CHAPTER 3

TOPIC : BASIC TRANSMISSION SYSTEM CONCEPTS

Basic Transmission System

The purpose of this chapter is to focus attention on the various aspect of transmission of electric power. Generally electricity transmission is carried out on high voltage and lower current due to the following reasons:

Advantages of High Transmission Voltage

(i) **Reduces volume of conductor materials:** For a given values of constant parameters i.e. resistance, length of conductor, resistivity and cross sectional area, the volume of the conductor material required is inversely proportional to the square of transmission voltage and power factor. That is to say, the greater the transmission voltage, the lesser is the conductor material required.

(ii) **Increases transmission efficiency:** Since the values of parameters are constants, it follows that the transmission efficiency increases when the line voltage is increased.

(iii) Decreases percentage line drop: With the constants parameters, percentage line drop decreases when the transmission voltage increases.

Though it is advisable to use the highest possible voltage for transmission of power in a bid to save conductor materials, high transmission voltage results in **increased cost of insulating the conductors** and also, **cost of transformers, switchgear and other terminal apparatus**. Therefore, there is a limit to the higher transmission voltage which can be economically employed in a particular case.

Various System of Power transmission

Generally world over the adopted method for transmission of electric power is the 3-phase, 3-wire a.c. system.

However, there are other systems that can also be used for transmission under special circumstances such as;

(i) D.C. system which could use two-wire, two-wire with mid-point earthed or three wire.

(ii) Single-phase A.C. system comprising single-phase two-wire, single-phase two-wire with mid-point earthed or single-phase three-wire.

(iii) Two-phase A.C. system using two-phase four-wire or two-phase three-wire

(iv) Three-phase A.C. system of either three-phase three-wire or three-phase-four wire.

The best system for transmission of power is that which the volume of conductor material required is minimum.

For comparing the amount of conductor material required in various systems, the proper comparison shall be on the basis of equal maximum stress on the dielectric, whether it is overhead or underground system.

In overhead the comparison is on the basis of maximum voltage between conductor and earth while for underground is based on maximum potential difference between conductors.

Comparison of Conductor Material in Overhead Systems

In comparing the relative amounts of conductor material necessary for different systems of transmission we assume similar conditions in each case such as, same power (P watts) transmitted, the distance (l meters) over which power is transmitted, the same line loss (W watts) in each case and the same maximum voltage between any conductor and earth (V_m).

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

In the 2-wire d.c. system one is the positive wire and the other is the negative wire and the load is connected between the two wires Fig. 3.1.

Max. voltage between conductors = V_m

Power to be transmitted = P

Load current, $I_1 = P/V_m$

If R_1 is the resistance of each line conductor, then, $R_1 = \rho l/a_1$

Where a_1 is the cross sectional area (CSA)

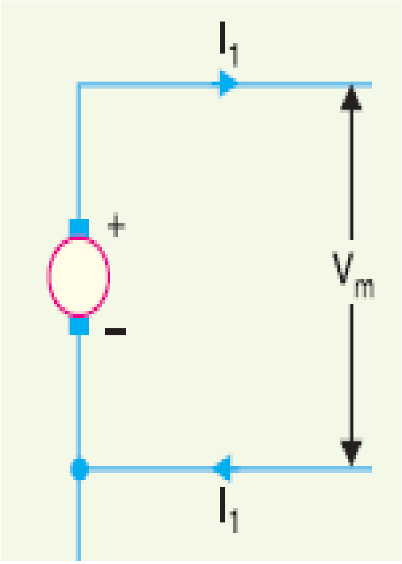


Fig. 3.1

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

$\therefore$

CSA of conductor , $a_1 = \frac{2P^2\rho l}{WV_m^2}$

Volume of conductor material required $= 2a_1 l = 2\left(\frac{2P^2\rho l}{WV_m^2}\right) l = \frac{4P^2\rho l^2}{WV_m^2}$

The two- wire d.c. system with one conductor earthed is usually used as the reference system for comparison with other. The volume of conductor material required for this system from the expressions shown shall be taken as the basic quantity. That is, volume of conductor is,

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

2. Two-wire d.c. system with mid-point earthed

Since the maximum voltage between and two conductor and earth is V_m so the

maximum voltage between conductor is 2 V_m Fig. 3.2.

Load current, $I_2 = P / 2V_m$

Let a_2 be the CSA of the conductor .

Line losses,

$$W = 2I_2^2 R_2 = 2\left(\frac{P}{2V_m}\right)^2 \times \frac{\rho l}{a_2}$$

$$W = \frac{P^2 \rho l}{2a_2 V_m^2} \qquad R_2 = \frac{\rho l}{a_2}$$

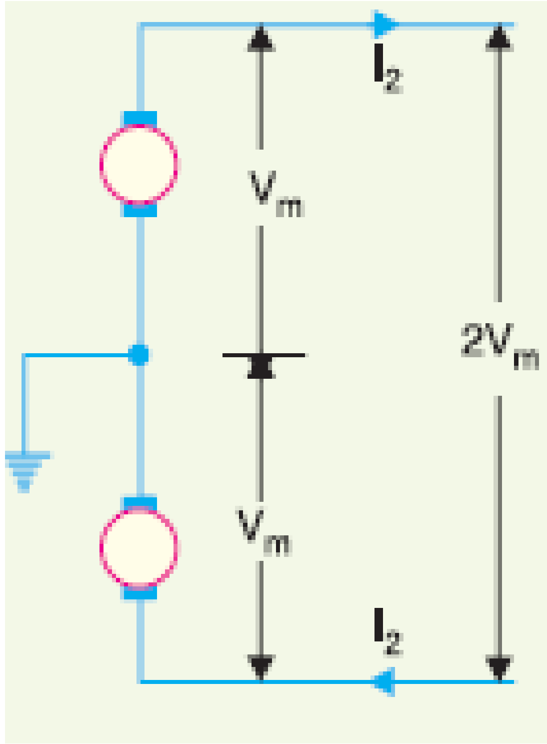


Fig. 3.2

$\therefore$ CSA of conductor, $a_2 = \dfrac{P^2 \rho l}{2WV_m^2}$

$\therefore$ Volume of conductor material required,

$$= 2a_2 l = 2\left(\frac{P^2 \rho l}{2WV_m^2}\right) l = \frac{P^2 \rho l^2}{WV_m^2}$$

This can be written as ,

$$= \frac{K}{4}$$

where, $K = \dfrac{4P^2 \rho l^2}{WV_m^2}$

This shows that the volume of conductor material required in the system is one-fourth of that required in a 2-wire d.c. system with one conductor earthed.

3. Three-wire d.c. system

In this system, there are two outers and a middle or neutral wire which is earthed at the generator end as shown in Fig. 3.3. If the load is balanced, the current in the neutral wire is zero.

Assuming balanced load, Load current , $I_3 = P/2V_m$

Let a_3 be the CSA of each outer conductor.

