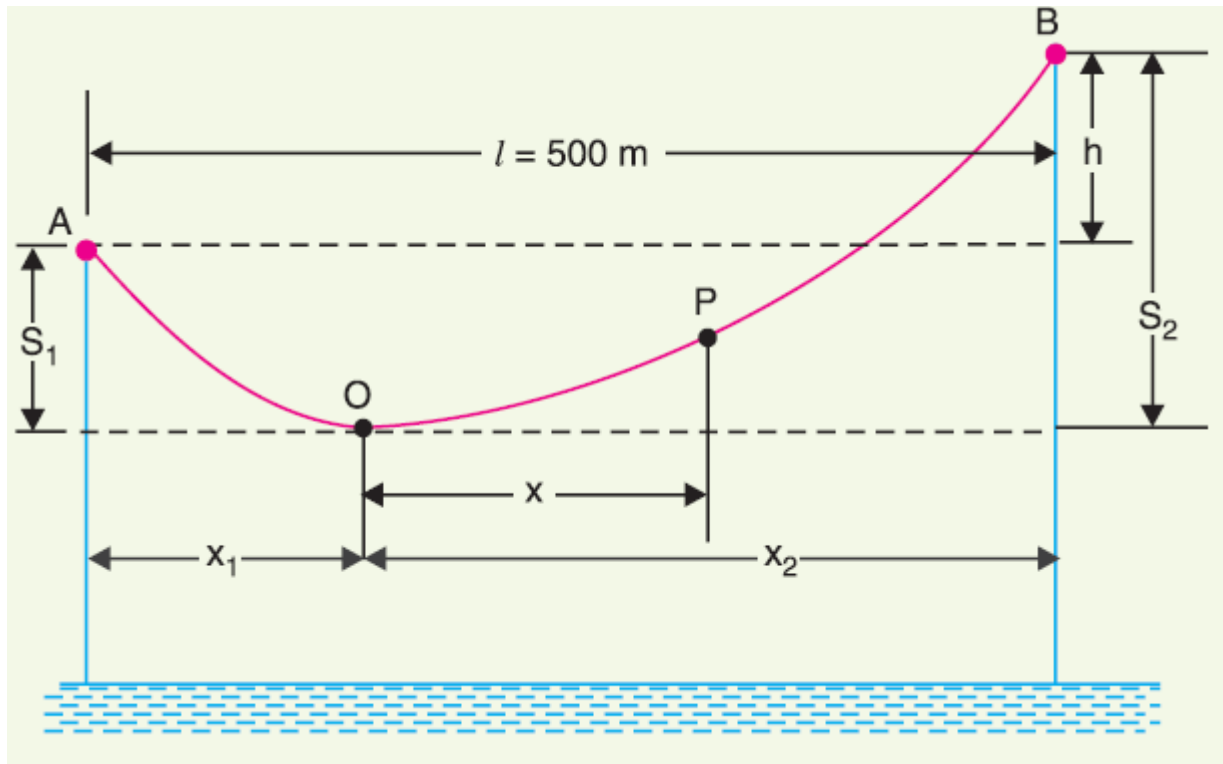


Figure 3.2.4 Conductor b/w two Supports

[Source: "Principles of Power System" by V.K.Mehta Page: 193]

$$\text{Sag } S_1 = \frac{w x_1^2}{2T} \quad \text{and} \quad \text{Sag } S_2 = \frac{w x_2^2}{2T}$$

$$h = S_2 - S_1 = \frac{w x_2^2}{2T} - \frac{w x_1^2}{2T}$$

$$60 = \frac{w}{2T} (x_2 + x_1)(x_2 - x_1)$$

$$x_2 - x_1 = \frac{60 \times 2 \times 1600}{1.5 \times 500} = 256 \text{ m}$$

we get, $x_1 = 122 \text{ m}$; $x_2 = 378 \text{ m}$

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

$$= \frac{1.5 \times (122)^2}{2 \times 1600}$$

$$= 7m$$

Clearance of the lowest point O from water level

$$= 30 - 7 = \mathbf{23 \text{ m}}$$

Let the mid-point P be at a distance x from the lowest point O .

Clearly,

$$x = 250 - x_1$$

$$= 250 - 122$$

$$= 128 \text{ m}$$

Sag at mid-point P ,

$$S_{mid} = \frac{wx^2}{2T}$$

$$= \frac{1.5 \times (128)^2}{2 \times 1600}$$

$$= 7.68 \text{ m}$$

Clearance of mid-point P from water level

$$= 23 + 7.68$$

$$= 30.68 \text{ m}$$

3.3 TOWERS

The towers shall be of following types:-

- a) Double circuit (DA, DB, DC & DD type) of HVPN's KRR Design for both 0.4sq" ACSR Zebra and 0.2sq" ACSR Panther.
- b) Single Circuit (A, B,C & D) of 0.4sq" ACSR Zebra to be designed by the Bidder. The towers are of self supporting lattice steel type, designed to carry the line conductors with necessary insulators, earthwire and all fittings under all loading conditions.

The tower shall be fully galvanized structure.

New Design 132kV S/C towers and 132kV D/C KRR Design towers to be fabricated shall have a combination of two grades of steel, as detailed in structural drawings/bill of material. One is MS steel and other is HT steel conforming to IS:2062.

3.3.1 TYPE OF TOWERS

The towers are classified as given below for 132 KV lines.

A) FOR KRR Design D/C Towers:-

Type of Tower	Deviation limit	Typical use
DA DB	0 deg.-2 deg. 2 deg.-15 deg.	To be used as tangent tower. a) Tension towers with tension insulators string. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Also to be designed for anti-cascading condition.
	0 deg.	d) To be used as Section Tower
DC	15 deg.-30 deg.	a) Tension towers with tension insulators string. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Also to be designed for anti-cascading condition.
DD	30 deg.-60 deg.	a) Tension towers with tension insulators string. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Dead end with 0 deg. to 15 deg. deviation both on line and substation side (slack span).

55 deg

- d) When DD type tower used with +12m to +25m Extension by restricting the span to 250m.
- e) For river crossing anchoring with longer wind span with 0 deg. deviation on crossing span side and 0 to 30 deg. deviation on other side.

Table 3.3.1 Types of D/C Towers

[<https://www.electrical4u.com/electrical-transmission-tower-types-and-design/>]

B) For New 132kV S/C towers of 0.4sq" (to be designed by the Bidder):-

Type of Tower	Deviation limit	Typical use
A	0 deg.-2 deg.	To be used as tangent tower upto 2 deg. deviation
B	0 deg.-15 deg.	a) To be used for line Angle deviation from 0 to 15 Deg. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Also to be designed for anti-cascading condition. d) Section tower.
C	15 deg.-30 deg.	a) To be used for line Angle deviation from 15 to 30 Deg. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Also to be designed for anti-cascading condition.
D	30 deg.-60 deg.	a) To be used for line Angle deviation from 30 deg. to 60 Deg. b) Tension towers for uplift forces resulting from an uplift span upto 200 m. c) Complete Dead end with 0 deg. to 15 deg. deviation both on line and gantry side (slack span). d) For river crossing anchoring with longer wind span with 0 deg. deviation on crossing span side and 0 to 30 deg. deviation on other side.
	0 deg.	

Table 3.3.1 Types of S/C Towers

[<https://www.electrical4u.com/electrical-transmission-tower-types-and-design/>]

3.3.2 LINE SUPPORTS

The supporting structures for overhead line conductors are various types of poles and towers called line supports. In general, the line supports should have the following properties :

- (i) High mechanical strength to withstand the weight of conductors and wind loads etc.
- (ii) Light in weight without the loss of mechanical strength.
- (iii) Cheap in cost and economical to maintain.
- (iv) Longer life.
- (v) Easy accessibility of conductors for maintenance.

The line supports used for transmission and distribution of electric power are of various types including wooden poles, steel poles, R.C.C. poles and lattice steel towers. The choice of supporting structure for a particular case depends upon the line span, X-sectional area, line voltage, cost and local conditions.

1. Wooden poles.

These are made of seasoned wood (sal or chir) and are suitable for lines of moderate X-sectional area and of relatively shorter spans, say upto 50 metres. Such supports are cheap, easily available, provide insulating properties and, therefore, are widely used for distribution purposes in rural areas as an economical proposition. The wooden poles generally tend to rot below the ground level, causing foundation failure. In order to prevent this, the portion of the pole below the ground level is impregnated with preservative compounds like creosote oil. Double pole structures of the 'A' or 'H' type are often used (See Fig. 8.2) to obtain a higher transverse strength than could be economically provided by means of single poles.

The main objections to wooden supports are :

- (i) tendency to rot below the ground level
- (ii) comparatively smaller life (20-25 years)
- (iii) cannot be used for voltages higher than 20 kV
- (iv) less mechanical strength and (v) require periodical inspection.

2. Steel poles.

The steel poles are often used as a substitute for wooden poles. They possess greater mechanical strength, longer life and permit longer spans to be used. Such poles are generally used for distribution purposes in the cities. This type of supports need to be galvanised or painted in order to prolong its life. The steel poles are of three types *viz.*,

- (i) rail poles
- (ii) tubular poles and
- (iii) rolled steel joints.

3. RCC poles.

The reinforced concrete poles have become very popular as line supports in recent years. They have greater mechanical strength, longer life and permit longer spans than steel poles. Moreover, they give good outlook, require little maintenance and have good insulating properties. The holes in the poles facilitate the climbing of poles and at the same time reduce the weight of line supports. The main difficulty with the use of these poles is the high cost of transport owing to their heavy weight. Therefore, such poles are often manufactured at the site in order to avoid heavy cost of transportation.

4. Steel towers.

In practice, wooden, steel and reinforced concrete poles are used for distribution purposes at low voltages, say upto 11 kV. However, for long distance transmission at higher voltage, steel towers are invariably employed. Steel towers have greater mechanical strength, longer life, can withstand most severe climatic conditions and permit the use of longer spans. The risk of interrupted service due to broken or punctured insulation is considerably reduced owing to longer spans. Tower footings are usually grounded by driving rods into the earth. This minimises the lightning troubles as each tower acts as a lightning conductor.

3.4 TYPES OF INSULATOR

There are mainly three types of insulator likewise

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

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

1. Pin Type Insulators

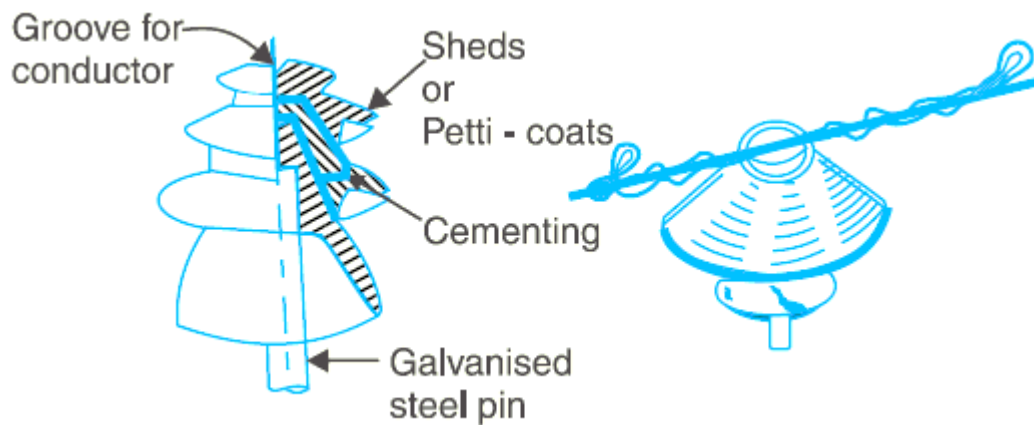


Figure 3.4.1 Pin Type Insulators

[Source: "Principles of Power System" by V.K.Mehta Page: 165]

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

Causes of Insulator Failures:

Insulators are required to withstand both mechanical and electrical stresses. The latter type is primarily due to line voltage and may cause the breakdown of the insulator. The electrical breakdown of the insulator can occur either by flash-over or puncture.

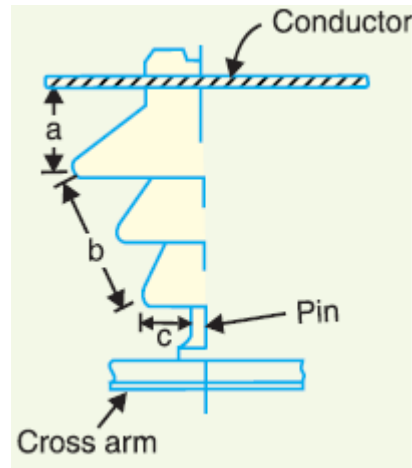


Figure 3.4.2 Insulator Failures

[Source: "Principles of Power System" by V.K.Mehta Page: 166]

In flashover, an arc occurs between the line conductor and insulator pin (i.e., earth) and the discharge jumps across the air gaps, following shortest distance. Figure shows the arcing distance (i.e. $a + b + c$) for the insulator. In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator. In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat. In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor.

2. Suspension Type

For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Figure. Consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

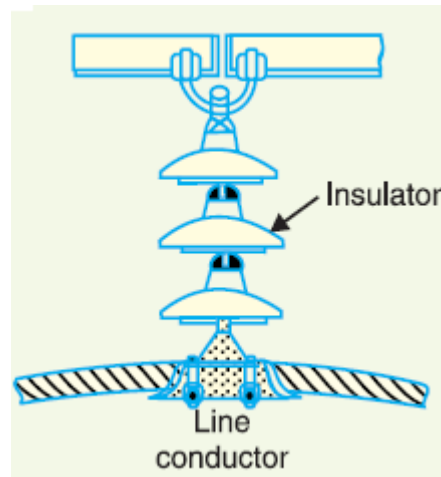


Figure 3.4.2 Suspension Type

[Source: "Principles of Power System" by V.K.Mehta Page: 166]

Advantages of suspension type:

- Suspension type insulators are cheaper than pin type insulators for voltages beyond 33 kV.
- Each unit or disc of suspension type insulator is designed for low voltage, usually 11 kV.

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

- If anyone disc is damaged, the whole string does not become useless because the damaged disc can be replaced.
- The suspension arrangement provides greater flexibility to the line. The connection at the cross arm is such that insulator string is free to swing in any direction and can take up the position where mechanical stresses are minimum.
- In case of increased demand on the transmission line, it is found more satisfactory to supply the greater demand by raising the line voltage than to provide another set of conductors. The additional insulation required for the raised voltage can be easily obtained in the suspension arrangement by adding the desired number of discs.
- The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain Insulators

When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used. For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Figure.

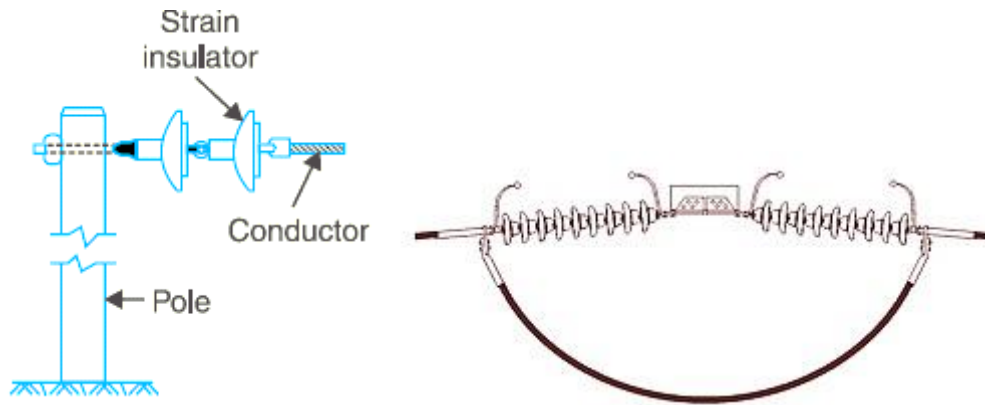


Figure 3.4.3 Strain Insulators

[Source: "Principles of Power System" by V.K.Mehta Page: 167]

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

4. Shackle Insulators

In early days, the shackle insulators were used as strain insulators. But now a day, they are frequently used for low voltage distribution lines.

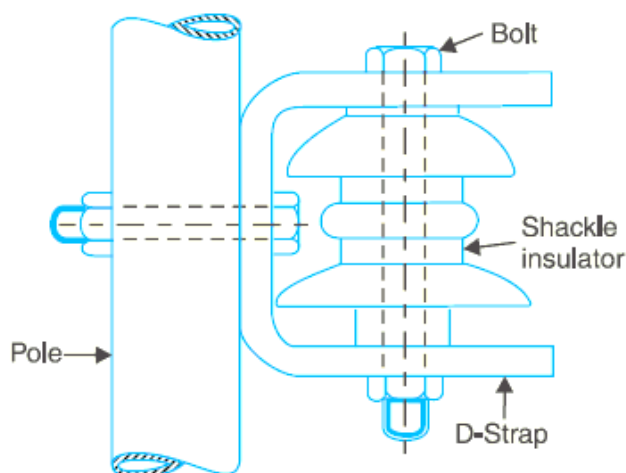


Figure 3.4.4 Shackle Insulators

[Source: "Principles of Power System" by V.K.Mehta Page: 167]

Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm.