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

CSA of conductor, $a_3 = \frac{P^2 \rho l}{2WV_m^2}$

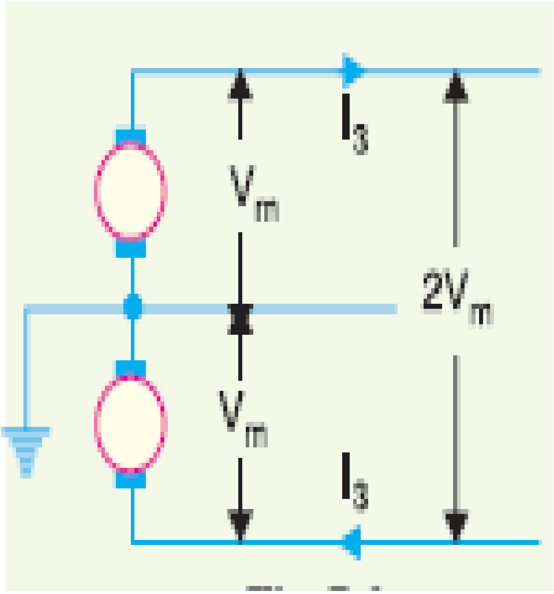


Fig. 3.3

Assuming the cross sectional area (CSA) of neutral conductor to be half of the outer conductor, Volume of conductor material required,

$$2.5a_3l = 2.5\left(\frac{P^2\rho l}{2WV_m^2}\right)l = \frac{2.5}{2}\left(\frac{P^2\rho l}{WV_m^2}\right)$$

That is, $= \frac{5}{16}K$ where , $K = \frac{4P^2\rho l^2}{WV_m^2}$

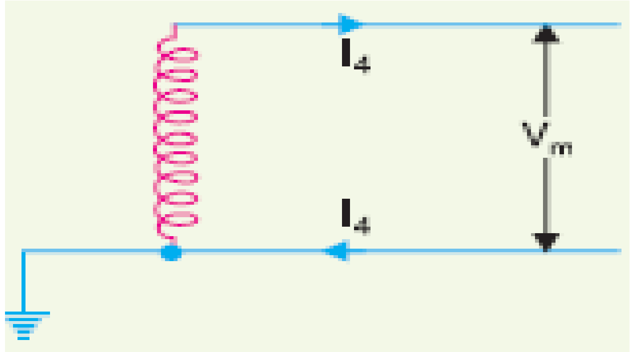
Hence the volume of conductor material required in the system is 5/16th of what is

required for a 2-wire d.c. system with one conductor earthed.

4. Single-phase two-wire a.c. system with one conductor earthed

In this case also, the maximum voltage between conductors is V_m so the r.m.s value of the

voltage between them is $V_m / \sqrt{2}$



Assuming the load power factor to be cos ϕ

Load current,

$$I_4 = \frac{P}{\left(V_m/\sqrt{2}\right)\cos\phi} = \frac{\sqrt{2}P}{V_m \cos\phi}$$

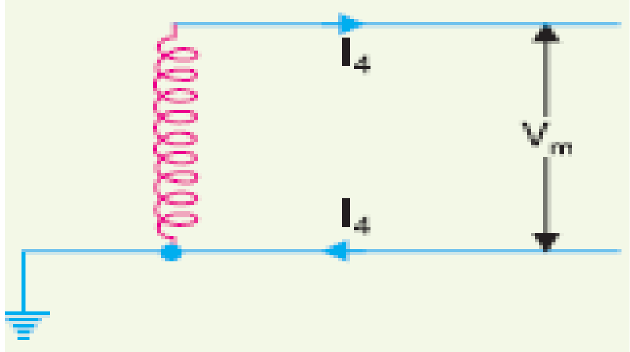


Fig 3.4

Let a_4 be the CSA of the conductor. Line loss,

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

$\therefore$ CSA of conductor, $$a_4 = \frac{4P^2 \rho l}{\cos^2 \phi W V_m^2}$$

Volume of conductor material required,

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

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

where, $$K = \frac{4P^2 \rho l^2}{W V_m^2}$$

This shows that the volume of conductor material required in this system is $2/\cos^2 \phi$ times that of

2-wire d.c. system with one conductor earthed.

5. Single phase 2-wire system with mid-point earthed

The two wires posses equal and opposite voltage to earth V_m. Therefore the maximum voltage between the two is $2V_m$. The r.m.s. value of the voltage between conductor is $= 2V_m/\sqrt{2} = \sqrt{2}V_m$ Fig. 3.5. Assuming the power factor of the load to be $\cos\phi$,

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

Let a_5 be the CSA of the conductor.

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

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

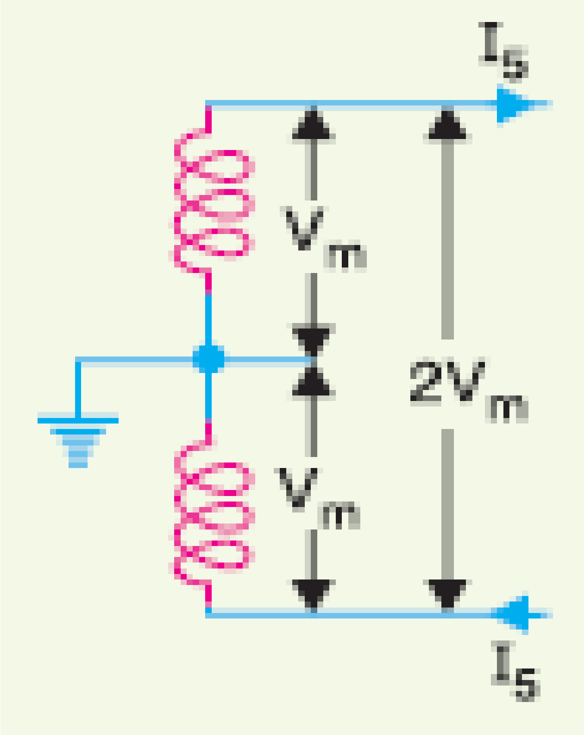


Fig. 3.5

CSA of conductor, $a_5 = \dfrac{P^2 \rho l}{W V_m^2 \cos^2 \phi}$

Volume of conductor material required,

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

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

$$= \frac{K}{2\cos^2 \phi}$$

where, $K = \dfrac{4P^2 \rho l^2}{W V_m^2}$

Hence, the volume of conductor material required in the system is $1/2\cos^2 \phi$

times that of the reference system.

6. Single-phase, 3-wire system

Just like the three-wire d.c. system. The single phase 3-wire system consists of two outers and neutral wire taken from the mid-point of the phase winding Fig. 3.6. If the load is balanced, the current through the neutral wire is zero.

Assuming balanced load,

Max. voltage between conductors = $2V_m$

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

If the p.f of the load is cos ϕ , then,

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

Let a_6 be the CSA of each conductor.

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

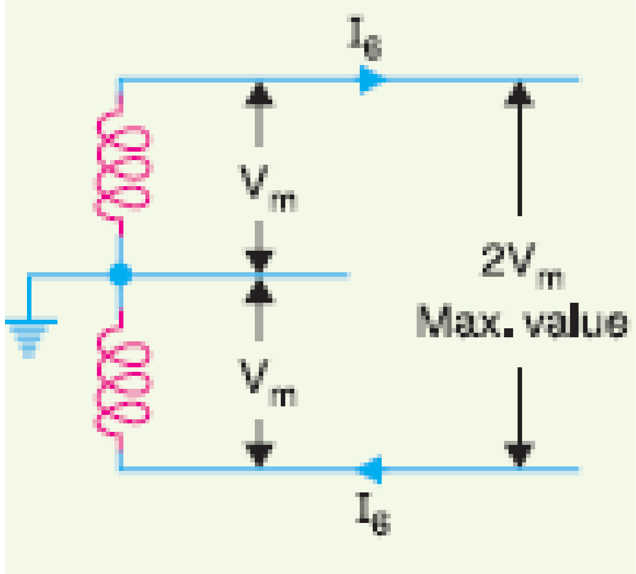


Fig. 3.6

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

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

Also, assuming the CSA of neutral wire to be half that of the outer wire,

Volume of conductor material required,

$$= 2.5 a_6 l = 2.5\left(\frac{P^2 \rho l}{W V_m^2 \cos^2 \phi}\right) l = \frac{2.5 P^2 \rho l^2}{W V_m^2 \cos^2 \phi}$$

$$= \frac{2.5}{\cos^2 \phi} \times \frac{P^2 \rho l}{W V_m^2}$$

$$= \frac{5K}{8 \cos^2 \phi}$$ where, $K = \frac{4 P^2 \rho l^2}{W V_m^2}$

Therefore, the volume of conductor material required in this system is $5/8 \cos^2 \phi$ times that of the reference 2-wire d.c. system with one conductor earthed.

7. Two phase, 4-wire a.c. system

The four wires are taken from the ends of the two-phase windings and the mid-points of the two windings are connected together. This system can be considered as two independent single phase systems, sees Fig. 3.7 each transmitting one half of the total power.

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

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

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

If the p.f. of the load is cos ϕ,

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

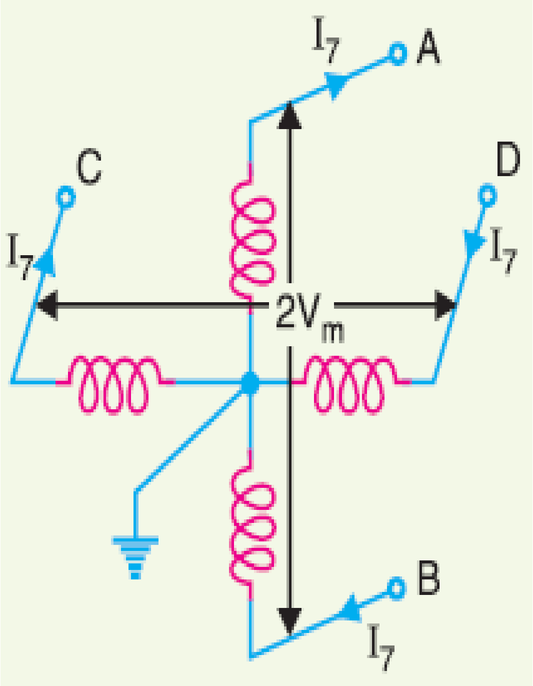


Fig. 3.7

Let a_7 be the CSA of one conductor.

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

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

CSA of conductor, $a_7 = \dfrac{P^2 \rho l}{2WV_m^2 \cos^2 \phi}$

Volume of conductor material required $= 4a_7 l$

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

$$= \frac{1}{2\cos^2 \phi} \times \frac{4P_2^2 \rho l}{WV_m^2}$$

$$= \frac{K}{2\cos^2 \phi}$$

where, $K = \dfrac{4P^2 \rho l^2}{WV_m^2}$

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

8. Two-phase, 3-wire system

The third or neutral wire is taken from the junction of two-phase windings whose voltages are in quadrature with each other. Each phase transmits one half of the total power Fig 3.8.

The R.M.S. voltage between outgoing conductor and neutral

.

Current in each outer, $I_8 = \dfrac{P/2}{\dfrac{V_m}{\sqrt{2}}\cos\phi} = \dfrac{P}{\sqrt{2}V_m\cos\phi}$

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

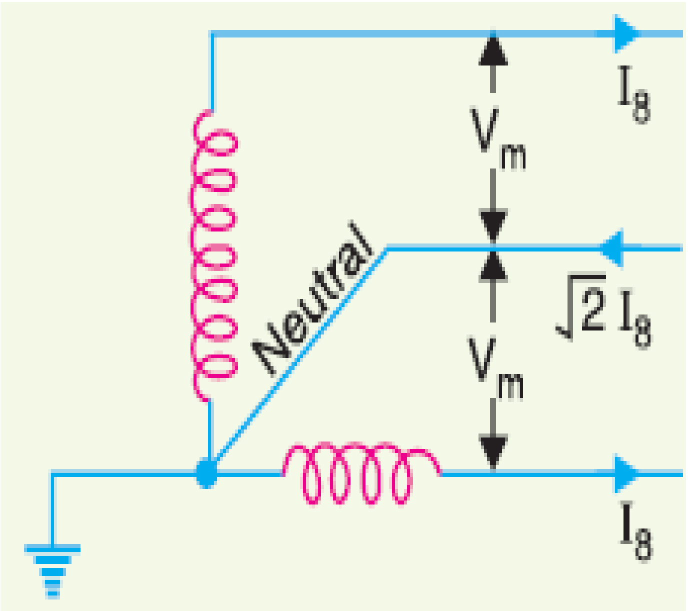


Fig 3.8

Assuming the current density to be constant, the CSA of neutral wire is $\sqrt{2}$ times that of either of the outers.

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

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

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

Therefore, CSA of conductor $a_8 = \frac{P^2 \rho l}{2 W V_m^2 \cos^2 \phi}\left(2 + \sqrt{2}\right)$

Volume of conductor material required., $= 2a_8 l + \sqrt{2} a_8 l = a_8 l \left(2+\sqrt{2}\right) \quad = \frac{P^2 \rho l^2}{2WV_m^2 \cos^2\phi}\left(2+\sqrt{2}\right)^2$

$$= \frac{1.457}{\cos^2\phi} K$$

where, $$K = \frac{4P^2 \rho l^2}{WV_m^2}$$

Therefore, the volume of conductor material required for this system is $1.457/\cos^2\phi$ times that of 2-wire d,c, system with one conductor earthed

9. 3-Phase, 3-wire system

This system is almost universally adopted for transmission of electric power. **The 3-phase, 3-wire system may be star or -delta connected.**

Fig 3.9. shows 3-phase, 3-wire star connected system. The neutral point N is earthed.

R.M.S. voltage per phase $= V_m/\sqrt{2}$

Power transmitted per phase $= P/3$

Load current per phase,

$$I_9 = \frac{P/3}{(V_m/\sqrt{2}\cos\phi} = \frac{\sqrt{2}P}{3V_m\cos\phi}$$

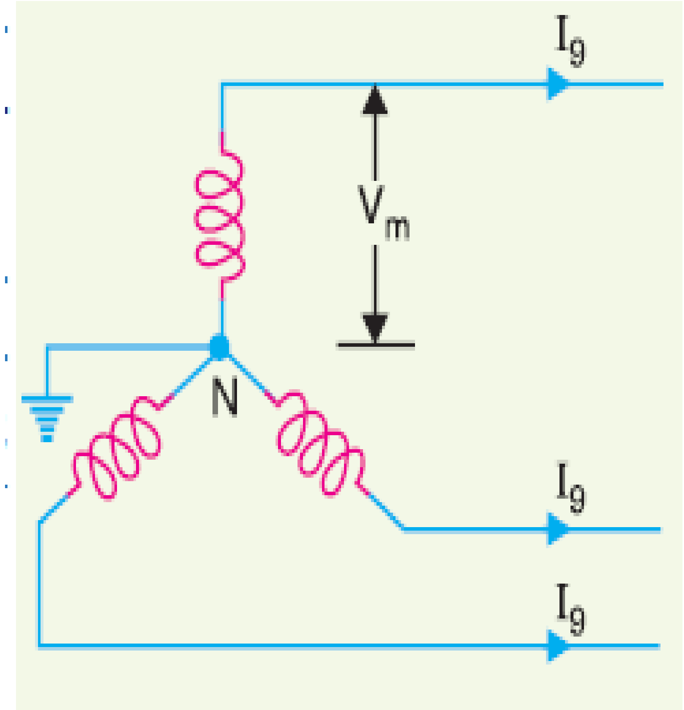


Fig. 3.9

Let a_9 be the CSA of each conductor.

Line losses,

$$W = 3I_9^2R_9 = 3\left(\frac{\sqrt{2}P}{3V_m\cos\phi}\right)^2\frac{\rho l}{a_9} = \frac{2P^2\rho l}{3a_9V_m^2\cos^2\phi}$$

Therefore, CSA of conductor, $a_9 = \dfrac{2P^2\rho l}{3WV_m^2\cos^2\phi}$

Volume of conductor material required is, $= 3a_9 l = 3\left(\dfrac{2P^2\rho l}{3WV_m^2\cos^2\phi}\right)l = \dfrac{2P^2\rho l^2}{WV_m^2\cos^2\phi} = \dfrac{0.5K}{\cos^2\phi}$

where,

$$K = \frac{4P^2\rho l^2}{WV_m^2}$$

Hence, the volume of the conductor material required for this system is $0.5/\cos^2\phi$ **times that required for 2-wire d.c. system with one conductor earthed.**

10. 3-Phase, 4-wire System

The 4th or neutral wire is taken from the neutral point Fig. 3.10. The CSA of the neutral wire is generally one-half that of the line conductor.