5. Stay Insulator

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

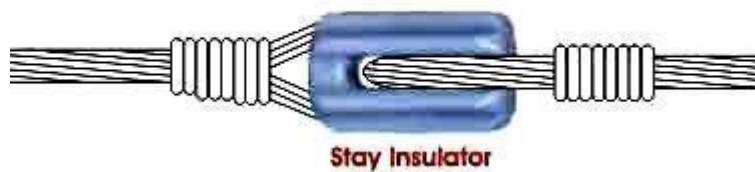


Figure 3.4.5 Shackle Insulators

[<https://www.electrical4u.com/types-of-electrical-insulator-overhead-insulator/>]

3.5 POTENTIAL DISTRIBUTION OVER SUSPENSION INSULATOR STRING

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor C as shown in Fig. This is known as mutual capacitance or self-capacitance. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same i.e., $V/3$ as shown. However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as shunt capacitance C_1 . Due to shunt capacitance, charging current is not the same through all the discs of the string. Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig V_3 will be much more than V_2 or V_1 .

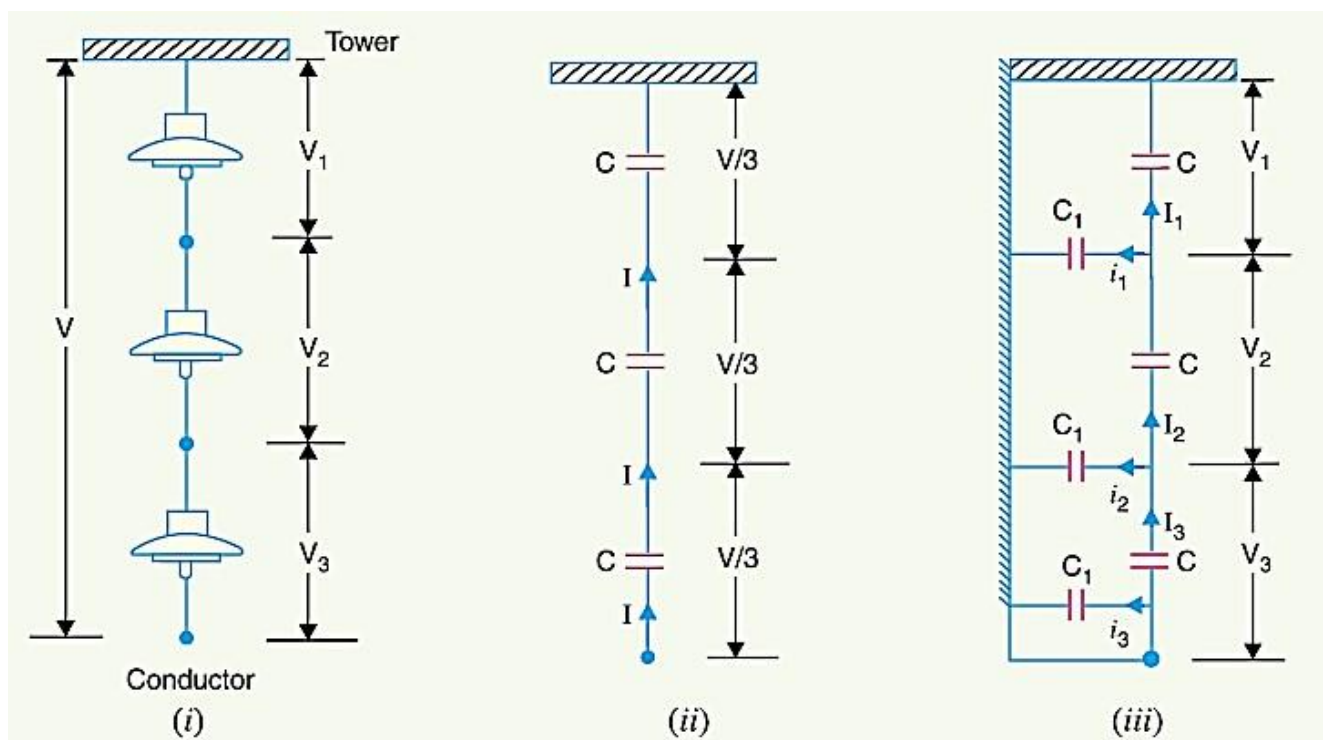


Figure 3.1 Potential Distribution

[Source: "Principles of Power System" by V.K.Mehta Page: 168]

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

- The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.
- The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.
- The unit nearest to the conductor is under maximum electrical stress and is likely to be punctured. Therefore, means must be provided to equalize the potential across each unit.
- If the voltage impressed across the string were d.c., then voltage across each unit would be the same. It is because insulator capacitances are ineffective for d.c.

3.6 STRING EFFICIENCY

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

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

$$\text{string efficiency} = \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}}$$

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.

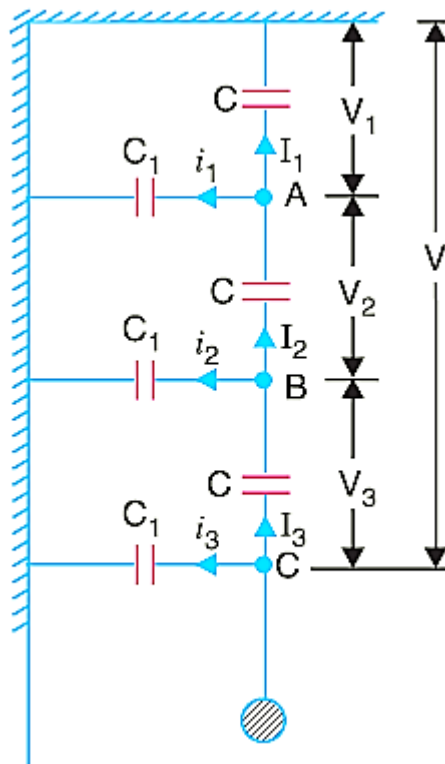


Figure 3.6.1 Equivalent Circuit - 3-Disc String

[Source: "Principles of Power System" by V.K.Mehta Page: 169]

Mathematical Expression. Fig. Shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C1 is some fraction K of self capacitance i.e., $C_1 = KC$. Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.

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

$$I_2 = I_1 + i_1$$

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

$$\text{or } V_2 \omega C = V_1 \omega C + V_1 \omega K C$$

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

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

$$I_3 = I_2 + i_2$$

$$\text{or } V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega C_1$$

$$\text{or } V_3 \omega C = V_2 \omega C + (V_1 + V_2) \omega K C$$

$$\text{or } V_3 = V_2 + (V_1 + V_2)K \quad \dots(ii)$$

$$= KV_1 + V_2 (1 + K)$$

$$= KV_1 + V_1 (1 + K)^2 \quad [\because V_2 = V_1 (1 + K)]$$

$$= V_1 [K + (1 + K)^2]$$

$$\therefore V_3 = V_1 [1 + 3K + K^2] \quad \dots(iii)$$

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

$$V = V_1 + V_2 + V_3$$

$$= V_1 + V_1(1 + K) + V_1 (1 + 3K + K^2)$$

$$= V_1 (3 + 4K + K^2)$$

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

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

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

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

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

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

$$\begin{aligned}\% \text{ string efficiency} &= \frac{\text{Voltage across the string}}{n \times \text{Voltage across disc nearest to conductor}} \times 100 \\ &= \frac{V}{n \times 3V_3} \times 100\end{aligned}$$

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

- (i) If $K = 0.2$ (Say), then from exp. (iv), we get, $V_2 = 1.2 V_1$ and $V_3 = 1.64 V_1$. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm is approached.
- (ii) The greater the value of $K (= C1/C)$, the more non-uniform is the potential across the Discs and lesser is the string efficiency.
- (iii) The inequality in voltage distribution increases with the increase of number of discs in the string. Therefore, shorter string has more efficiency than the larger one.

3.7 METHODS OF IMPROVING STRING EFFICIENCY

It has been seen above that potential distribution in a string of suspension insulators is not uniform. The maximum voltage appears across the insulator nearest to the line conductor and decreases progressively as the cross arm is approached. If the insulation of the highest stressed insulator breaks down or flash over takes place, the breakdown of other units will take place in succession. This necessitates equalizing the potential across the various units of the string *i.e.* to improve the string efficiency. The various methods for this purpose are:

(i) By Using Longer Cross- Arms

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

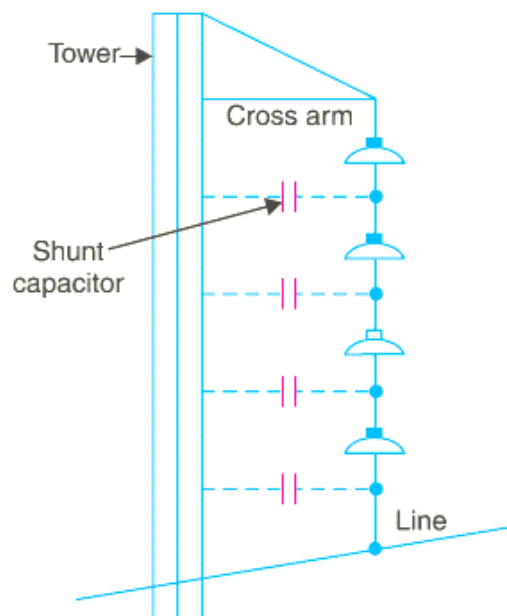


Figure 3.7.1 Longer Cross- Arms

[Source: "Principles of Power System" by V.K.Mehta Page: 170]

(ii) By Grading the Insulators

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

(iii) By Using A Guard Ring

The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i_1, i_2 etc. are equal to metal fitting line capacitance currents i'_1, i'_2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

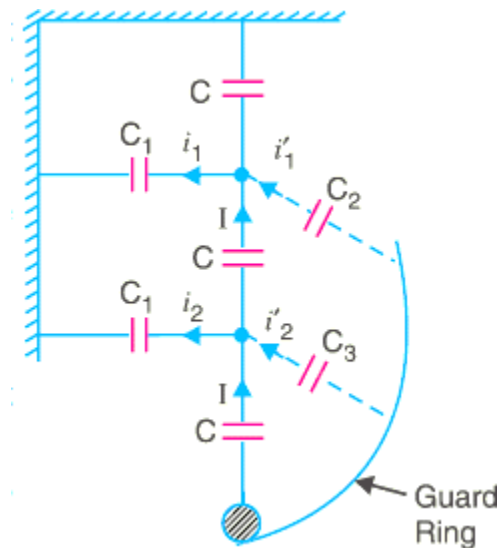


Figure 3.7.2 A Guard Ring

[Source: "Principles of Power System" by V.K.Mehta Page: 171]

Problem 1

In a 33 kV overhead line, there are three units in the string of insulators. If the capacitance between each insulator pin and earth is 11% of self-capacitance of each insulator, find (i) the distribution of voltage over 3 insulators and (ii) string efficiency.

Solution

The equivalent circuit of string insulators is,

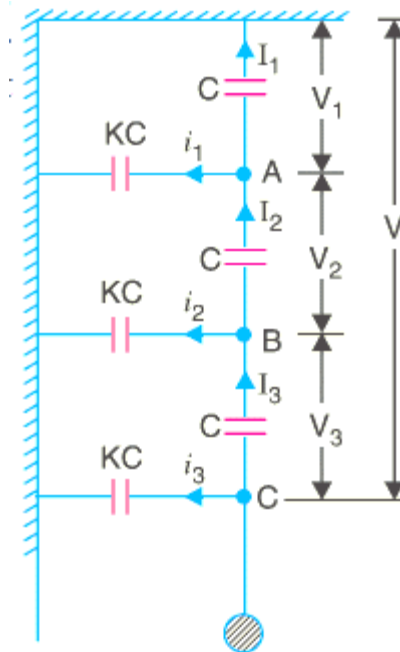


Figure 3.7.3 Equivalent circuit of string insulators

[Source: "Principles of Power System" by V.K.Mehta Page: 171]

$$K = \frac{\text{Shunt Capacitance}}{\text{Self-capacitance}} = 0.11$$

$$\text{Voltage across string, } V = 33/\sqrt{3} = 19.05 \text{ kV}$$

At Junction A

$$I_2 = I_1 + i_1$$

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

$$V_2 = V_1 (1 + K) = V_1 (1 + 0.11)$$

$$V_2 = 1.11 V_1$$

At Junction B

$$I_3 = I_2 + i_2$$

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

$$V_3 = V_2 + (V_1 + V_2) K$$

$$= 1.11 V_1 + (V_1 + 1.11 V_1) 0.11$$

$$V_3 = 1.342 V_1$$

(i) Voltage across the whole string is

$$V = V_1 + V_2 + V_3 = V_1 + 1.11 V_1 + 1.342 V_1 = 3.452 V_1$$
$$19.05 = 3.452 V_1$$

$$\therefore \text{Voltage across top unit, } V_1 = 19.05/3.452$$
$$= 5.52$$

$$\text{Voltage across middle unit, } V_2 = 1.11 V_1 = 1.11 \times 5.52$$
$$= 6.13 \text{ kV}$$

$$\text{Voltage across bottom unit, } V_3 = 1.342 V_1 = 1.342 \times 5.52$$
$$= 7.4 \text{ kV}$$

$$= \frac{\text{Voltage across string}}{\text{No. of insulators} \times V_3} \times 100 = \frac{19.05}{3 \times 7.4} \times 100$$

$$= 85.8 \%$$

3.8 TESTING OF INSULATOR

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

(i) Cracking Of Insulator

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

(ii) Defective Insulation Material

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

(iii) Porosity In The Insulation Materials

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

(iv) Improper Glazing on Insulator Surface

If the surface of porcelain insulator is not properly glazed, moisture can stick over it. This moisture along with deposited dust on the insulator surface, produces a conducting path. As a result the flash over distance of the insulator is reduced. As the flash over distance is reduced, the chance of failure of insulator due to flash over becomes more.

(v) Flash Over Across Insulator

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

(vi) Mechanical Stresses on Insulator

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

3.8.1 Types of 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.

3.8.2 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/cm² 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.

3.8.3 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.

4.1 UNDERGROUND CABLES

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

- (i) The conductor used in cables should be tinned stranded copper or aluminum of high conductivity. Stranding is done so that conductor may become flexible and carry more current.
- (ii) The conductor size should be such that the cable carries the desired load current without overheating and causes voltage drop within permissible limits.
- (iii) The cable must have proper thickness of insulation in order to give high degree of safety and reliability at the voltage for which it is designed.
- (iv) The cable must be provided with suitable mechanical protection so that it may withstand the rough use in laying it.
- (v) The materials used in the manufacture of cables should be such that there is complete chemical and physical stability throughout.

4.2 TYPES OF UNDERGROUND CABLES

The classification of Underground cables can be done on the basis of several criteria. Various aspects are taken into account while classification and these include:

1. Number of conductors in the cable
2. Voltage rating of the cable
3. Construction of cable
4. Type and thickness of insulation used
5. Installation and Laying of the cables

4.2.1 Classification Based Upon Number Of Conductors In The Cable

1. Single core cable
2. Three core cable

Typically, an Underground cable has either one, three or four cores. These cables are of course, constructed accordingly. Underground cables are usually employed to deliver 3 phase power. A 3 cored cable is preferred up to 66 kV. Beyond that, insulation required for the cable is too much. For higher voltages, 3 cored constructions become too bulky, and hence, even with some limitations we employ single cored cables.

4.2.2 Classification Based Upon Voltage Rating Of The Cable

1. Low tension cables: These have a maximum voltage handling capacity of 1000 V (1 kV)
2. High tension cables: These have a maximum voltage handling capacity of 11 kV.
3. Super tension cables: These have a maximum voltage handling capacity of 33 kV.
4. Extra high tension cables: These have a maximum voltage handling capacity of 66 kV.
5. Extra super voltage cables: These are used for applications with voltage requirement above 132 kV.

4.2.3 Classification Based Upon Construction of The Cable

1. Belted Cable

In such cables, the conductors (usually three) are bunched together and then bounded with an insulating paper 'belt'. In such cables, each conductor is insulated using paper impregnated with a suitable dielectric. The gaps between the conductors and the insulating paper belt are filled with a fibrous dielectric material such as Jute or Hessian. This provides flexibility as well as a circular shape. As we discussed earlier (in Construction of Cables), the jute layer is then covered by a metallic sheath and armouring for protection. One particular speciality of this cable is that its shape may not be perfectly circular. It is kept non-circular to use the available space more effectively.

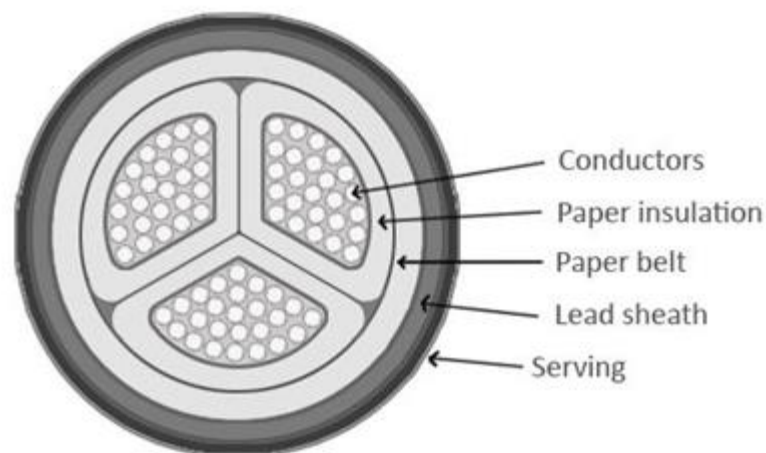


Figure 4.2.1 Belted Cable

[Source:<https://www.electricaleasy.com/2017/03/types-of-underground-cables.html>]

There are some limitations of such construction. Since the electric field is tangential, the insulation provided is stressed. As a result, the dielectric strength falls over time. Hence, such construction isn't preferred for voltage levels above 11 kV.