For a balanced load, the current through the neutral wire is zero. Assuming balanced loads and p.f. of the load is $\cos\phi$.

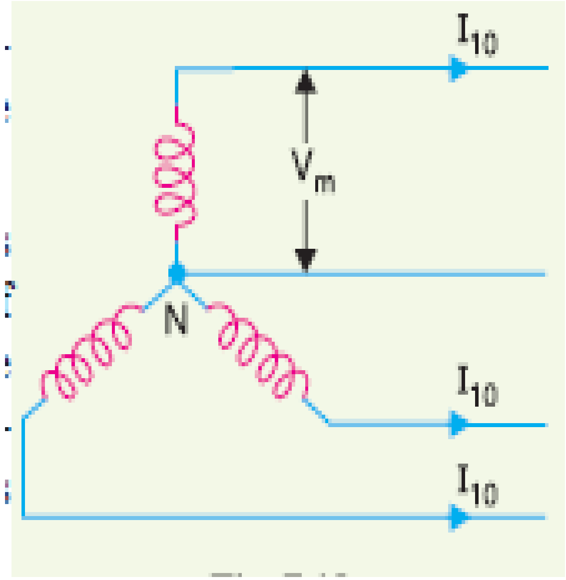


Fig. 3.10

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

$$W = \frac{2P^2\rho l}{3a_{10}V_m^2\cos^2\phi}$$

Therefore, CSA, $a_{10} = \frac{2P^2\rho l}{3WV_m^2\cos^2\phi}$

As the CSA of neutral wire is one-half that of any line conductor,

Volume of conductor material required $= 3.5a_{10}l = 3.5\left(\frac{2P^2\rho l}{3WV_m^2\cos^2\phi}\right)\times l$

$$= \frac{7P^2\rho l^2}{3WV_m^2\cos^2\phi} = \frac{7}{3\cos^2\phi}\times\frac{P^2\rho l^2}{WV_m^2} = \frac{7K}{12\cos^2\phi}$$

Where , $K = \frac{4P^2\rho l^2}{WV_m^2}$

Therefore, the volume of conductor material required for this system is $7/12\cos^2\phi$ times that required for 2-wire d.c. system with one conductor earthed.

Comparison of Conductor Material in Underground System

In an underground transmission using multi-core belted type cables, the major stress on the insulation is usually between conductors. Also, the following assumption are made.

(i) The same power **(P watts)** is transmitted by each system.

(ii) The distance **(*l* metres)** over which power is transmitted remain the same

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

(iv) The maximum voltage between conductors **(V_m)** is the same in each case.

1. Two-wire d.c. system

If V_m denotes the maximum potential difference between the conductors, it will also be the working voltage in this case Fig. 3.11.

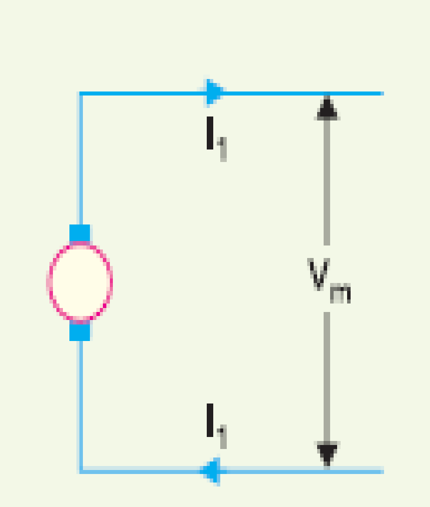


Fig 3.11

Load current, $I_1 = P/V_m$

Line losses,

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

$$= \frac{2P^2\rho l}{a_1V_m^2}$$

Therefore, CSA, $a_1 = \dfrac{2P^2\rho l}{WV_m^2}$

Volume of conductor material required $= 2a_1l = 2\left(\dfrac{2P^2\rho l}{WV_m^2}\right)l = \dfrac{4P^2\rho l^2}{WV_m^2} = K(say)$

This volume shall be taken as the basic quantity and comparison made for other systems.

2. Two-wire d.c. system with mid point earthed

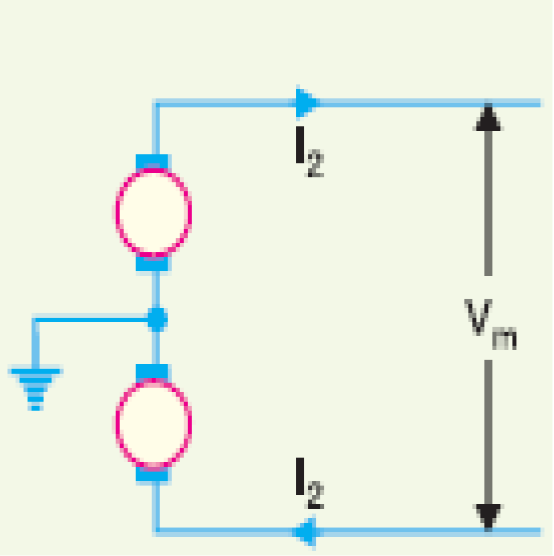


Fig 3.12

Line current, $I_2 = P/V_m$

Line losses, $W = 2I_2^2 R_2 = 2\left(\frac{P}{V_m}\right)^2 \rho \frac{l}{a_2}$

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

So, CSA of conductor, $a_2 = \frac{2P^2 \rho l}{W V_m^2}$

Volume of conductor material required, $= 2a_2 l = 2\left(\frac{2P^2 \rho l}{W V_m^2}\right) l = \frac{4P^2 \rho l^2}{W V_m^2} = K$

Hence, the volume of conductor material required in this system is the same as

that for 2-wire d.c. system.

3. Three wire d.c. system

The maximum voltage between the outers is V_m Fig. 3.13. Assuming balanced load, the current through the neutral wire will be zero.

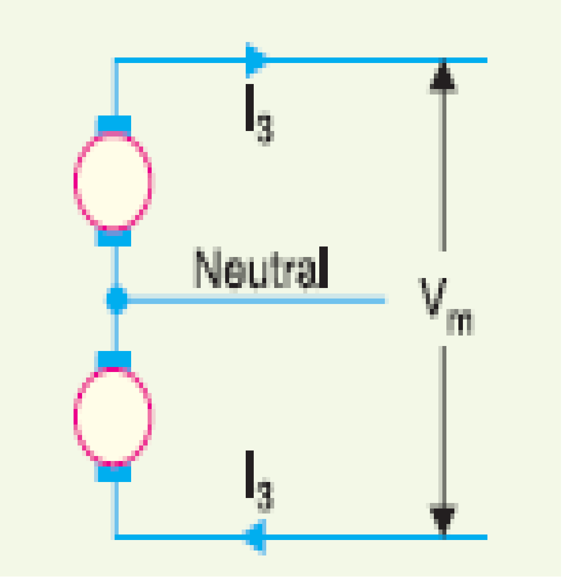


Fig 3.13

Load current, $I_3 = P/V_m$

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

$$= \frac{2P^2\rho l}{V_m^2 a_3}$$

Therefore, CSA of conductor, $a_3 = \frac{2P^2\rho l}{WV_m^2}$

Assuming the CSA of neutral wire to be half of that of either outers,

Volume of conductor material,

$$= 2.5a_3 l = 2.5\left(\frac{2P^2\rho l}{WV_m^2}\right)l = \frac{5P^2\rho l^2}{WV_m^2} \quad = 1.25K$$

Hence, the volume of conductor required in the system is 1.25 times that required for 2-wire d.c. system.

4 Single phase, 2-wire a.c. system

The maximum voltage between conductors is V_m, therefore, r.m.s. value of voltage is $V_m/\sqrt{2}$ Fig. 3.14.

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

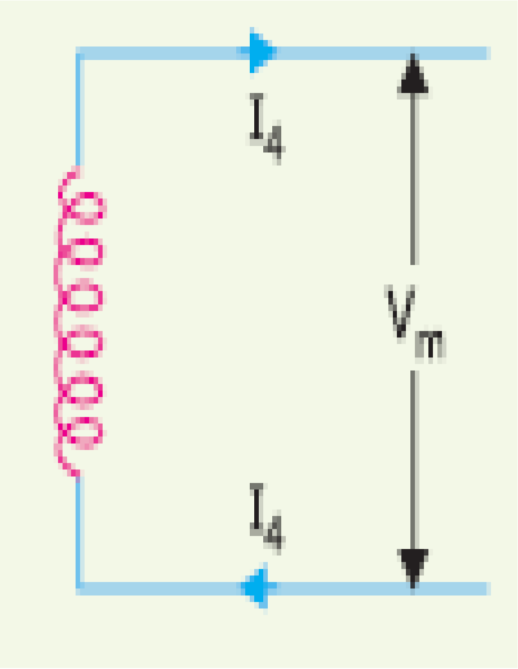


Fig. 3.14

Load current, $I_4 = \dfrac{P}{V_m/\sqrt{2}\cos\phi} = \dfrac{\sqrt{2}P}{V_m\cos\phi}$

Line losses, $W = 2I_4^2R_4$

$$= 2\left(\frac{\sqrt{2}P}{V_m\cos\phi}\right)^2\rho\frac{l}{a_4} = \frac{4P^2\rho l}{a_4V_m^2\cos^2\phi}$$

Therefore, CSA of conductor, $a_4 = \dfrac{4P^2\rho l}{WV_m^2\cos^2\phi}$

Volume of conductor material required,

$$= 2a_4 l = 2\left(\frac{4P^2\rho l}{WV_m^2\cos^2\phi}\right)l = \frac{8P^2\rho l^2}{WV_m^2\cos^2\phi}$$

$$= \frac{2}{\cos^2\phi} \times \frac{4P^2\rho l^2}{WV_m^2}$$

$$= \frac{2K}{\cos^2\phi}$$

where, $$K = \frac{4P^2\rho l^2}{WV_m^2}$$

Therefore, the volume of conductor material required for this system is $2/\cos^2\phi$ times that required in a 2-wire d.c. system.

5. Single-phase 2-wire system with mid-point earthed

The maximum value of voltage between the outers is V$_m$. Therefore, the r.m.s. value of voltage is $V_m/\sqrt{2}$ Fig 3.15. If the p.f. of the load is $\cos\phi$ then,

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

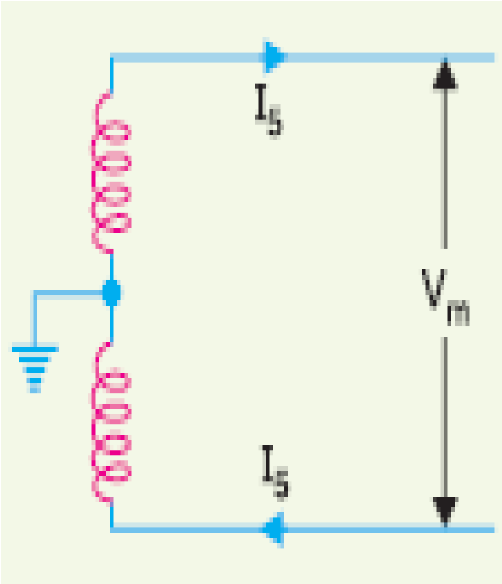


Fig 3.15

Line losses, $W = 2I_5^2 R_5 = 2\left(\dfrac{\sqrt{2}P}{V_m \cos\phi}\right)^2 \rho \dfrac{l}{a_5}$

$$= \frac{4P^2 \rho l}{a_5 V_m^2 \cos^2\phi}$$

Therefore, CSA of conductor, $a_5 = \dfrac{4P^2 \rho l}{W V_m^2 \cos^2\phi}$

Volume of conductor material required, $= 2a_5 l = 2\left(\dfrac{4P^2 \rho l}{W V_m^2 \cos^2\phi}\right) l = \dfrac{8P^2 \rho l^2}{W V_m^2 \cos^2\phi}$

$$= \frac{2}{\cos^2\phi} \times \frac{4P^2\rho l}{WV_m^2} = \frac{2K}{\cos^2\phi} \qquad \text{where,} \qquad K = \frac{4P^2\rho l}{WV_m^2}$$

The volume of conductor material required in this is $2/\cos^2\phi$ times that required in 2-wire d.c. system.

6. Single phase, 3-wire system.

If the load is considered balanced, the system reduces to a single phase 2-wire except that a neutral wire is provided in addition Fig 3.16. Assuming the CSA of the neutral conductor to be half of either of the outers,

Volume of conductor material required $= 2.5^* a_4 l = 2.5\left(\frac{4P^2\rho l}{WV_m^2\cos^2\phi}\right) l = \frac{10P^2\rho l^2}{WV_m^2\cos^2\phi} = \frac{2.5}{\cos^2\phi} \times \frac{4P^2\rho l^2}{WV_m^2}$

$$= \frac{2.5K}{\cos^2\phi} \qquad \text{where,} \qquad K = \frac{4P^2\rho l^2}{WV_m^2}$$

Hence the volume of conductor material required in this system is $2.5/\cos^2\phi$ times that required in 2-wire d.c. system.

**CSA of conductor for single phase 2-wire system*

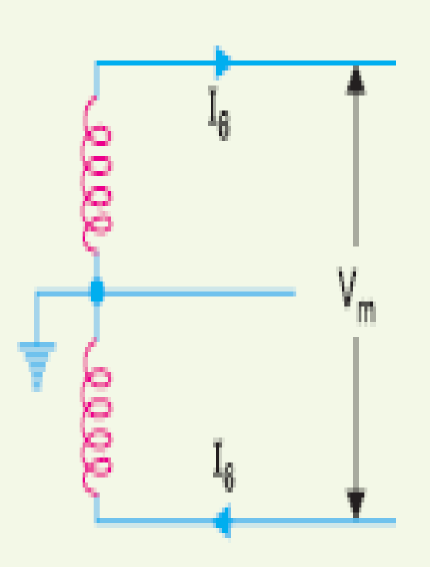


Fig 3.16

7. Two-phase, 4-wire system

This can be considered as two independent single phase systems, each transmitting one-half of the total power. Fig 3.17. **clearly show that voltage across outers (AB or CD) is twice that of single phase 2-wire** . Therefore, current (I_7) in each conductor is half that in single-phase 2-wire system. Thus, CSA of each conductor is also half but as there are four wires, so volume of conductor material used is the same as in a single phase, 2-wire system. That is, volume of conductor material required, $= \dfrac{2K}{\cos^2\phi}$

Consequently, the volume of conductor material required in the system is $2/\cos^2\phi$ times that required in 2-wire d.c. system.