2. Screened Cable

Further divided as

1.H-type and

2.S.L. - type cables.

1.H-Type Cables

It was first designed by M. Hochstadter. The three cores are individually insulated with paper and then covered by a metallic screen / cover. These metallic covers are perforated. As a result, such construction allows the three metallic screens to touch each other. These three metallic covers are then grouped together in a metallic tape usually made of copper. A lead sheath surrounds this construction. The metallic covers and the sheath are grounded.

The obvious advantage is the electric stresses are radial, not tangential and hence of lesser magnitudes. Also, the metallic covers improve the heat dissipation.

2. S.L Type Cables

It is similar to the H type cables, with the difference that each of the three cores has its own lead sheath. With this provision, the need for the overall sheath used previously is eliminated. The advantage of such a construction is that the chances of a core-to-core breakdown are greatly minimized. Also, the flexibility of the cable is improved.

The limitations are severe. Such construction is limited for voltages up to 66kV only. The individual sheaths are thinner, and if there are constructional defects, moisture may enter the cable and reduce its dielectric strength.

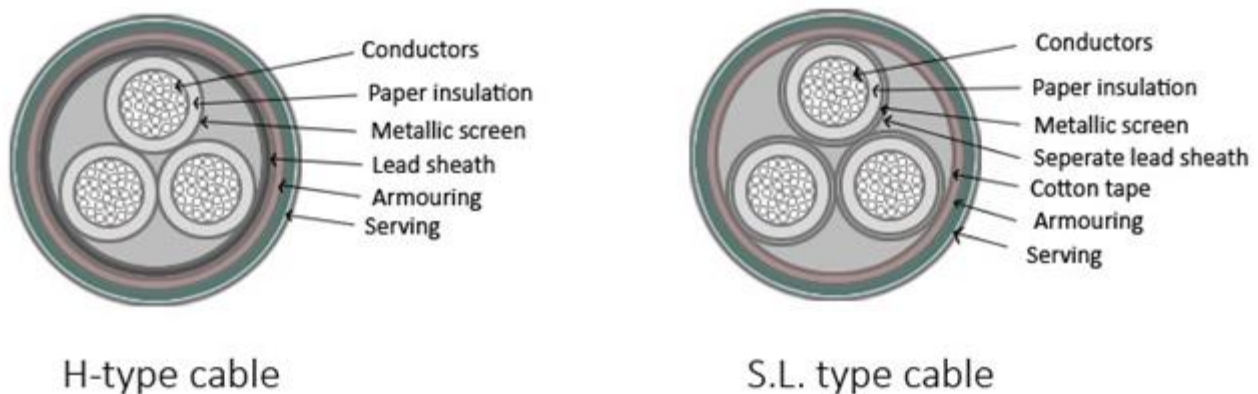


Figure 4.2.2 Screened Cable

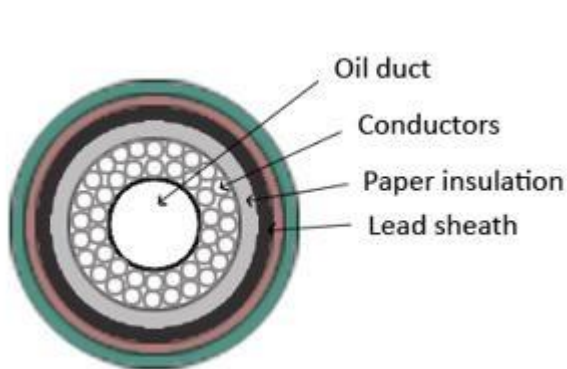
[Source:<https://www.electricaleasy.com/2017/03/types-of-underground-cables.html>]

- **H.S.L. Type Cables:** This type of cable is combination of H type and S.L. type cable. In these cables each core is insulated with impregnated paper and provided with separate lead sheaths.

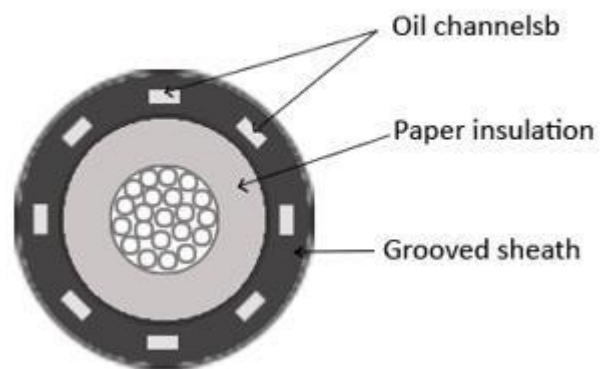
3. Pressure Cables

For voltages beyond 66 kV, the electrostatic stresses in the cables exceed the acceptable values and solid cables become unreliable. This occurs mainly because voids are created when voltages exceed 66 kV. Hence, instead of solid cables, we use Pressure cables. Typically, such cables are either oil filled or gas filled.

- **Oil Filled Cables:** Oil is circulated under suitable pressure through ducts provided for such purpose. This oil supply and pressure are maintained through reservoirs kept at proper distances. The oil used is the same that is employed for impregnation of paper insulators.
- **Gas Filled Cables:** Pressurized gas (usually dry nitrogen) is circulated around cables in an air-tight steel pipe. Such cables are cable of carrying higher values of load current and can operate at higher values of voltage. But the overall cost is more.



(i) Conductor channel



(ii) Sheath channel

Figure 4.2.2 Oil filled – Pressure Cable

[Source:<https://www.electricaleasy.com/2017/03/types-of-underground-cables.html>]

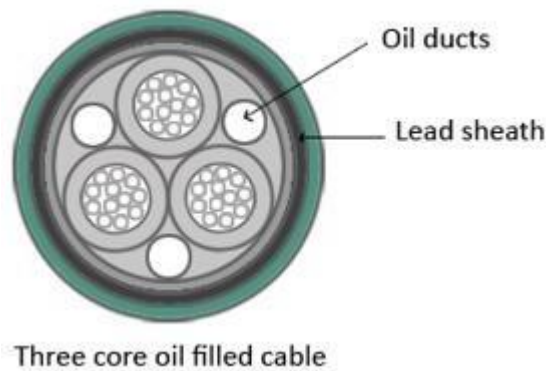


Figure 4.2.3 Oil filled – 3-Core Pressure Cable

[Source: <https://www.electricalcaeasy.com/2017/03/types-of-underground-cables.html>]

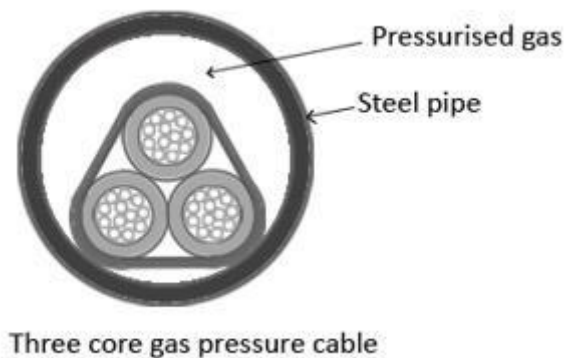


Figure 4.2.4 Gas filled – 3-Core Pressure Cable

[Source: <https://www.electricalcaeasy.com/2017/03/types-of-underground-cables.html>]

4.2.4 Classification Based Upon Insulation of the Cable

Various insulating materials used in cable construction are Rubber, Paper, PVC, XLPE (Cross linked Polyethylene) etc. Such classification is based upon operating temperature limitations. Following are some insulating materials used and their maximum operating temperatures.

Insulation material	Max. operating temperature
PVC TYPE A	75°C
PVC TYPE B	85°C

PVC TYPE C	85°C
XLPE	90°C
RUBBER	90°C
RUBBER – EPR IE-2, EPR IE-3, EPR IE-4, SILICON IE-5	150°C

Table 4.2.3 Insulation Material used in cables under various temperature

[Source: <https://www.electricaleasy.com/2017/03/types-of-underground-cables.html>]

4.2.5 Classification Based Upon Installation and Laying of the Cable

- **Direct Buried:** As the name suggests, the conductors are buried underground in a trench without additional accessories. Sometimes cooling pipes are added if required. Once the cables are installed, there's no visible sign above the ground.
- **Trough:** Concrete troughs are dug and cables are installed in them. They're visible on the surface. Maintenance is easier.
- **Tunnels:** Sometimes, tunnels are dug up for this purpose. Such construction is mainly employed if a river needs to be crossed or if the intended power distribution is to a major city. Maintenance and future expansion is easier, but initial cost is higher.
- **Gas Insulated Lines:** This is a relatively new technology. For cables operating at higher voltages and currents, and handling high power, such gas insulated line construction is safer. It is being employed nowadays for advanced projects.

4.3 CONSTRUCTION OF CABLES

Fig. 4.3.1 shows the general construction of a 3-conductor cable. The various parts are,

a) Cores or Conductors

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

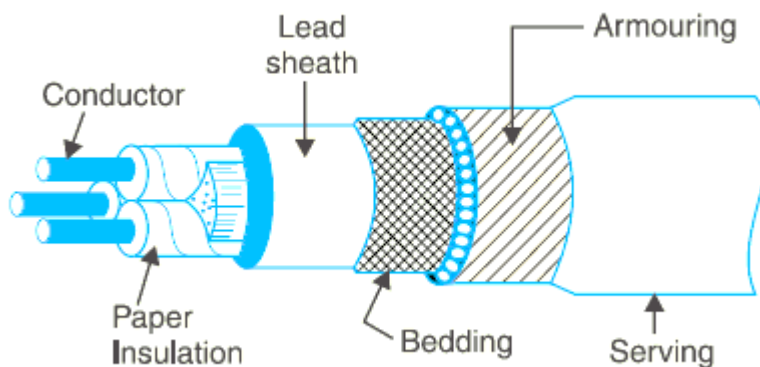


Figure 4.3.1 Construction of a Cable

[Source: "Principles of Power System" by V.K.Mehta Page: 265]

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.

4.4 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.4.4.1

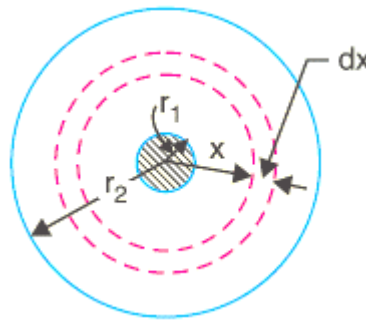


Figure 4.1.1 Single core cable

[Source: "Principles of Power System" by V.K.Mehta Page: 273]

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 $2\pi x l$.

Insulation resistance of considered layer

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

Insulation resistance of the whole cable is

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

$\therefore$

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

4.5 CAPACITANCE OF A SINGLE-CORE CABLE

A single-core cable can be considered to be equivalent to two long co-axial cylinders. The conductor (or core) of the cable is the inner cylinder while the outer cylinder is represented by lead sheath which is at earth potential. Consider a single core cable with conductor diameter d and inner sheath diameter D . Let the charge per metre axial length of the cable be Q coulombs and ϵ be the permittivity of the insulation material between core and lead sheath.

Obviously $\epsilon = \epsilon_0 \epsilon_r$ where ϵ_r is the relative permittivity of the insulation.

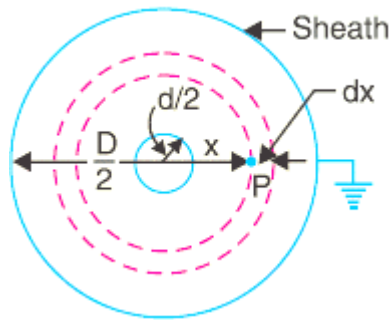


Figure 4.5.1 Single core cable

[Source: "Principles of Power System" by V.K.Mehta Page: 128]

Consider a cylinder of radius x metres and axial length 1 metre. The surface area of this cylinder is $= 2 \pi x \times 1 = 2 \pi x \text{ m}^2$

$\therefore$ Electric flux density at any point P on the considered cylinder is

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

$$\text{at point P, } E_x = \frac{D_x}{\epsilon} = \frac{Q}{2 \pi x \epsilon} = \frac{Q}{2 \pi x \epsilon_0 \epsilon_r} \text{ volts/m}$$

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

$$V = \int_{d/2}^{D/2} E_x dx = \int_{d/2}^{D/2} \frac{Q}{2\pi x \epsilon_0 \epsilon_r} dx = \frac{Q}{2\pi \epsilon_0 \epsilon_r} \log_e \frac{D}{d}$$

Capacitance of the cable is

$$\begin{aligned} C &= \frac{Q}{V} = \frac{Q}{\frac{Q}{2\pi \epsilon_0 \epsilon_r} \log_e \frac{D}{d}} \text{ F/m} \\ &= \frac{2\pi \epsilon_0 \epsilon_r}{\log_e(D/d)} \text{ F/m} \\ &= \frac{2\pi \times 8.854 \times 10^{-12} \times \epsilon_r}{2.303 \log_{10}(D/d)} \text{ F/m} \\ &= \frac{\epsilon_r}{41.4 \log_{10}(D/d)} \times 10^{-9} \text{ F/m} \end{aligned}$$

If the cable has a length of l metres, then capacitance of the cable is

$$C = \frac{\epsilon_r l}{41.4 \log_{10} \frac{D}{d}} \times 10^{-9} \text{ F}$$

Problem 1

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

Solution:

$$C = \frac{\epsilon_r l}{41.4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

$$\epsilon_r = 4; \quad l = 1000 \text{ m}$$

$$D = 1.8 \text{ cm}; \quad d = 1 \text{ cm}$$

$$C = \frac{4 \times 1000}{41.4 \log_{10}(1.8/1)} \times 10^{-9} \text{ F} = 0.378 \times 10^{-6} \text{ F}$$

Problem 2

A 33 kV, 50 Hz, 3-phase underground cable, 4 km long uses three single core cables. Each of the conductor has a diameter of 2.5 cm and the radial thickness of insulation is 0.5 cm. Determine (i) capacitance of the cable/phase (ii) charging current/phase (iii) total charging kVAR. The relative permittivity of insulation is 3.

Solution:

$$C = \frac{\epsilon_r l}{41.4 \log_{10}(D/d)} \times 10^{-9} \text{ F}$$

$$\begin{aligned} \epsilon_r &= 3 & ; & \quad l = 4 \text{ km} = 4000 \text{ m} \\ d &= 2.5 \text{ cm} & ; & \quad D = 2.5 + 2 \times 0.5 = 3.5 \text{ cm} \end{aligned}$$

$$\begin{aligned} C &= \frac{3 \times 4000 \times 10^{-9}}{41.4 \times \log_{10}(3.5/2.5)} \\ &= 1.984 \times 10^{-6} \end{aligned}$$

(ii) Voltage/phase, V_{ph}

$$= \frac{33 \times 10^3}{\sqrt{3}} = 19.05 \times 10^3 \text{ V}$$

Charging current/phase, I_C

$$\begin{aligned} I_C &= \frac{V_{ph}}{X_C} = 2\pi f C V_{ph} \\ &= 2\pi \times 50 \times 1.984 \times 10^{-6} \times 19.05 \times 10^3 \\ &= 11.87 \text{ A} \end{aligned}$$

Total charging kVAR

$$\begin{aligned} &= 3 V_{ph} I_C = 3 \times 19.05 \times 10^3 \times 11.87 \\ &= 678.4 \times 10^3 \text{ KVAR} \end{aligned}$$

4.6 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 (g_{max}) at the conductor surface and goes on decreasing as we move towards the sheath. The maximum voltage that can be safely applied to a cable depends upon g_{max} i.e., electrostatic stress at the conductor surface. For safe working of a cable having homogeneous dielectric, the strength of dielectric must be more than g_{max} . If a dielectric of high strength is used for a cable, it is useful only near the conductor where stress is maximum. But as we move away from the conductor, the electrostatic stress decreases, so the dielectric will be unnecessarily overstrong. The unequal stress distribution in a cable is undesirable for two reasons. Firstly, insulation of greater thickness is required which increases the cable size. Secondly, it may lead to the breakdown of insulation. In order to overcome above disadvantages, it is necessary to have a uniform stress distribution in cables. This can be achieved by distributing the stress in such a way that its value is increased in the outer layers of dielectric. This is known as grading of cables.

The following are the two main methods of grading of cables :

- (i) Capacitance grading
- (ii) Intersheath grading

(i) Capacitance Grading

The process of achieving uniformity in the dielectric stress by using layers of different dielectrics is known as capacitance grading.

In capacitance grading, the homogeneous dielectric is replaced by a composite dielectric. The composite dielectric consists of various layers of different dielectrics in such a manner that relative permittivity r of any layer is inversely proportional to its distance from the center. Under such conditions, the value of potential gradient any point in the dielectric is constant and is independent of its distance from the center. In other words, the dielectric stress in the cable is same everywhere and the grading is ideal one. However, ideal grading requires the use of an infinite number of dielectrics which is an

impossible task. In practice, two or three dielectrics are used in the decreasing order of permittivity, the dielectric of highest permittivity being used near the core.