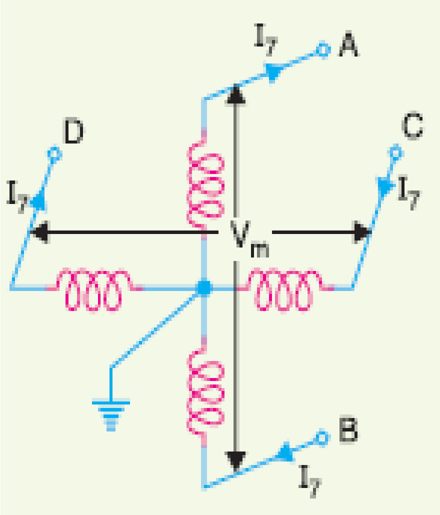


Fig 3.17

8. Two-phase, 3-wire system

In the two-phase , 3-wire a.c. system let us assume that the maximum voltage between the outers is V_m. Then maximum voltage between either outer and neutral conductor is $V_m/\sqrt{2}^*$ Fig 3.18.

R.M.S. voltage between outer and neutral conductor, $= \dfrac{V_m/\sqrt{2}}{\sqrt{2}} = \dfrac{V_m}{2}$

Current in each outer, $I_8 = \dfrac{P/2}{V_m/2\cos\phi} = \dfrac{P}{V_m\cos\phi}$

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

Assuming the current density to be constant, the CSA of neutral conductor will be $\sqrt{2}$ times that of either of the outers

Resistance of neutral conductor, $= \frac{R_8}{\sqrt{2}} = \frac{\rho l}{\sqrt{2} a_8}$

Line losses,

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

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

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

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

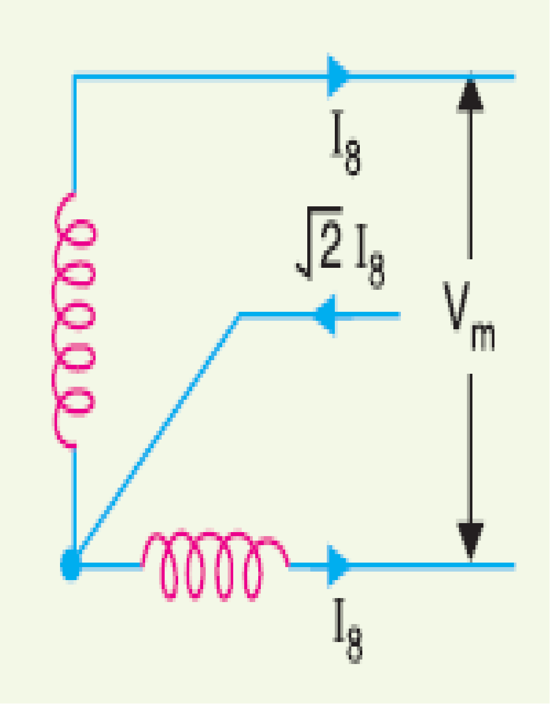


Fig 3.18

Volume of conductor material required, $= 2a_8 l + \sqrt{2} a_8 l = a_8 l (2 + \sqrt{2})$

$$= \frac{P^2 \rho l^2}{W V_m^2 \cos^2 \phi} \left(2 + \sqrt{2}\right)^2 \qquad = \frac{2.194 K}{\cos^2 \phi}$$

where,

$$K = \frac{4P^2 \rho l^2}{W V_m^2}$$

The volume of conductor material required in this is $2.914 / \cos^2 \phi$ times that required in 2-wire d.c. reference system.

9. 3-Phase, 3- wire System.

Suppose that the maximum value of voltage between the conductors is V_m. Then maximum voltage between each phase and neutral is $V_m / \sqrt{3}$ Fig. 3.19.

Hence the r.m.s. value of voltage per phase is $= V_m / \sqrt{3} \times 1 / \sqrt{2} = V_m / \sqrt{6}$

Power transmitted per phase $= P/3$

Load current per phase, $I_9 = \dfrac{P/3}{V_m/\sqrt{6}\cos\phi} = \dfrac{\sqrt{6}P}{3V_m\cos\phi}$

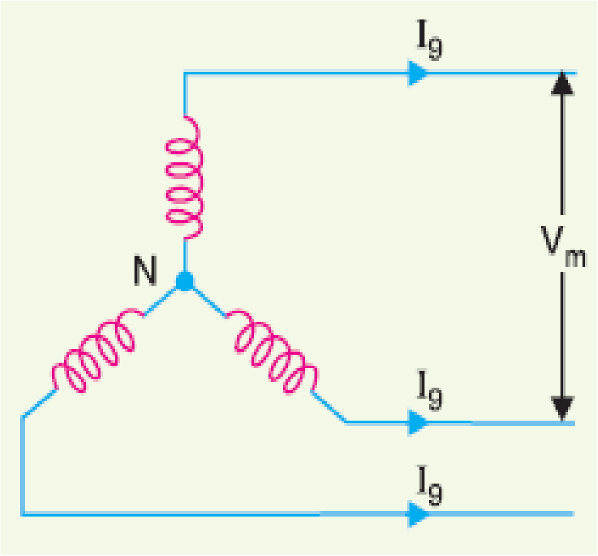


Fig 3.19

Line losses, $W = 3I_9^2 R_9$

$$= 3\left(\frac{\sqrt{6}P}{3V_m\cos\phi}\right)^2 \times \rho\frac{l}{a_9}$$

$$= \frac{2P^2\rho l}{a_9 V_m^2\cos^2\phi}$$

CSA of conductor , $a_9 = \dfrac{2P^2 \rho l}{W V_m^2 \cos^2 \phi}$

Volume of conductor material required, $= 3a_9 l = 3\left(\dfrac{2P^2 \rho l}{W V_m^2 \cos^2 \phi}\right) l = \dfrac{6P^2 \rho l^2}{W V_m^2 \cos^2 \phi}$

$$= \frac{1.5}{\cos^2 \phi} \times \frac{4P^2 \rho l^2}{W V_m^2}$$

where, $K = \dfrac{4P^2 \rho l^2}{W V_m^2}$ $\quad = \dfrac{1.5K}{\cos^2 \phi}$

From this the volume of conductor material required in this system is $1.5/\cos^2 \phi$

times that required in 2-wire d.c. system.

10. 3-Phase, 4-wire System

In a 4-wire system if the loads are balanced, then neutral wire carries no current. Invariably, the system reduces to a 3-phase, 3-wire system except that there is additional neutral wire. Assuming the CSA of the neutral conductor to be half that of line conductor Fig.3.20, Volume of conductor material required,

$$= 3.5 a_9 l \quad = 3.5\left(\frac{2P^2 \rho l}{WV_m^2 \cos^2\phi}\right) l$$

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

$$= \frac{7}{\cos^2\phi} \times \frac{P^2 \rho l^2}{WV_m^2} \qquad = \frac{1.75K}{\cos^2\phi}$$

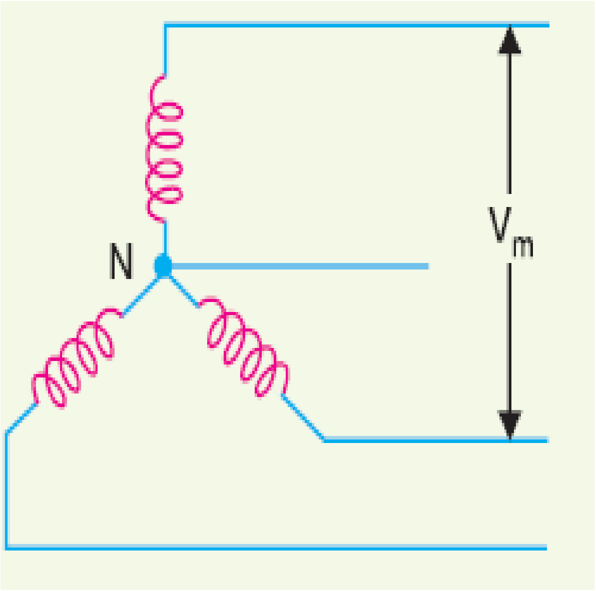


Fig. 3.20

where, $K = \frac{4P^2 \rho l^2}{WV_m^2}$

Hence the volume of conductor material required in this system is $1.75/\cos^2\phi$ times that required in 2-wire d.c system.