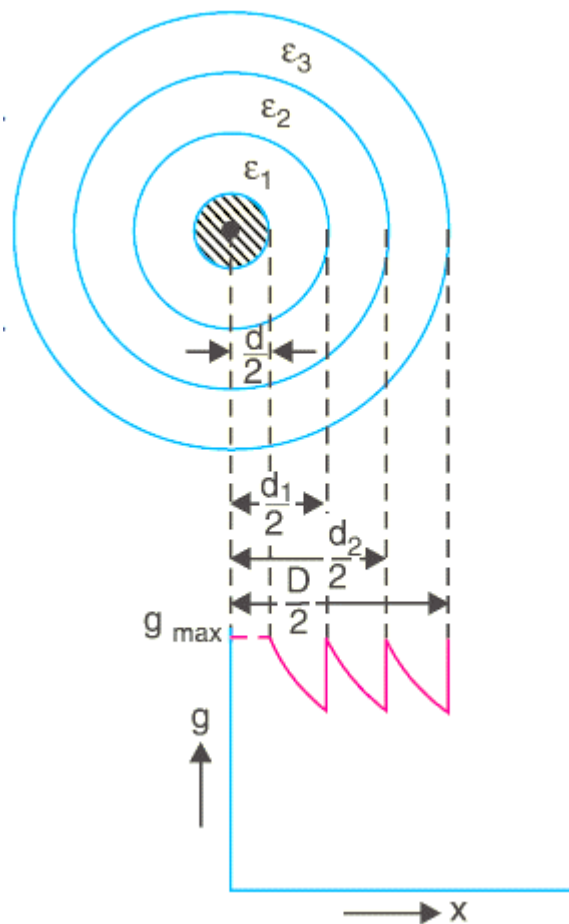


Figure 4.6.1 Capacitance Grading

[Source: "Principles of Power System" by V.K.Mehta Page: 281]

The capacitance grading can be explained beautifully by referring to Fig. There are three dielectrics of outer diameter d_1 , d_2 and D and of relative permittivity 1, 2 and 3 respectively. If the permittivity are such that $1 > 2 > 3$ and the three dielectrics are worked at the same maximum stress, then,

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

Potential difference across the inner layer is

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

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

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

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

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

Total p.d. between core and earthed sheath is

$$V = V_1 + V_2 + V_3$$

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

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,

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

Obviously, $V > V'$ i.e., for given dimensions of the cable, a graded cable can be worked at a greater potential than non-graded cable. Alternatively, for the same safe potential, the size of graded cable will be less than that of non-graded cable. The following points may be noted :

- (i) As the permissible values of g_{max} are peak values, therefore, all the voltages in above expressions should be taken as peak values and not the r.m.s. values.
- (ii) If the maximum stress in the three dielectrics is not the same, then,

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

(ii) Intersheath Grading

In this method of cable grading, a homogeneous dielectric is used, but it is divided into various layers by placing metallic intersheaths between the core and lead sheath. The intersheaths are held at suitable potentials which are in between the core potential and earth potential. This arrangement improves voltage distribution in the dielectric of the cable and consequently more uniform potential gradient is obtained.

Consider a cable of core diameter d and outer lead sheath of diameter D . Suppose that two intersheaths of diameters d_1 and d_2 are inserted into the homogeneous dielectric and maintained at some fixed potentials.

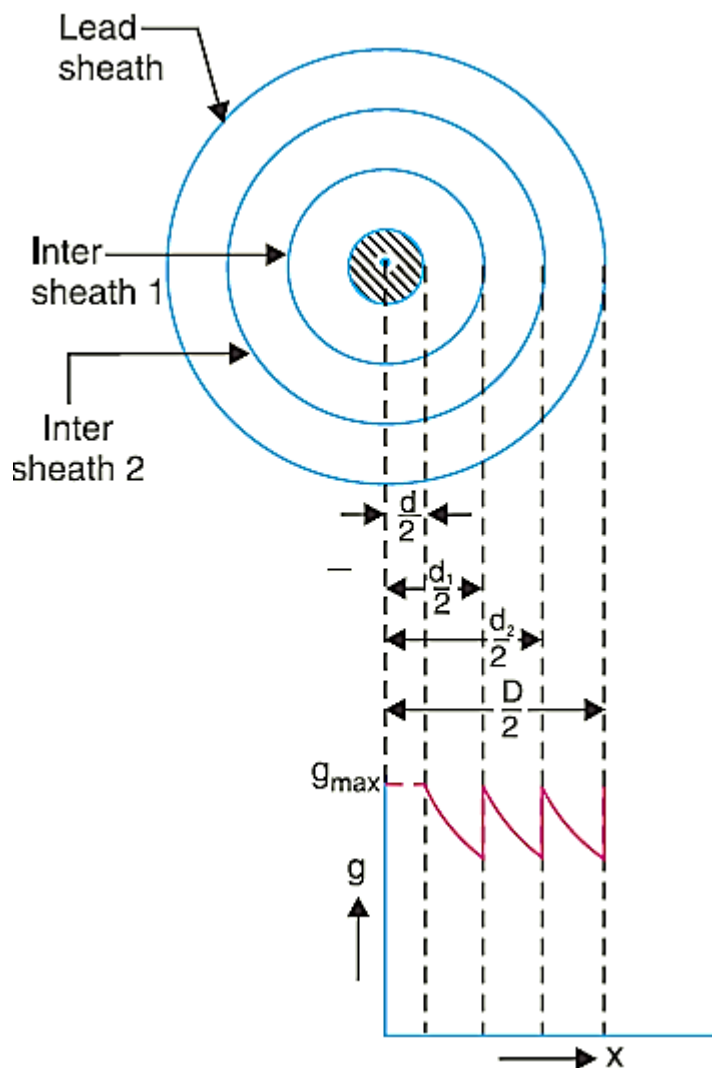


Figure 4.6.1 Intersheath Grading

[Source: "Principles of Power System" by V.K.Mehta Page: 285]

Let V_1 , V_2 and V_3 respectively be the voltage between core and intersheath 1, between intersheath 1 and 2 and between intersheath 2 and outer lead sheath. As there is a definite potential difference between the inner and outer layers of each intersheath, therefore, each sheath can be treated like a homogeneous single core cable.

Maximum stress between core and intersheath 1 is

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

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

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

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

$$g_{1max} = g_{2max} = g_{3max} = g_{max}$$

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

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

$$V = V_1 + V_2 + V_3$$

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

Problem 1

A single core cable of conductor diameter 2 cm and lead sheath of diameter 5.3 cm is to be used on a 66 kV, 3-phase system. Two intersheaths of diameter 3.1 cm and 4.2 cm are introduced between the core and lead sheath. If the maximum stress in the layers is the same, find the voltages on the intersheaths.

Solution:

$$d = 2 \text{ cm} ; \quad d_1 = 3.1 \text{ cm} ; \quad d_2 = 4.2 \text{ cm}$$

$$D = 5.3 \text{ cm} ; \quad V = \frac{66 \times \sqrt{2}}{\sqrt{3}} = 53.9 \text{ kV}$$

$$g_{1max} = \frac{V_1}{\frac{d}{2} \log_e \frac{d_1}{d}} = \frac{V_1}{1 \times \log_e \frac{3.1}{2}} = 2.28 V_1$$

$$g_{2max} = \frac{V_2}{\frac{d_1}{2} \log_e \frac{d_2}{d_1}} = \frac{V_2}{1.55 \log_e \frac{4.2}{3.1}} = 2.12 V_2$$

$$g_{3max} = \frac{V_3}{\frac{d_2}{2} \log_e \frac{D}{d_2}} = \frac{V_3}{2.1 \log_e \frac{5.3}{4.2}} = 2.04 V_3$$

$$g_{1max} = g_{2max} = g_{3max}$$

$$2.28 V_1 = 2.12 V_2 = 2.04 V_3$$

$$V_2 = (2.28/2.12) V_1 = 1.075 V_1$$

$$V_3 = (2.28/2.04) V_1 = 1.117 V_1$$

$$V_1 + V_2 + V_3 = V$$

$$V_1 + 1.075 V_1 + 1.117 V_1 = 53.9$$

$$V_1 = 53.9/3.192 = 16.88 \text{ kV}$$

$$V_2 = 1.075 V_1 = 1.075 \times 16.88 = 18.14 \text{ kV}$$

Voltage on first intersheath (i.e., near to the core)

$$= V - V_1 = 53.9 - 16.88 = 37.02 \text{ kV}$$

Voltage on second intersheath = $V - V_1 - V_2 = 53.9 - 16.88 - 18.14 = 18.88 \text{ kV}$

Problem 2

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.

Solution:

$$d = 2 \text{ cm} ; d_1 = ? ; d_2 = ? ; D = 8 \text{ cm}$$

$$\epsilon_1 = 5 ; \epsilon_2 = 4 ; \epsilon_3 = 3 ; g_{max} = 40 \text{ kV/cm}$$

As the maximum stress in the three dielectrics is the same,

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

$$5 \times 2 = 4 \times d_1 = 3 \times d_2$$

$$\therefore d_1 = 2.5 \text{ cm and } d_2 = 3.34 \text{ cm}$$

$$\begin{aligned} &= \frac{g_{max}}{2} \left[d \log_e \frac{d_1}{d} + d_1 \log_e \frac{d_2}{d_1} + d_2 \log_e \frac{D}{d_2} \right] \\ &= \frac{40}{2} \left[2 \log_e \frac{2.5}{2} + 2.5 \log_e \frac{3.34}{2.5} + 3.34 \log_e \frac{8}{3.34} \right] \\ &= 20 [0.4462 + 0.7242 + 2.92] \text{ kV} \\ &= 20 \times 4.0904 = 81.808 \text{ kV} \end{aligned}$$

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

$$\begin{aligned} &= \frac{81.808}{\sqrt{2}} \\ &= 57.84 \text{ KV} \end{aligned}$$

4.7 POTENTIAL GRADIENT

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 infact 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

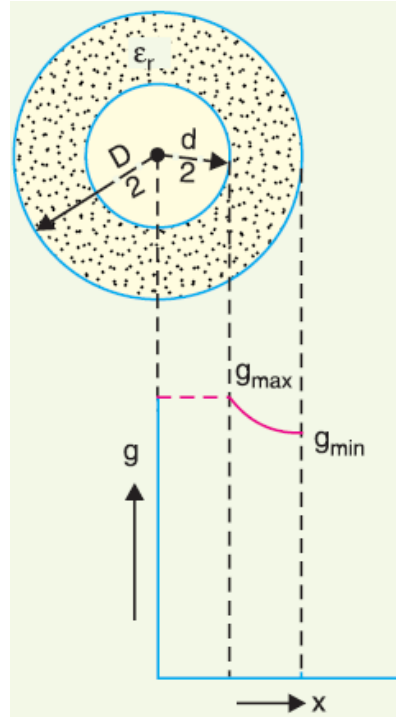


Figure 4.7.1 Potential Gradient – Cable

[Source: “Principles of Power System” by V.K.Mehta Page: 277]

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

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

$$g = E_x$$

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

.....(i)

$$V = \frac{Q}{2\pi\epsilon_o\epsilon_r} \log_e \frac{D}{d} \text{ volts}$$

$$Q = \frac{2\pi\epsilon_o\epsilon_r V}{\log_e \frac{D}{d}} \dots\dots(ii)$$

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

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

It is clear from exp. (iii) that potential gradient varies inversely as the distance x . Therefore, potential gradient will be maximum when x is minimum *i.e.*, when $x = d/2$ or at the surface of the conductor. On the other hand, potential gradient will be minimum at $x = D/2$ or at sheath surface.

Maximum potential gradient is,

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

Minimum potential gradient is,

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

4.8 CAPACITANCE OF 3-CORE CABLES

The capacitance of a cable system is much more important than that of overhead line because in cables (i) conductors are nearer to each other and to the earthed sheath (ii) they are separated by a dielectric of permittivity much greater than that of air. Fig.4.8.1 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.4.8.1 (i). These electrostatic fields give rise to core-core capacitances C_c and conductor- earth capacitances C_e as shown in Fig.4.8.1 (ii). The three C_c are delta connected whereas the three C_e are star connected, the sheath forming the star point.

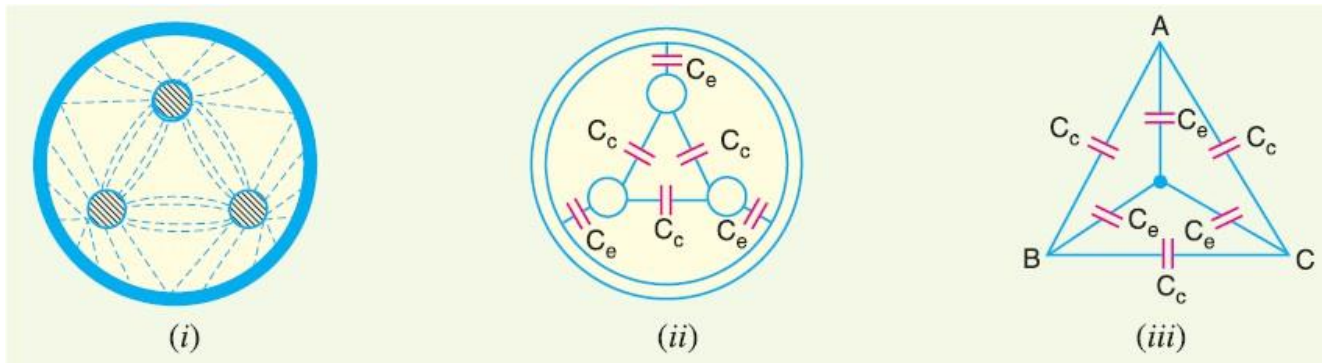


Figure 4.8.1 Capacitance of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

The layout of a belted cable makes it reasonable to assume equality of each C_c and each C_e . The three delta connected capacitances C_c [See Fig. 4.8.2 (i)] can be converted into equivalent star connected capacitances as shown in Fig. 4.8.2 (ii). It can be easily shown that equivalent star capacitance C_{eq} is equal to three times the delta capacitance C_c i.e. $C_{eq} = 3C_c$.

The system of capacitances shown in Fig. 4.8.1 (iii) reduces to the equivalent circuit shown in Fig.4.8.3 (i). Therefore, the whole cable is equivalent to three star-connected capacitors each of capacitance,

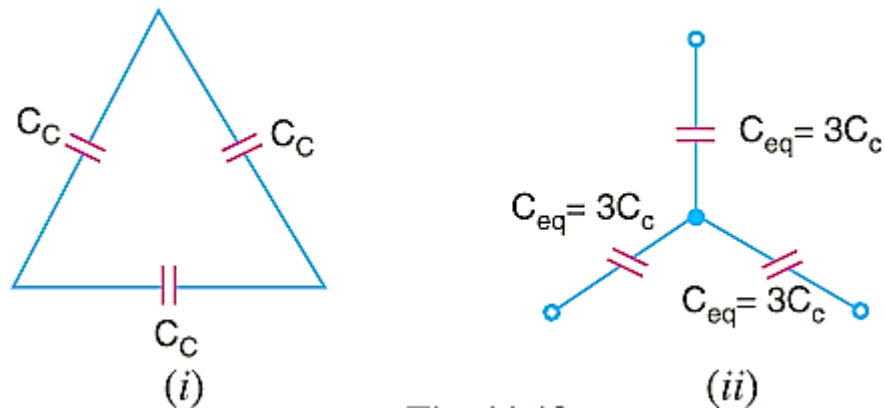


Figure 4.8.2 Delta Connected Capacitor of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

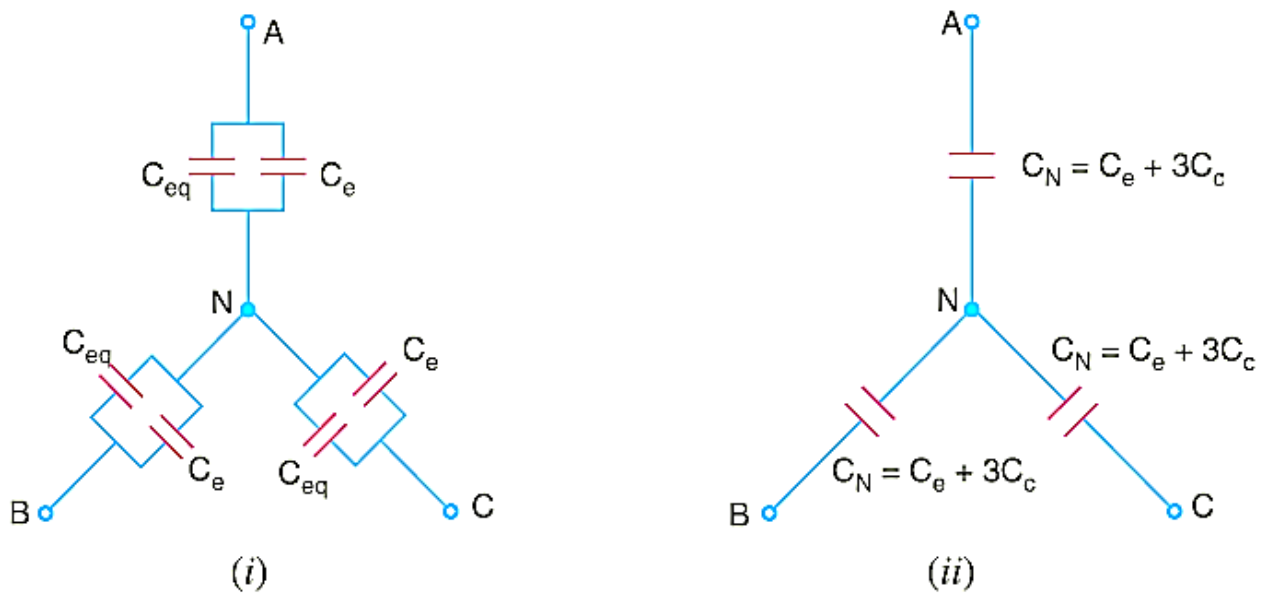


Figure 4.8.2 Star Connected Capacitor of 3-Core Cables

[Source: "Principles of Power System" by V.K.Mehta Page: 288]

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

$$= C_e + 3C_c$$

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

$$I_C = \frac{V_{ph}}{\text{Capacitive reactance per phase}}$$

$$= 2 \pi f V_{ph} C_N$$

$$= 2 \pi f V_{ph} (C_e + 3C_c)$$

4.9 POWER FACTOR OF CABLE

If the temperature continues to increase, the cable insulation will be damaged. a length of 6 km. The cable is operated at 60 Hz and 7.2 kV. The dielectric constant is 3.5, the dielectric power factor is 0.03 ($\delta = \cos\phi_d$) and dielectric resistivity of the insulation is $1.3 \times 10^7 \text{ M}\Omega\cdot\text{cm}$

4.9.1 HEATING OF CABLE

The temperature rise of cable depends on the following factors:

1. The production of heat within the external periphery of the cable.
2. The conveyance of the heat as far as the periphery - that is, up to the boundary of the surrounding medium.
3. The conveyance of the heat through this medium, and therefore away from the cable.
4. The current rating of the cables.
5. The nature of the load, i.e. whether continuous or intermittent; not infrequently the rating under short-circuit conditions has to be considered.