Summary of Comparison of Various Systems of Transmission

The table below shows summary of the ratio of conductor-material in any system compared with that in the corresponding 2-wire d.c. system.

Cos θ is the power factor in an a.c. system.

System	Same maximum voltage to earth	Same max. voltage between conductors
1. D.C. system		
(i) 2-wire	1	1
(ii) 2-wire with mid-point earthed	0.25	1
(iii) 3-wire	0.3125	1.25
2. Single phase system		
(i) 2-wire	$2/\cos^2\theta$	$2/\cos^2\theta$
(ii) 2-wire with mid-point earthed	$0.5/\cos^2\theta$	$2/\cos^2\theta$
(iii) 3-wire	$0.625/\cos^2\theta$	$2.5/\cos^2\theta$
3. Two phase system		
(i) 2-phase, 4-wire	$0.5/\cos^2\theta$	$2/\cos^2\theta$
(ii) 2-phase, 3-wire	$1.457/\cos^2\theta$	$2.194/\cos^2\theta$
4. Three-phase system		
(i) 3-phase, 3-wire	$0.5/\cos^2\theta$	$1.5/\cos^2\theta$
(ii) 3-phase, 4-wire	$0.583/\cos^2\theta$	$1.75/\cos^2\theta$

Points to Note:

(i) There is a greater saving in conductor material if d.c. system is adopted for transmission for electric power but due to technical difficulties, d.c. system is not used for transmission.

(ii) Considering the a.c. system, the 3-phase a.c. system is most suitable for transmission due to (a) there is considerable saving in conductor material (b) it is convenient and efficient.

Worked Example:

1. What is the percentage saving in feeder copper if the line voltage in a 2-wire d.c system is raised from 200 volts to 400 volts for the same power transmitted over the same distance and having the same power loss?

Solution:

Let P be the power delivered and W be power loss in both cases. Let v_1 and a_1 be the volume and CSA for 200 V system and v_2 and a_2 for that of 400 V system

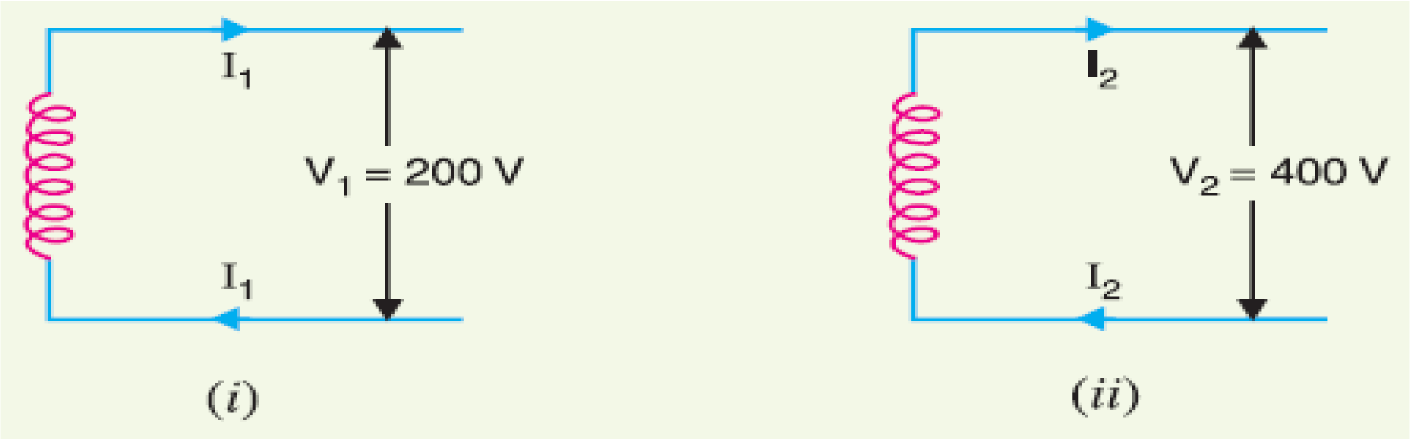


Fig. 3.21

The same power is delivered in both cases,

So, $P = V_1 I_1 = 200 I_1$ $P = V_2 I_2 = 400 I_2$

Therefore, $200 I_1 = 400 I_2$ or $I_2 = (200/400) I_1 = 0.5 I_1$

Power loss in 200 V system, $W_1 = 2 I_1^2 R_1$

Power loss in 400 V system, $W_2 = 2 I_2^2 R_2 = 2(0.5 I_1)^2 R_2 = 0.5 I_1^2 R_2$

As power loss in the two cases is the same,

$$W_1 = W_2$$

That is, $2I_1^2R_1 = 0.5I_1^2R_2$, $R_2/R_1 = 2/0.5 = 4$

$a_1/a_2 = 4$ and $v_1/v_2 = 4$

$$v_2/v_1 = 1/4 = 0.25$$

$\therefore$ % age saving in feeder copper, $= \frac{v_1 - v_2}{v_1} \times 100 = \left(\frac{v_1}{v_1} - \frac{v_2}{v_1} \right) \times 100 \quad = (1 - 0.25) \times 100 = 75\%$

2. A 50 km long transmission line supplies a load of 5 MVA at 0.8 p.f. lagging at 33 kV. The efficiency of transmission is 90%. Calculate the volume of aluminium conductor required for the line (i) single phase, 2- wire system is used (ii) 3-phase, 3-wire system is used. The resistivity of aluminium is $2.85 \times 10^{-8} \Omega m.$

Solution.

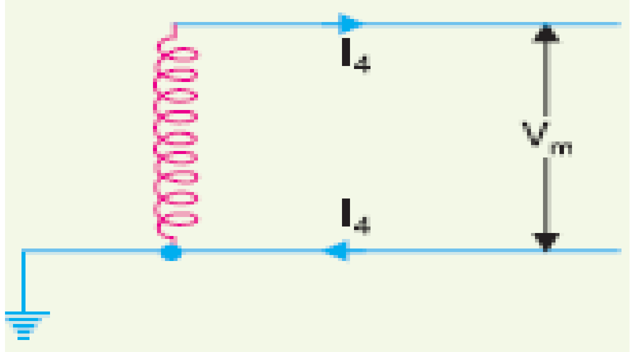
Power transmitted $= MVA \times \cos\phi = 5 \times 0.8 = 4MW = 4 \times 10^6 W$

Line loss, $W = 10\%$ of power transmitted,

$\therefore$ Line loss $= (10/100) \times 4 \times 10^6 = 4 \times 10^5 W$

Length of line, $l = 50km = 50 \times 10^3 m$

(i) Single phase, 2-wire system



Apparent power (S) $= VI_1$

Therefore,

$$I_1 = \frac{S}{V} = \frac{5 \times 10^6}{33 \times 10^3} = 151.5A$$

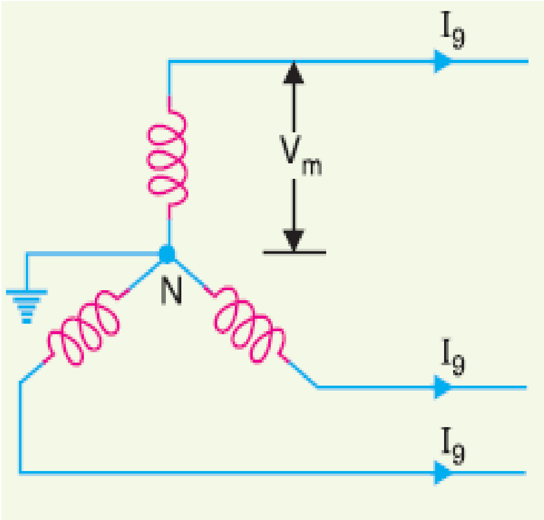
Suppose a_1 is the cross sectional area (CSA) of aluminium conductor.