Heat generation in cable

Following are the sources of heat generation in the cable

- a) I^2R losses in the conductors
- b) Dielectric losses in the cable insulation
- c) Sheath and armour loss

a) I^2R losses in the conductors

Copper loss is the term often given to heat produced by electrical currents in the conductors, or other electrical devices. Copper losses are an undesirable transfer of energy, as are core losses, which result from induced currents in adjacent components.

The term is applied regardless of whether the windings are made of copper or another conductor, such as aluminium.

Resistance of conductor at an temperature of 70 deg. C (assumed) is determined from the resistance given in standard table (usually at 20 deg,C) from the following relation-

$$R_h = R_a(1 + \alpha (70 - 20))$$

Where R_h , R_a are the hot resistance, resistance at 20deg.C.

b) Dielectric losses in the cable insulation

The energy losses occurring in the dielectric of cables are due to leakage and so called dielectric hysteresis.

The charging current of cable I_c is assumed to have two components –

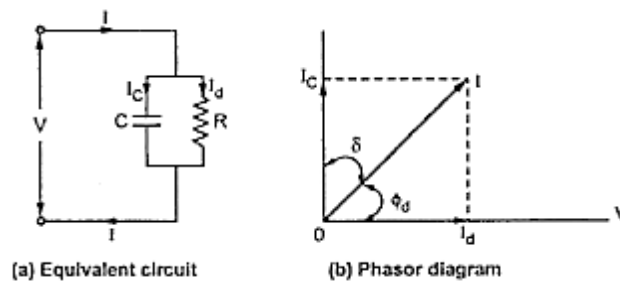


Figure 4.2.1 Belted Cable

[Source: <https://bralpowerassociate.blogspot.com/2013/11/heating-in-cable.html>]

One being true capacitance current which is equal to $\omega C V$ and leads the applied voltage by 90deg.

- The other being the energy component which in phase with the applied voltage and represents the dielectric loss components of current.

If V is the applied voltage, C is the capacitance, of cable, Φ is the phase angle between voltage and current called the power factor of the cable and δ is the loss angle of the dielectric,

Charging current, $I_c = V/X_c = \omega C V$

The dielectric loss, due to leakage and hysteresis effects in the dielectric, is usually expressed in terms of the loss angle, δ :

$$\delta = 90^\circ - \phi$$

Where, ϕ is the dielectric power factor angle.

$$\text{Dielectric loss} = \omega C V^2 \tan \delta,$$

Where,

C = capacitance to neutral

V = phase voltage

A typical value of $\tan \delta$ lies in the range 0.002 to 0.003. In low voltage cables the dielectric loss is negligible, but is appreciable in EHV cables.

c) Sheath loss

In 3 core cable the effect is negligible but for single core cable the effect is of great importance. The electromagnetic fields produced by the current flowing through the conductors induce emfs in sheath and under certain condition heavy currents are set up therein. The actual current flowing along the sheath depends magnitude and frequency of the current in the conductor, the arrangement and spacing between the cables. Two different cables having sheath electrically connected are bounded or unbounded. The induced sheath currents are of two types-

- i) The currents, which have both outward and inward directions, called the sheath eddies.
- ii) The currents, which have outward and inward current path in separate sheath called the sheath circuit eddies.

The approximate formulae for eddy loss for unbounded cables given by Arnold is as under-

$$\text{Sheath loss} = I^2 \left[\frac{78\omega^2}{R_s} \left(\frac{r}{d} \right)^2 \times 10^{-9} \right] \text{ watts/phase}$$

Where,

I = current per conductor,

r = mean radius of sheath,

d =inter axial spacing of conductors

R_s = sheath resistance in ohm

4.10 DC CABLES

The DC cable has the following characteristics compared with the AC cable.

1. The system used is different. The DC cable is used in the rectified DC transmission system, and the AC cable is often used in the power frequency (domestic 50 Hz) power system.
2. Compared with the AC cable, the power loss during the transmission of the DC cable is small. The power loss of the DC cable is mainly the DC resistance loss of the conductor, and the insulation loss is small (the size depends on the current fluctuation after rectification); while the AC resistance of the low-voltage AC cable is slightly larger than the DC resistance, the high-voltage cable is obvious, mainly because of the proximity effect and the skin effect, the loss of insulation resistance accounts for a large proportion, mainly the impedance generated by the capacitor and the inductor.
3. High transmission efficiency and low line loss.
4. It is convenient to adjust the current and change the power transmission direction.
5. Although the price of the converter equipment is higher than that of the transformer, the cost of using the cable line is much lower than that of the AC cable. The DC cable is positive and negative poles, and the structure is simple; the AC cable is three-phase four-wire or five-wire system, the insulation safety requirements are high, the structure is complex, and the cable cost is more than three times that of the DC cable.
6. DC cable is safe to use:
 - 1) The inherent characteristics of DC transmission, it is difficult to generate induced current and leakage current, and it will not interfere with the electric field generated by other cables.
 - 2) The single-core laying cable does not affect the cable transmission performance due to the hysteresis loss of the steel structure bridge.
 - 3) It has higher interception capability and over-cut protection than AC cables of the same structure.
 - 4) A straight, alternating electric field of the same voltage is applied to the insulation, and the DC electric field is much safer than the AC electric field.
7. The installation and maintenance of the DC cable is simple and the cost is low. Requirements for the same cable insulation for the same AC and DC voltage and current

When an AC and DC electric field of the same voltage is applied to the insulation, the electric field of the DC cable is much smaller than the AC electric field. Due to the large difference in the structure of the two electric fields, the maximum electric field when the AC cable is energized is concentrated near the conductor, and the maximum electric field when the DC cable is energized is mainly concentrated within the insulating surface layer, which is more secure (2.4 times).

Third, the mutual conversion relationship between AC and DC voltage

There are many different understandings on the mutual conversion of AC and DC voltages. However, our company is uniformly calculated according to GB12528.1, that is, the same AC cable, the rated voltage of the DC cable is 1.5 times the phase voltage of the AC cable. But our company's 1500V DC cable is designed according to the voltage of DC3000V, which has safe electrical insulation performance.

5.1 DISTRIBUTION SYSTEMS – GENERAL ASPECTS

The electrical energy produced at the generating station is conveyed to the consumers through a network of transmission and distribution systems. It is often difficult to draw a line between the transmission and distribution systems of a large power system. It is impossible to distinguish the two merely by their voltage because what was considered as a high voltage a few years ago is now considered as a low voltage. In general, distribution system is that part of power system which distributes power to the consumers for utilization.

The transmission and distribution systems are similar to man's circulatory system. The transmission system may be compared with arteries in the human body and distribution system with capillaries. They serve the same purpose of the ultimate consumer in the city with the life-giving blood of civilization—electricity. In this chapter, we shall confine our attention to the general introduction to distribution.

5.1.1 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 substation fed by the Transmission system and the consumer's meters. It generally consists of feeders, distributors, and 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 localized 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. AB, 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 $\pm 6\%$ of rated value at the consumers' terminals.

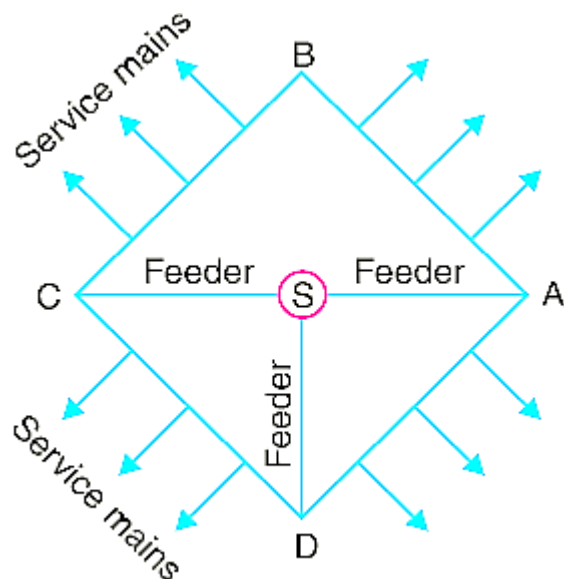


Figure 5.1 Distribution System

[Source: "Principles of Power System" by V.K.Mehta Page: 301]

(iii) Service mains

A service mains is generally a small cable which connects the distributor to the consumers' terminals

5.2 KELVIN'S LAW

Kelvin's Law states that the most economical area of conductor is that for which the variable part of annual charge is equal to the cost of energy losses per year.

5.2.1 Graphical illustration of Kelvin's law.

Kelvin's law can also be illustrated graphically by plotting annual cost against X-sectional area ' a ' of the conductor as shown in Fig. 7.28.

In the diagram, the straight line

(1) shows the relation between the annual charge (i.e., $P_1 + P_2a$) and the area of X-section a of the conductor.

Similarly, the rectangular hyperbola

(2) gives the relation between annual cost of energy wasted and X-sectional area a . By adding the ordinates of curves (1) and (2), the curve (3) is obtained.

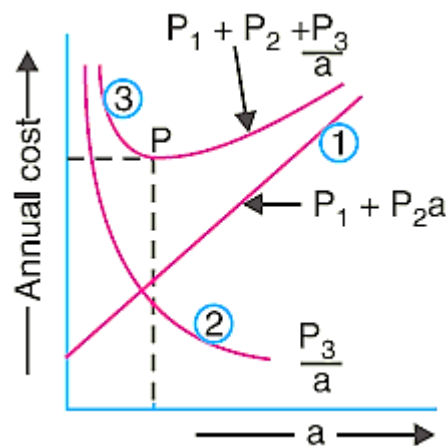


Figure 5.2.1 Graphical Representation of Kelvin's Law

[Source: "Principles of Power System" by V.K.Mehta Page: 128]

This latter curve shows the relation between total annual cost ($P_1 + P_2a + \frac{P_3}{a}$) of transmission line and area of X-section a . The lowest point on the curve (i.e., point P) represents the most economical area of X-section.

Limitations of Kelvin's law.

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

5.3 AC DISTRIBUTION

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

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

- i. Primary distribution system and
- ii. 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.5.3.1 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.

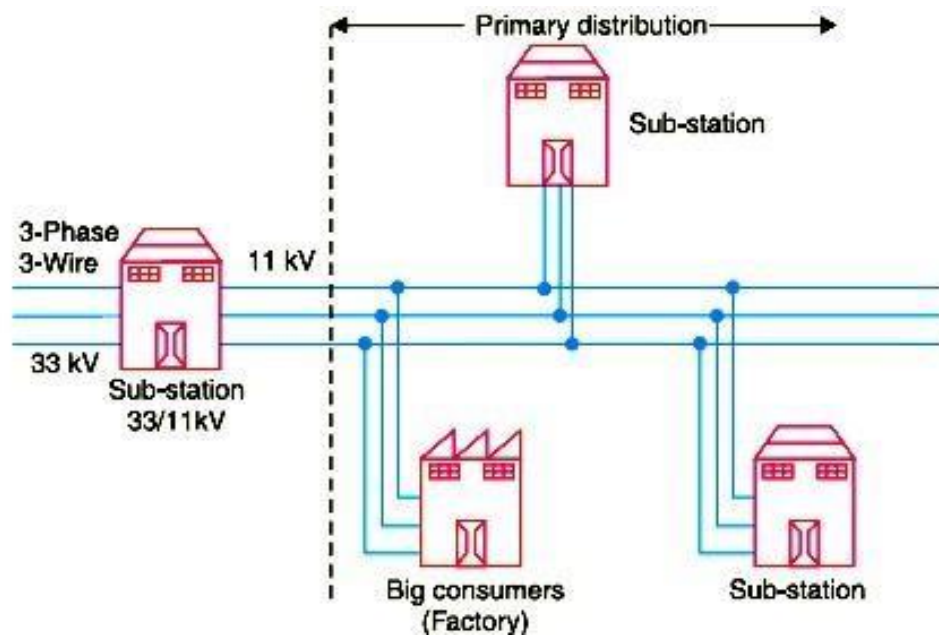


Figure 5.3.1 Primary AC Distribution System

[Source: "Principles of Power System" by V.K.Mehta Page: 302]

ii) Secondary distribution system

It is that part of a.c. distribution system. The secondary distribution employs 400/230V, 3-phase, 4-wire system. Fig.5.3.2 shows a typical secondary distribution system. The primary distribution circuit delivers power to various substations, called distribution substations.

The substations are situated near the consumers' localities and contain step-down transformers. At each distribution substation, the voltage is stepped down to 400V and power is delivered by 3-phase, 4-wire a.c. system. The voltage between any two phases is 400V and between any phase and neutral is 230V. The single phase domestic loads are connected between any one phase and the neutral, whereas 3-phase 400V motor loads are connected across 3-phase lines directly.

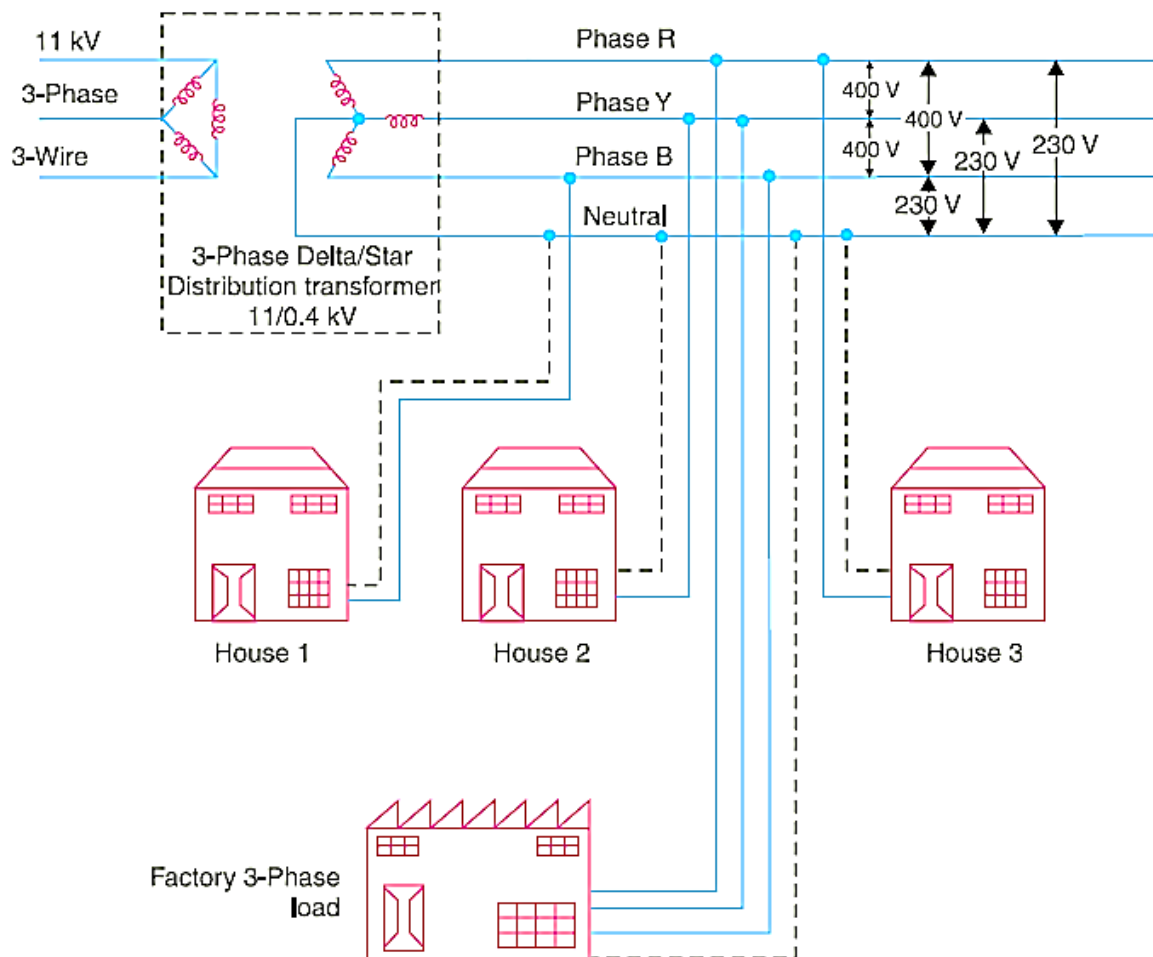


Figure 5.3.2 Secondary AC Distribution System

[Source: "Principles of Power System" by V.K.Mehta Page: 303]

5.4 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.

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

As the name implies, this system of distribution consists of two wires. One is the outgoing or positive wire and the other is the return or negative wire. The loads such as lamps, motors etc. are connected in parallel between the two wires as shown in Fig. 12.4. This system is never used for transmission purposes due to low efficiency but may be employed for distribution of d.c. power.

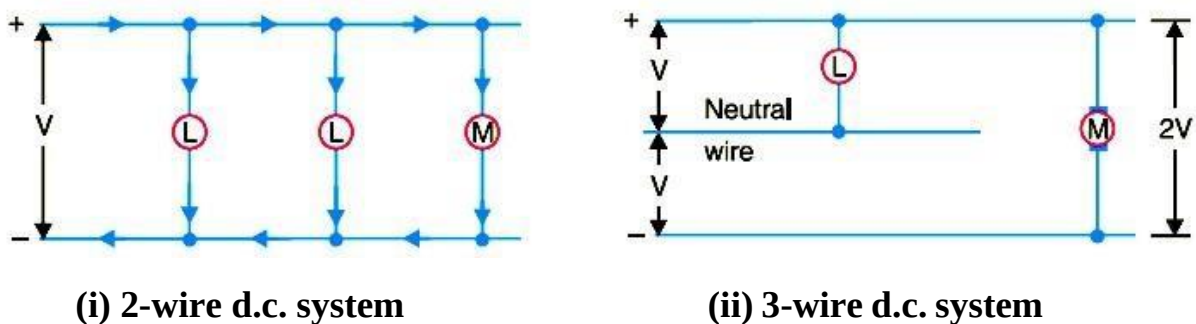


Figure 5.4.1 DC Distribution System

[Source: "Principles of Power System" by V.K.Mehta Page: 303]

(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. 12.5. 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.

5.4.1 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.

5.5 EHVAC and HVDC TRANSMISSION SYSTEM

EHVAC

The first 735 kV system was commissioned in Canada in 1965. Since then, voltage levels up to 765 kV have been introduced in Russia with neighboring countries, U.S.A, South Africa, Brazil, Venezuela and South Korea. The general trend of 800 kV investments is indicated in the diagram, which shows the total capacity of power transformers and generator step-up transformers for 800 kV delivered by ABB. Since the 90's, the investments in 800 kV systems have been much lower compared to the 70's and 80's. However, plans are under way for future introduction of 800 kV in India and China. The planned introductions of voltages in the UHV range, i.e. 1000 kV and above, have been cancelled or postponed in several countries. e.g. Russia, Italy and U.S.A. Future 1000 kV lines are only considered in Japan.

HVDC

The first HVDC system for ± 500 kV and above was the Cabora Bassa project, commissioned in 1979. The Brazilian Itaipu project is the only HVDC system operating at ± 600 kV so far. The major HVDC investments at these voltage levels were made in the late 80's and early 90's. However, an increasing interest in high-capacity HVDC links have been noted in recent years, as seen from the diagram, which shows all HVDC projects for ± 500 kV and above. The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long. From a technical point of view, there are no special obstacles against higher DC voltages. Present solutions are extendable to e.g. ± 800 kV when the need arises. The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long. From a technical point of view, there are no special obstacles against higher DC voltages. Present solutions are extendable to e.g. ± 800 kV when the need arises.

Design aspects for AC DC transmission lines

The general design criteria for AC and DC transmission lines can be divided into electrical and mechanical aspects, both having considerable effects on the investment and operation costs. The power transmission capacity determines the voltage level and the number of parallel circuits, which has a great influence on the investment costs. Other aspects are emergency loading capability and reactive power compensation of AC lines. The power losses affects mainly the operating costs and should therefore be optimized with regard to investment cost of the line conductors at the given voltage level. The insulation performance is determined by the overvoltage levels, the air clearances, the environmental conditions and the selection of insulators. The requirements on the insulation performance affect mainly the investment costs for the towers. The corona performance influences heavily on the design of the conductor bundles and, subsequently, on the mechanical forces on the towers from wind and ice loading of the conductors. Any constraints on the electromagnetic fields at the ground level will, however, primarily influence the costs for the right-of-way. The mechanical loading, and hence the investment cost of towers, insulators and conductors, depends mainly on the design of the conductor bundles and the climatic conditions.

5.5.1 MERITS & DEMERITS OF HVDC

Merits of HVDC

- Undersea cables, where high capacitance causes additional AC losses. (e.g., 250 km Baltic Cable between Sweden and Germany)
- Endpoint-to-endpoint long-haul bulk power transmission without intermediate.
- Increasing the capacity of an existing power grid in situations where additional wires are difficult or expensive to install.
- Power transmission and stabilization between unsynchronized AC distribution systems.

- Connecting a remote generating plant to the distribution grid, for example Nelson River Bipolar.
- Stabilizing a predominantly AC power-grid, without increasing prospective short circuit current.
- Reducing line cost. HVDC needs fewer conductors as there is no need to support multiple phases. Also, thinner conductors can be used since HVDC does not suffer from the skin effect.
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies.
- Synchronize AC produced by renewable energy sources.

Demerits

- Circuit breaking is difficult in D.C circuits, therefore the cost of dc circuit is high.
- D.C system does not have step up or step down transformers to change the voltage level.
- The cost of converter station is very high. Both ac and dc harmonics are generated. System control stability is quite difficult.

5.5.2 ECONOMICAL COMPARISON EHVAC and HVDC

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

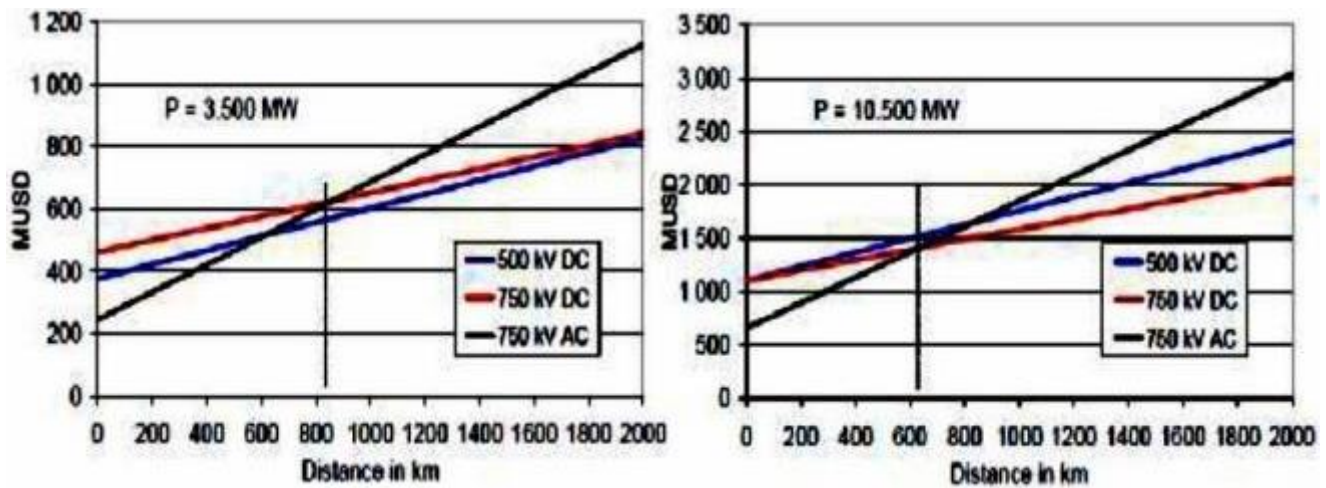


Figure 1.1 Economical Comparision EHVAC And HVDC

[Source: https://www.brainkart.com/article/EHVAC-and-HVDC-Transmission-System_12351/]

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

5.6 SUBSTATION

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.

5.6.1 Classification of Sub-Stations

There are several ways of classifying sub-stations. However, the two most important ways of classifying them are according to

- (1) service requirement and
- (2) constructional features.

1. According to service requirement

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

i)Transformer sub-stations.

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

(ii) Switching sub-stations

These sub-stations do not change the voltage level i.e. incoming and outgoing lines have the same voltage. However, they simply perform the switching operations of power lines.

(iii) Power factor correction sub-stations.

Those sub-stations which improve the power factor of the system are called power factor correction sub-stations. Such sub-stations are generally located at the receiving end of transmission lines. These sub-stations generally use synchronous condensers as the power factor improvement equipment.

(iv) Frequency changer sub-stations

Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilisation.

(v) Converting sub-stations

Those sub-stations which change a.c. power into d.c. power are called converting sub-stations. These sub-stations receive a.c. power and convert it into d.c power with suitable apparatus to supply for such purposes as traction, electroplating, electric welding etc.

(vi) Industrial sub-stations

Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

2. According to constructional features

A sub-station has many components (e.g. circuit breakers, switches, fuses, instruments etc.) which must be housed properly to ensure continuous and reliable service.

According to constructional features, the sub-stations are classified as :

- (i) Indoor sub-station
- (ii Outdoor sub-station
- (iii) Underground sub-station
- (iv) Pole-mounted sub-station

(i) Indoor sub-stations

For voltages upto 11 kV, the equipment of the sub-station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages upto 66 kV.

(ii) Outdoor sub-stations

For voltages beyond 66 kV, equipment is invariably installed out- door. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor.

(iii) Underground sub-stations

In thickly populated areas, the space available for equipment and building is limited and the cost of land is high. Under such situations, the sub-station is created underground.

(iv) Pole-mounted sub-stations

This is an outdoor sub-station with equipment installed over- head on H-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such sub-stations. For complete discussion on pole-mounted sub-station,

5.6.2 Transformer Sub-Stations

The majority of the sub-stations in the power system are concerned with the changing of voltage level of electric supply. These are known as transformer sub-stations because transformer is the main component employed to change the voltage level. Depending upon the purpose served, transformer sub-stations may be classified into :

(i) Step-up sub-station (ii) Primary grid sub-station

(iii) Secondary sub-station (iv) Distribution sub-station

Fig. 5.6.1 shows the block diagram of a typical electric supply system indicating the position of above types of sub-stations. It may be noted that it is not necessary that all electric supply schemes include all the stages shown in the figure. For example, in a certain supply scheme there may not be secondary sub-stations and in another case, the scheme may be so small that there are only distribution sub-stations.

(i) Step-up sub-station.

The generation voltage (11 kV in this case) is stepped up to high voltage (220 kV) to affect economy in transmission of electric power. The sub-stations which accomplish this job are called step-up sub-stations. These are generally located in the power houses and are of outdoor type.

(ii) Primary grid sub-station.

From the step-up sub-station, electric power at 220 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. Here, electric power is received by the primary grid sub-station which reduces the voltage level to 66 kV for secondary transmission. The primary grid sub-station is generally of outdoor type.

(iii) Secondary sub-station.

From the primary grid sub-station, electric power is transmitted at 66 kV by 3-phase, 3-wire system to various secondary sub-stations located at the strategic points in the city. At a secondary sub-station, the voltage is further stepped down to 11 kV. The 11 kV lines run along the important road sides of the city. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub station stations. The secondary sub-stations are also generally of outdoor type.

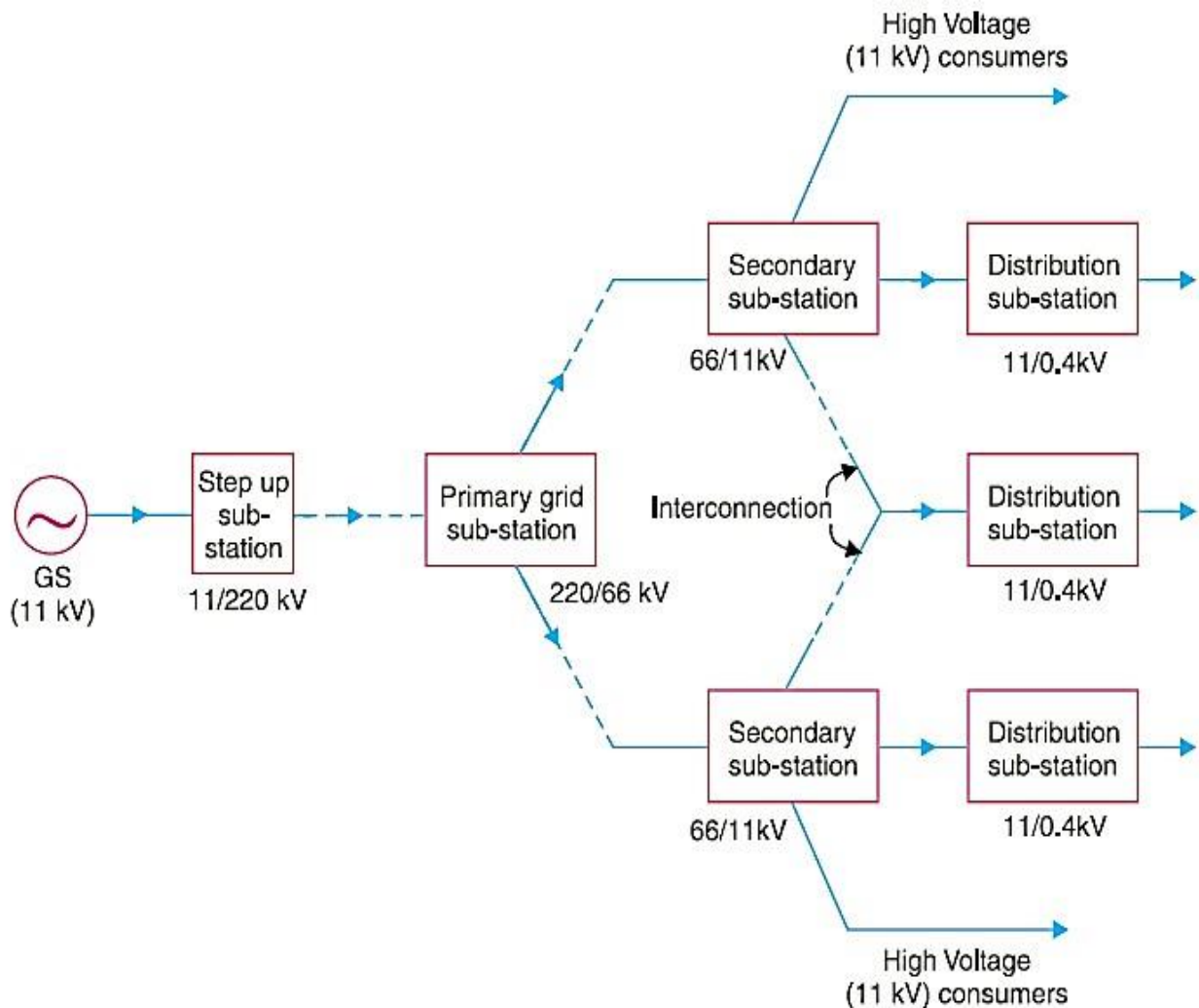


Figure 5.6.1 Transformer Sub-Stations

[Source: “Principles of Power System” by V.K.Mehta Page: 572]

(iv) Distribution sub-station.

The electric power from 11 kV lines is delivered to distribution sub-stations. These sub-stations are located near the consumers localities and step down the voltage to 400 V, 3-phase, 4-wire for supplying to the consumers. The voltage between any two phases is 400V and between any phase and neutral it is 230 V. The single phase residential lighting load is connected between any one phase and neutral whereas 3-phase, 400V motor load is connected across 3-phase lines directly. It may be worthwhile to mention here that majority of the distribution substations are of pole-mounted type.

5.6.3 Pole-Mounted Sub-Station

It is a distribution sub-station placed overhead on a pole. It is the cheapest form of sub-station as it does not involve any building work. Fig 5.6.2 (i) shows the layout of pole-mounted sub-station whereas Fig.5.6.2 (ii) shows the schematic connections.

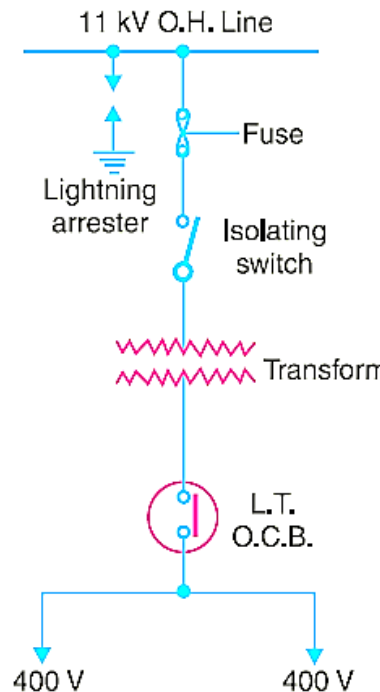


Figure 5.6.2 Pole-Mounted Sub-Station

[Source: "Principles of Power System" by V.K.Mehta Page: 573]

The transformer and other equipment are mounted on H-type pole (or 4-pole structure). The 11 kV line is connected to the transformer (11kV / 400 V) through gang isolator and fuses. The lightning arresters are installed on the H.T. side to protect the sub-station from lightning strokes. The transformer steps down the voltage to 400V, 3-phase, 4-wire supply. The voltage between any two lines is 400V whereas the voltage between any line and neutral is 230 V. The oil circuit breaker (O.C.B.) installed on the L.T. side automatically isolates the transformer from the consumers in the event of any fault. The pole-mounted sub-stations are generally used for transformer capacity upto 200 kVA. The following points may be noted about pole-mounted sub-stations :

(i) There should be periodical check-up of the dielectric strength of oil in the transformer and O.C.B.

(ii) In case of repair of transformer or O.C.B., both gang isolator and O.C.B. should be shut off.

5.6.4 Underground Sub-Station

In thickly populated cities, there is scarcity of land as well as the prices of land are very high. This has led to the development of underground sub-station. In such sub-stations, the equipment is placed underground. Fig. 5.6.3 shows a typical underground sub-station. The design of underground sub-station requires more careful consideration than other types of sub-stations. While laying out an underground sub-station, the following points must be kept in view:

- (i)** The size of the station should be as minimum as possible.
- (ii)** There should be reasonable access for both equipment and personnel.
- (iii)** There should be provision for emergency lighting and protection against fire.
- (iv)** There should be good ventilation.

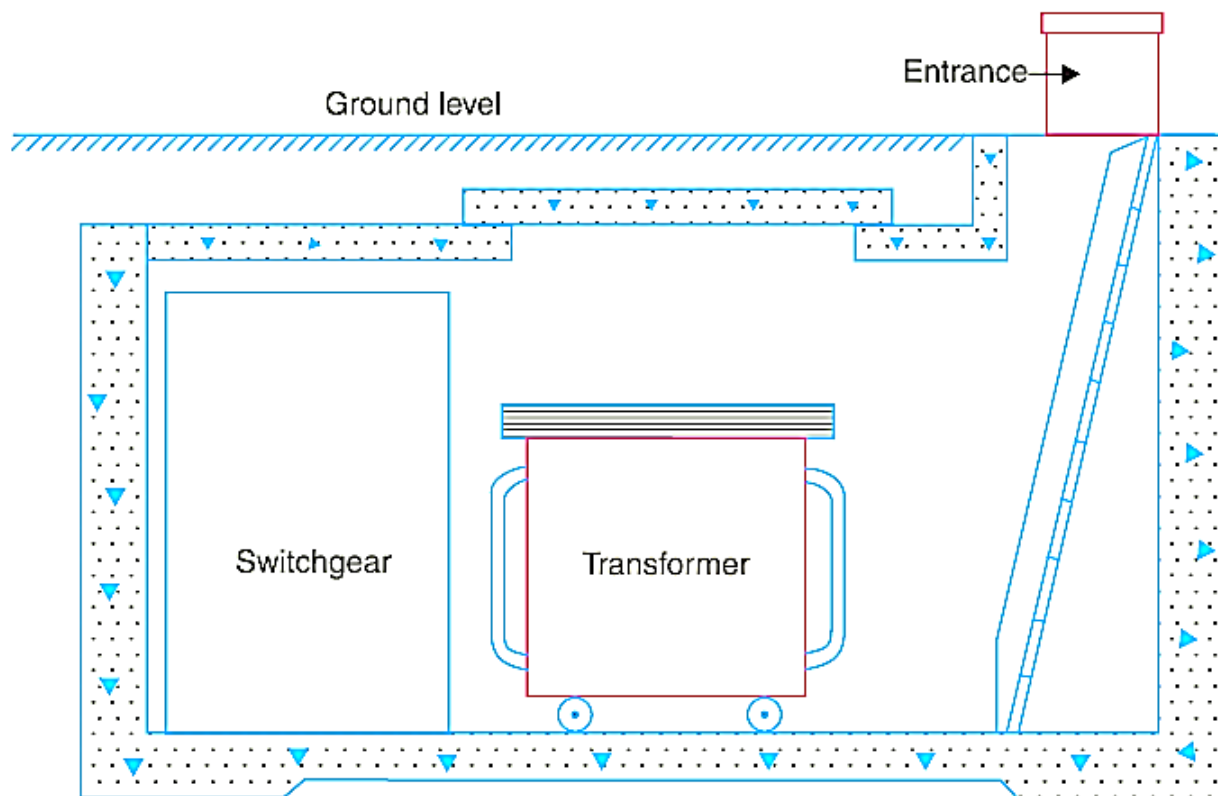


Figure 5.6.3 Underground Sub-Station

- (v) There should be provision for remote indication of excessive rise in temperature so that H.V. supply can be disconnected.
- (vi) The transformers, switches and fuses should be air cooled to avoid bringing oil into the premises.

5.6.5 Substation Layout

1. Substation Layout AIS

- AIS Substation Description

An Air Insulated Switchgear substation (AIS substation) uses atmospheric air as the phase to ground insulation for the switchgear of an electrical substation. The main advantage of the AIS substation is the scope of the substation for future offloading, for this reason AIS substations tend to be the most popular 400kV substation type. The equipment of an AIS substation is easily sourced and has a short lead-time; this means that the required future offloading does not need to be built immediately, unlike GIS where it must be considered. The main disadvantage to the AIS substation is its overall size. At 400kV level these substations can have a significant footprint and require sensitive locating in any rural environment. AIS are usually installed outdoor.

- AIS Substation Size

Based on the single line diagrams given in Appendix B the minimum size of an AIS substation for this project would be as follows:

1. Overall substation Compound Size 46,864.5m²(235.5m x 199m or approximately 11.6 acres)
2. Height of highest element of substation ~ 28m (lightning protection structures situated in the substation compound)

Note: The switchgear in an AIS substation is outdoors therefore no building sizes are considered.

- AIS Maintenance Requirements

1. Ongoing maintenance requirements, all equipment exposed to weather conditions

2. Disconnect contacts must be cleaned regularly, operating mechanisms must be checked and maintained

2. Substation Layout GIS

A gas insulated substation (GIS) is a high voltage substation in which the major structures are contained in a sealed environment with sulfur hexafluoride gas as the insulating medium. GIS technology originated in Japan, where there was a substantial need to develop technology to make substations as compact as possible. The clearance required for phase to phase and phase to ground for all equipment is much lower than that required in an air insulated substation; the total space required for a GIS is 10% of that needed for a conventional substation.

Gas insulated substations offer other advantages in addition to the reduced space requirements. Because the substation is enclosed in a building, a GIS is less sensitive to pollution, as well as salt, sand or large amounts of snow. Although the initial cost of building a GIS is higher than building an air insulated substation, the operation and maintenance costs of a GIS are less.

The primary applications for gas insulated substations include:

High voltage installations

The higher the voltage, the more favorable gas insulated technology becomes. The footprint of 765kV conventional substation is enormous, and GIS technology allows a significant size reduction.

Urban Installations

GIS technology can be used for installations in areas where the cost of real estate or aesthetic appeal is a significant consideration.

Indoor Installations

Building an air insulated substation indoors is usually impractical, but a GIS can easily go inside buildings.

Environmentally Sensitive Installations

GIS technology is popular in desert and arctic areas because it can be enclosed in a building with environmental control. Gas insulated substations also contain the electrical components within a Faraday cage and are therefore totally shielded from lightning.

5.7 METHODS OF GROUNDING

5.7.1 Grounding - Introduction

In power system, grounding or earthing means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth i.e. soil. This connection to earth may be through a conductor or some other circuit element (e.g. are resistor, a circuit breaker etc.) depending up on the situation, grounding or earthing offers two principal advantages. First, it provides protection to the power system. For example, If the neutral point of a star-connected system is grounded through a circuit breaker and phase to earth fault occurs on any one line, a large fault current will flow through the circuit breaker. The circuit breaker will open to isolate the faulty line. This protects the power system from the harmful effects of the fault. Secondly, earthing of electrical equipment ensures the safety of the persons handling the equipment. For example, if insulation fails, there will be a direct contact of the live conductor with the metallic part (i.e. frame) of the equipment. Any person in contact with the metallic part of this equipment will be subjected to a dangerous electrical shock which can be fatal. In this chapter, we shall discuss the importance of grounding or earthing in the line of power system with special emphasis on neutral grounding.

Concept of Grounding

The process of connecting the metallic frame (i.e. non-current carrying part) of electrical equipment or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called grounding or earthing. It is strange but true that grounding of electrical systems is less understood aspect of power system. Nevertheless, it is a very important subject. If grounding is done systematically in the line of the power system, we can effectively prevent accidents and damage to the equipment of the power system and at the same time continuity of supply can be maintained. Grounding or earthing may be classified as:(i) Equipment grounding (ii) System grounding. Equipment grounding deals with earthing the non-current-carrying metal parts of the electrical equipment. On the other

hand, system grounding means earthing some part of the electrical system e.g. earthing of neutral point of star-connected system in generating stations and substations.

5.7.2 Neutral Grounding

The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element is called neutral grounding. Neutral grounding provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (e.g. a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig.

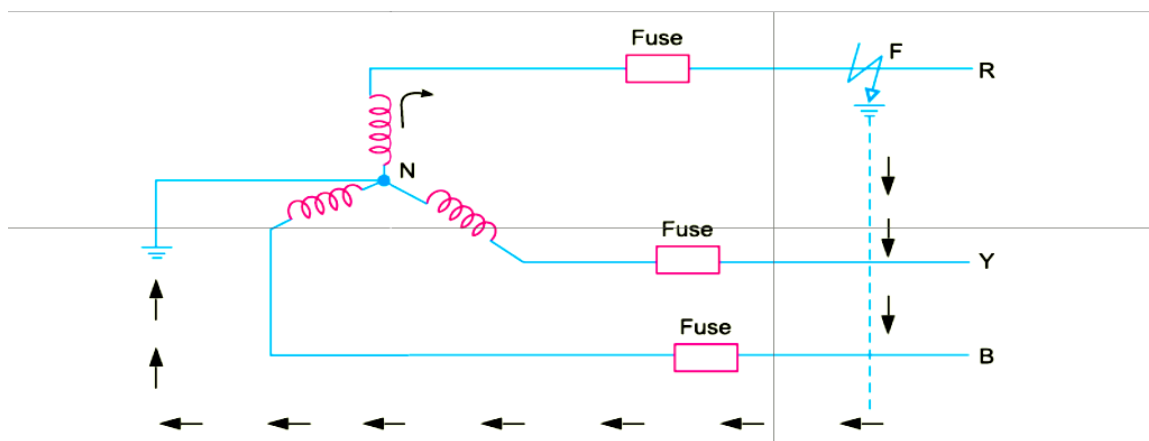


Figure 5.7.1 Neutral Grounding

[Source: "Principles of Power System" by V.K.Mehta Page: 593]

Fig.5.9.3 shows a 3-phase, star-connected system with neutral earthed. Suppose a single line to ground fault occurs in line R at point F. This will cause the current to flow through ground path as shown in Fig.1. Note that current flows from R phase to earth, then to neutral point N and back to R-phase. Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in R-phase and isolate the faulty line R. This will protect the system from the harmful effects of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system i.e. it will remain nearly constant.

Advantages of Neutral Grounding

The following are the advantages of neutral grounding

- (i) Voltages of the healthy phases do not exceed line to ground voltages i.e. they remain nearly constant.
- (ii) The high voltages due to arcing grounds are eliminated.
- (iii) The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.
- (iv) The over voltages due to lightning are discharged to earth.
- (v) It provides greater safety to personnel and equipment.
- (vi) It provides improved service reliability.
- (vii) Operating and maintenance expenditures are reduced

5.7.3 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

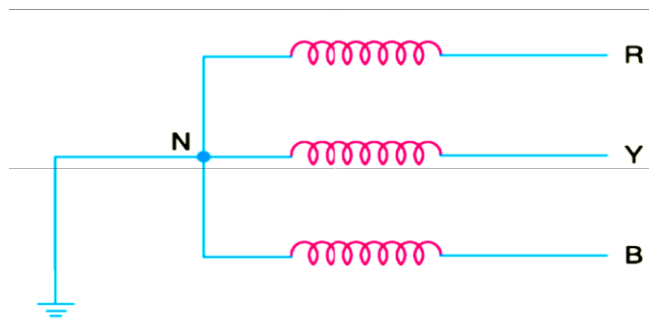


Figure 5.7.2 Solid Grounding

[Source: "Principles of Power System" by V.K.Mehta Page: 594]

When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called solid grounding or effective grounding. Fig. 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.

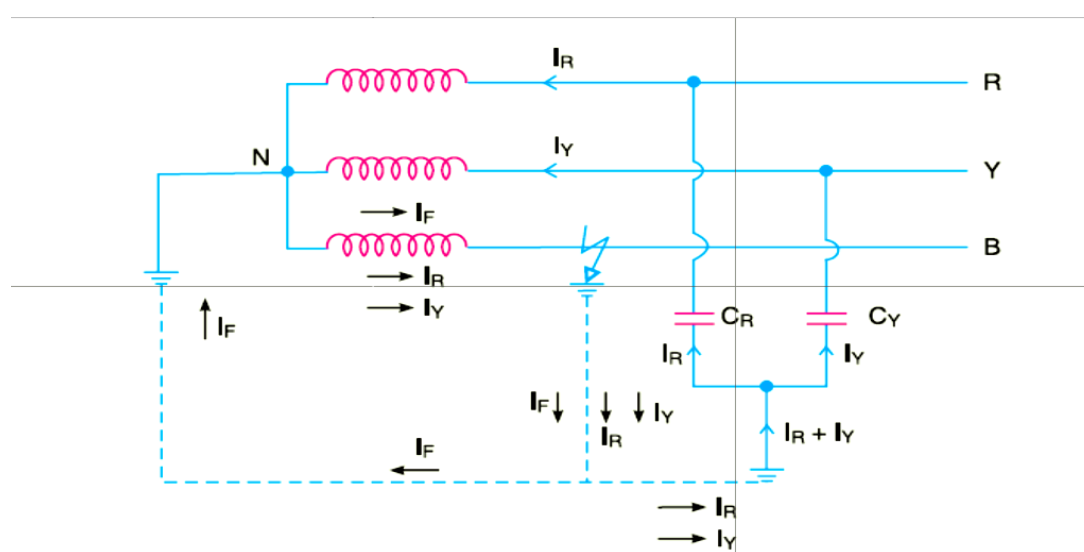


Figure 5.7.2 Solid Grounding – Fault Current

[Source: "Principles of Power System" by V.K.Mehta Page: 594]

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 I_C is in phase opposition to the fault current I_F . The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur. Consider a line to ground fault in line B as shown in Fig. The capacitive currents flowing in the healthy phases R and Y are I_R and I_Y respectively. The resultant capacitive current I_C is the phasor sum of I_R and I_Y . In addition to these capacitive currents, the power source also supplies the fault current I_F . 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 connect

the neutral point of a 3-phase system to earth through a resistor. This is called resistance grounding. When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.) is connected to earth (i.e. soil) through a resistor, it is called resistance grounding. Fig. 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

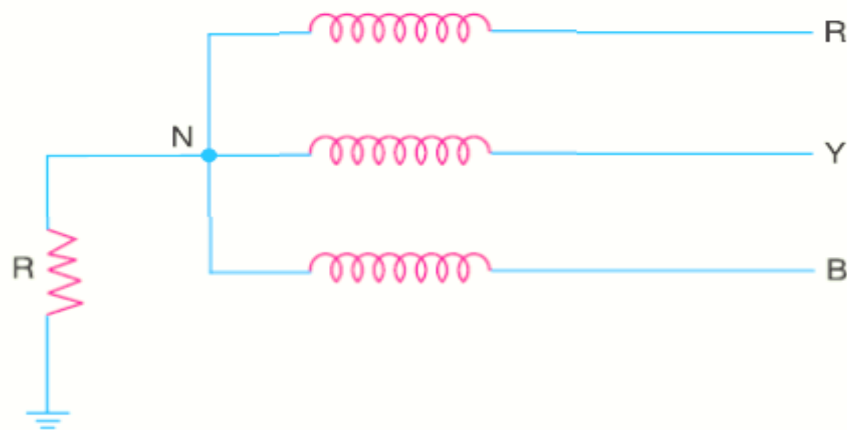


Figure 5.7.3 Resistance Grounding

[Source: "Principles of Power System" by V.K.Mehta Page: 596]

current is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of R is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.

Advantages

The following are the advantages of resistance earthing:

- i) The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.
- ii) It improves the stability of the system.

Disadvantages

The following are the disadvantages of resistance grounding :

- (i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.
- (ii)This system is costlier than the solidly grounded system.
- (iii)A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

Applications

It is used on a system operating at voltages between 2.2 kV and 33 kV with power source capacity more than 5000 kVA.

(iii)Reactance Grounding

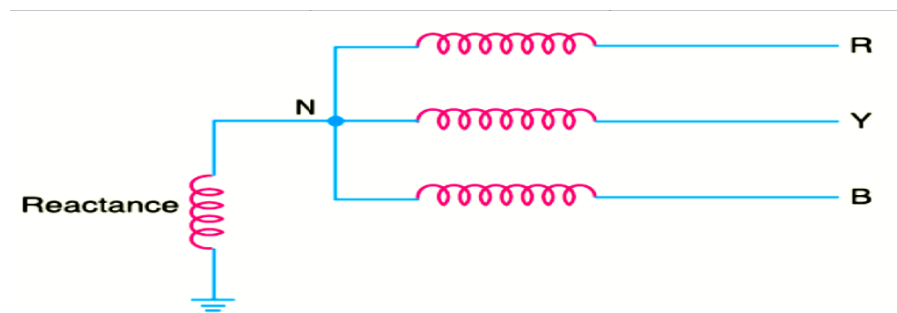


Figure 5.7.3 Reactance Grounding

[Source: "Principles of Power System" by V.K.Mehta Page: 597]

In this system, a reactance is inserted between the neutral and ground as shown in Fig. The purpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can be 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)

We have seen that capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth. If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current I_F flowing through L will be in phase opposition to the capacitive current I_C 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

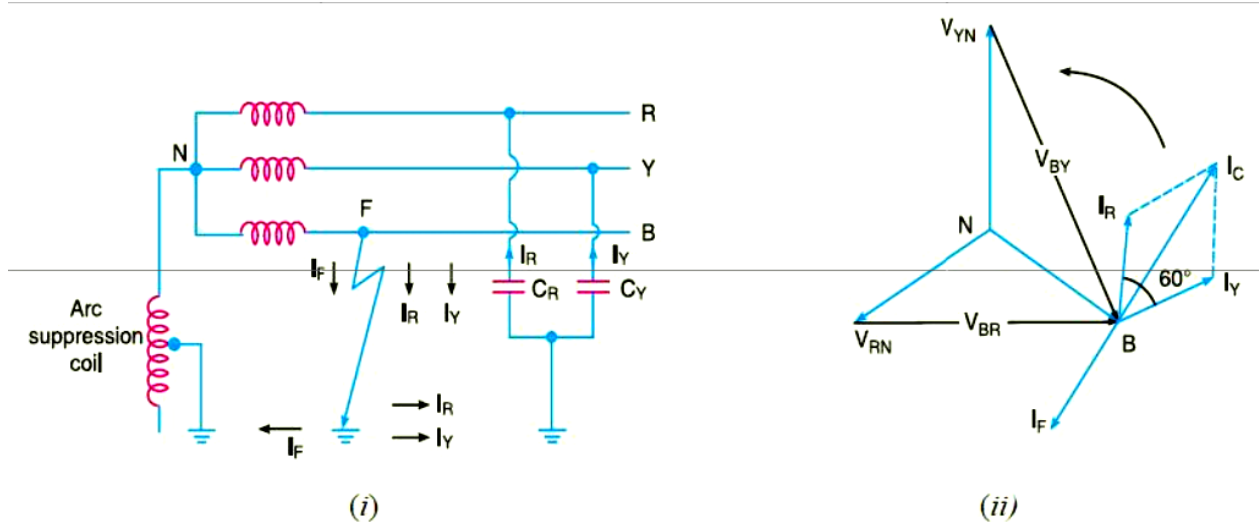


Figure 5.7.3 Reactance Grounding

[Source: "Principles of Power System" by V.K.Mehta Page: 597]

Value of L for resonant grounding . For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors C_R and C_Y

$$I_R = I_Y = \frac{\sqrt{3}V_{ph}}{X_C}$$

$$I_C = \sqrt{3} I_R = \sqrt{3} \times \frac{\sqrt{3}V_{ph}}{X_C} = \frac{3V_{ph}}{X_C}$$

$$\frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$$

$$X_L = \frac{X_C}{3}$$

$$\omega L = \frac{1}{3\omega C}$$

$$L = \frac{1}{3\omega^2 C}$$

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.

5.8 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”.

Description

The main objective of FACTS devices is to replace the existing slow acting mechanical controls required to react to the changing system conditions by rather fast acting electronic controls. The mechanical controls require power system operators and designers to provide generous margins to assure a stable and reliable operation of the system. As a result the existing systems cannot be made use of to their full capacity. However, with the use of fast acting controls, the power system margins could be reduced and power system capability could be more fully utilised while maintaining the present levels of quality and reliability.

The concept of FACTS is explaining as follows:

We know that, the power transfer between two systems interconnected through a tie line is given as

$$P = \frac{V_1 V_2}{X} \sin \delta$$

It can be seen that the power flow can be controlled by three parameters, the voltages at the two systems, the reactance of the tie-line and the difference in the voltage angles at the two ends. The FACTS devices can be used to control one or more of these parameters. The various devices used are (i) Static var compensators (SVC) (ii) Controlled series

compensation (iii) Static condensers (STATCOM) (iv) Advanced controlled series compensation (v) Thyristor controlled phase shifting transformer.

5.8.1 Stati Compensators (STATCOM)

Figure.5.8.1 shows a basic circuit of a STATCOM which is GTO (gate turn-off) based compensation system. These devices are known as STATCOM or static synchronous condensers as these exhibit characteristics similar to conventional synchronous condensers without the moving parts.

The basic elements of a Voltage Source Inverter (VSI) based STATCOM are an inverter, a d.c. capacitor and a transformer to match the line voltage as shown in Fig.5.8.1. Voltage source inverter inverts a d.c. voltage (PWM inverter) with a balanced set of three quasi-square voltage waveforms by connecting the d.c. source sequentially to three output terminals. The three phase a.c. generated by inverter is synchronised to the a.c. line through a small tie reactance, which is the leakage reactance of a transformer.

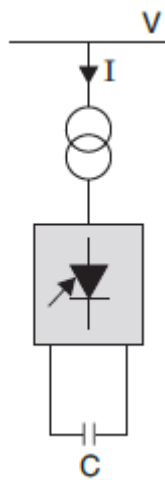


Figure 5.8.1 Statcom

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 714]

When the inverter fundamental output voltage is higher than the system line voltage, the STATCOM works as a capacitor and reactive vars are generated. However when the inverter voltage is lower than the system line voltage, the STATCOM acts as an inductor thereby absorbing the reactive Vars from the system. To control the reactive current, thus the magnitude of d.c. voltage is raised or lower by adjusting the phase angle of the inverter output voltage. The capacitor here does not play an active role in the var generation. It is

only required to maintain a smooth d.c. voltage while carrying the ripple current drawn by the inverter.

5.8.2 Thyristor Controlled Series Compensator

Just as static var compensator can be improved to STATCOM device using GTO converter, a controlled series compensator (CSC) can be improved to an ATCSC using a voltage-driven GTO converter in series with the line as shown in Fig.5.8.2.

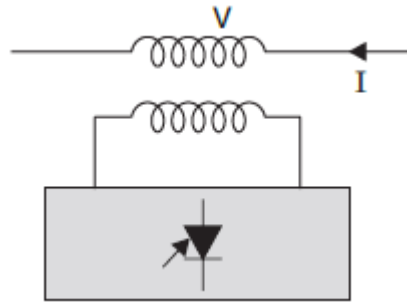


Figure 5.8.2 Thyristor Controlled Series Compensator

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 715]

Here the line current I is made perpendicular to the injected voltage V with the help of an ATCSC coordinator which forms a part of the whole control scheme.

5.8.3 Thyristor controlled phase shifting transformer

Thyristor controlled phase shifting transformer or phase angle regulator consists of a shunt transformer and a boosting transformer inserted in the line as shown in Fig.5.8.3.

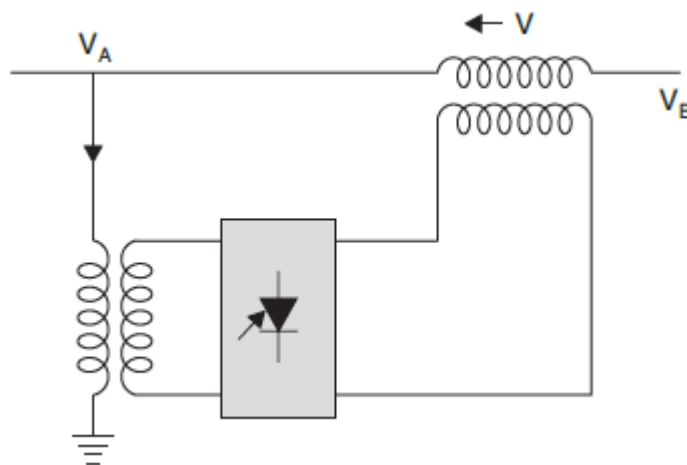


Figure 5.8.2 Thyristor controlled phase shifting transformer

[Source: "Electrical Power Systems" by C.L.Wadhwa Page: 715]

The voltage V is perpendicular to the terminal voltage V_A as shown in phasor diagram. Its' magnitude can be controlled by the thyristor converter. The reactive power required to induce voltage V is transmitted via the shunt transformer and the thyristor converter to the boosting transformer.

“TYPES OF INSULATOR & STRING EFFICIENCY”

TYPES OF INSULATORS

1) PIN TYPE INSULATORS

- Pin type insulator consists of a single or a multiple units.
- Pin type insulator can be used only up to 33kv.
- Beyond operating voltage of 33kv, the pin type insulator become too bulky and hence uneconomical.



2) SUSPENSION TYPE INSULATORS:



- Suspension insulator consists of porcelain disc units mounted one above each other. Each disc is provided with a metal cap at the top and a metal pin under.
- The conductor is suspended below the point of support by means of insulator string.
- The number of discs in a string depends on the line voltage and the atmospheric conditions.

The usual number of discs are:

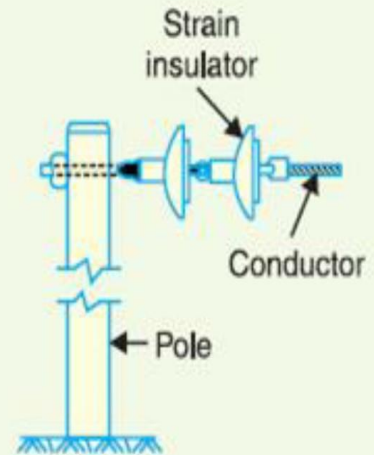
Voltage (kv) : 66 132 220 400

Number of discs: 4-5 9-10 15-16 22-23

- Suspension type insulators are cheaper than pin type insulator.
- If any one string is damaged, it can be replaced by a sound one.
- Each unit is designed for a low voltage. Depending upon the working voltage, number of units can be connected.

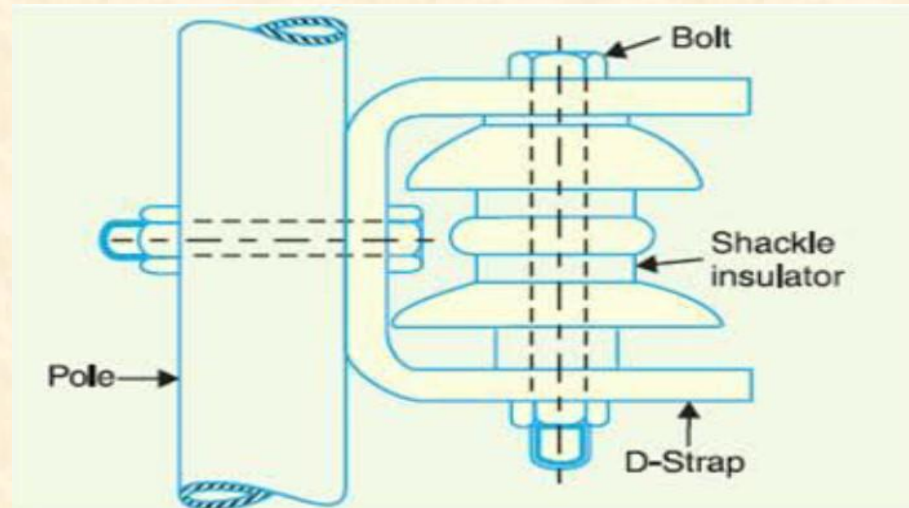
3) STRAIN INSULATORS:

- These are special mechanical strong suspension insulators.
- They are used to take the tension of the conductors at the line terminals, at angle towers and at road crossings.
- The string are placed in horizontal plane
- Two or three strings of insulators in parallel can be used when the tension in conductor is very high.



4) SHACKLE INSULATORS

- In early days, the shackle insulators were used as strain insulators. But now a days, they are used for low voltage distribution lines.
- Such insulators can either be used in horizontal or vertical position. They can directly be fixed to the pole with a bolt or to the cross arm.



$$\text{String Efficiency} = \frac{\text{voltage across the string}}{n * (\text{voltage across disc nearest to conductor})}$$

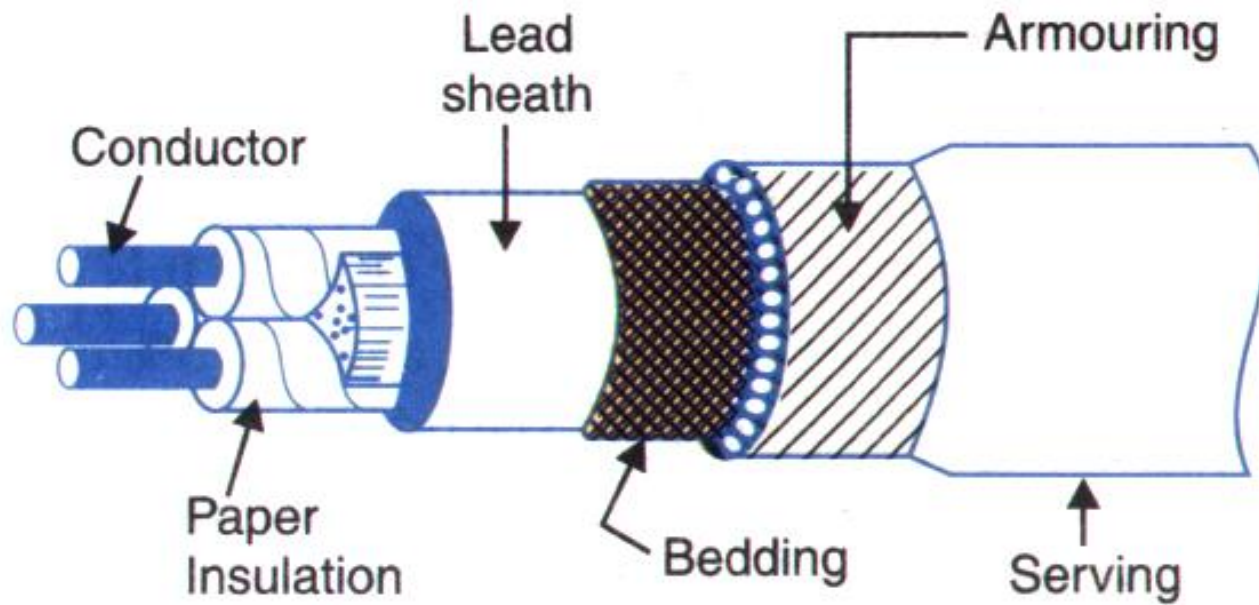
- V: Voltage across the insulator string
- n: number of insulator units
- V_{max}: Voltage across the insulator unit near to conductor.

CONCLUSION

- Thus, a brief idea about the types of insulator used in overhead transmission line has been obtained. Each type of insulator is having its own area of application
- For the equal potential distribution across the strings of insulator, the string efficiency and the methods of improving the string efficiency has been concluded.

Underground Cables

Construction of Cables



Construction of Cables

- **Core or Conductor**

A cable may have one or more than one core depending upon the type of service for which it is intended. The conductor could be of aluminum or copper and is stranded in order to provide flexibility to the cable.

- **Insulation**

The core is provided with suitable thickness of insulation, depending upon the voltage to be withstood by the cable.

The commonly used material for insulation are impregnated paper, varnished cambric or rubber mineral compound.

Construction of Cables

- **Metallic Sheath**

A metallic sheath of lead or aluminum is provided over the insulation to protect the cable from moisture, gases or others damaging liquids

- **Bedding**

Bedding is provided to protect the metallic sheath from corrosion and from mechanical damage due to armoring. It is a fibrous material like jute or hessian tape.

Construction of Cables

- **Armouring**

Its purpose is to protect the cable from mechanical injury while laying it or during the course of handling. It consists of one or two layers of galvanized steel wire or steel tape.

- **Serving**

To protect armouring from atmospheric conditions, a layer of fibrous material is provided.

CLSSIFICATION OF CABLES

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

Grading of Cables

- Since the stresses are maximum at surface of the conductor or inner most part of the dielectric.
- The stress goes on decreasing as outer most layer is reached.
- Since the process of achieving the uniform electrostatic stresses on the dielectric of cables is known as Grading of cables

Grading of Cables

- The unequal distribution of stresses is undesirable because,
- if dielectric is chosen according to maximum stress the thickness of cable increases or either this may lead to breakdown of insulation.
- The following are the two main methods of grading
 - Capacitance grading
 - Inter sheath grading