Line loss, $W = 2I_1^2 R_1 = 2I_1^2 \left(\rho \frac{1}{a_1} \right)$

CSA of conductor, $a_1 = \frac{2I_1^2 \rho l}{W} = \frac{2\times(151.5)^2\times\left(2.85\times10^{-8}\right)50\times10^3}{4\times10^5} \quad = 1.635\times10^{-4}\,m^2$

Volume of conductor required $= 2a_1 l = 2\times\left(1.635\times10^{-4}\right)\times50\times10^3 \quad = 16.35 m^3$

(ii) 3-phase, 3-wire system



Line Current, $I_2 = \frac{S}{\sqrt{3}V} = \frac{5\times10^6}{\sqrt{3}\times33\times10^3} = 87.5A$

Suppose a$_2$ is the CSA of the conductor in this case.

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

CSA of conductor, $a_2 = \frac{3I_2^2 \rho l}{W} = \frac{3\times(87.5)^2\times\left(2.85\times10^{-8}\right)\times50\times10^3}{4\times10^5}$

$= 0.818\times10^{-4}\,m^2$

Volume of conductor required, $= 3a_2 l = 3\times\left(0.818\times10^{-4}\right)\times50\times10^{3} = 12.27m^{3}$

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

Elements of a Transmission Line

For economic reasons, transmission of electric power is done at **high voltage by 3-phase, 3-wire overhead system**. The major elements of a high-voltage transmission line are:

(i) Conductors (3 for a single-circuit line and 6 for a double circuit line), which mostly is made from aluminium reinforced with steel.

(ii) Step-up and step-down transformers, at the sending and receiving end respectively

(iii) Line insulators, which mechanically support the line conductors and isolate them electrically from the ground

(iv) Support, which are generally steel towers and provide support to the conductors

(v) Protective devices, such as ground wires, lightning arrestors, circuit breakers, relays etc.

(vi) Voltage regulating devices, which maintain the voltage at the receiving end within permissible limits.

Economics of Power Transmission

The design of various parts of power transmission scheme is done in such a way that maximum economy is achieved. Two most important economic design consideration that influence the electrical design of a transmission line are **economic choice of conductor size** and **economic choice of transmission voltage.**

Economic Choice of Conductor Size

The most economical size or area of conductor is that which the total annual cost of transmission line is minimum. This is know as **Kelvin's law**. The total annual cost of transmission line can be divided broadly into two parts as, annual charge on capital outlay and annual cost of energy wasted in the conductor.

(i) The annual cost on capital outlay: deal on account of interest and depreciation on the capital cost of complete installation of transmission line. For overhead it will be the annual interest and depreciation on the capital cost of conductors and insulators and the cost of their construction. In overhead the insulator cost is constant, the cost of conductor is proportional to the cross sectional area (CSA) of the conductor and their erection is partly constant and partly proportional to CSA of the conductor. The annual charge on an overhead transmission line is expressed to be $= P_1 + P_2 a$ …(i) where P_1 and P_2 are constants and a is the cross sectional area of the conductor.

(ii) Annual cost of energy wasted: is on account of energy lost mainly in the conductor due to I^2R losses. Assuming a constant current in the conductor throughout the year, the energy lost in the conductor is proportional to resistance. As resistance is inversely proportional to the CSA of the conductor, the energy lost is inversely proportional to CSA.

Annual cost of wasted energy $= P_3/a$ ….(ii), where P_3 is a constant.

Total annual cost, $C = \exp.(i) + \exp.(ii) = (P_1 + P_2 a) + P_3/a$

$$C = P_1 + P_2 a + P_3/a \qquad \text{….(iii),}$$

In equation (iii), only the CSA a is variable. Therefore, the total cost of

transmission line will be minimum if differentiation of C with respect to a is

zero. i.e . $\frac{d}{da}(C) = 0$, or $\frac{d}{da}\left(P_1 + P_2 a + {}^{P_3}\!/_{a}\right) = 0$, or $P_2 - \frac{P_3}{a^2} = 0$, or $P_2 = P_3/a^2$

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

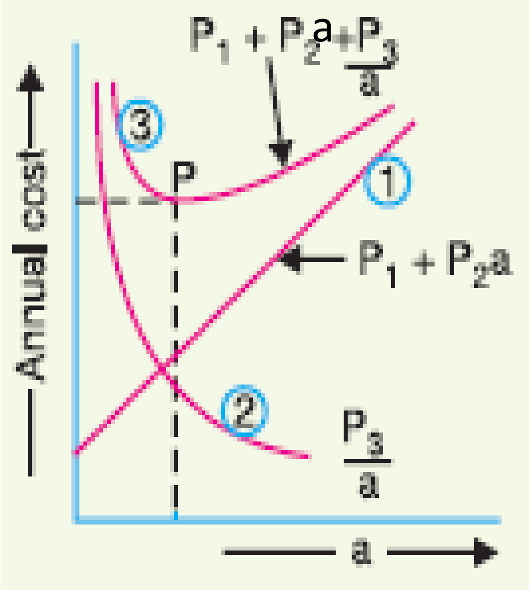
i.e. variable part of annual charge = Annual cost of energy wasted.

From the above Kelvin’s Law can be stated , the most economical area of conductor is that for which the variable part of annual charge is equal to the cost of energy losses per year.

Graphical illustration of Kevin’s law.

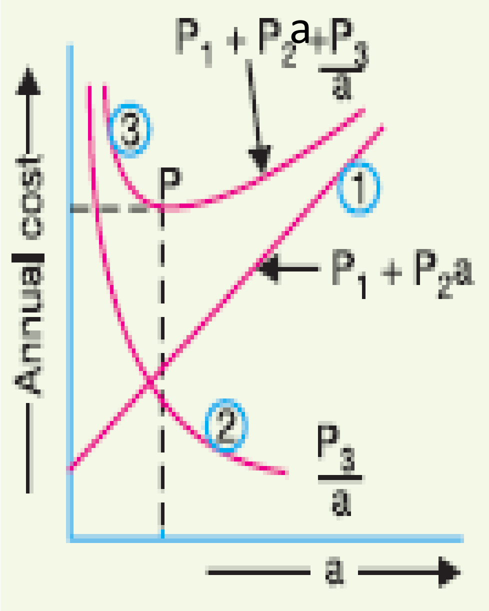
Kelvin’s law can be illustrated graphically by plotting annual cost against CSA “a” of the conductor as shown in Figure 3.21. In the diagram, the straight line (1) shows the relation between the annual charge and the CSA a of the conductor (i.e., P_1+P_2a). The rectangular hyperbola (2) gives the relationship between annual cost of energy wasted and CSA “a”. The addition of curve (1) and (2) the curve (3) is obtained.

Fig 3.21



This curve shows the relation between total annual cost of transmission line and CSA “a”.

The lowest point on the curve (i.e. point P) represents the most economical conductor CSA.



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Limitations of Kelvin’s law. Although theoretically Kelvin’s law holds good, it is often difficult to apply to proposed scheme of power transmission.

The practical limitation of the law are:

(i) It is difficult to estimate the energy loss in the line without actual load curves, which are not available at the same time of estimation.

(ii) The assumption that annual cost on account of interest and depreciation on the capital outlay is not very true as in cables for instance, 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.

Worked Example.

A 2-conductor cable 1km long is required to supply a constant current of 200 A throughout the year. The cost of cable including installation is RM (20a + 20) per metre where "a" is the CSA of the conductor in cm^2. The cost of energy is 5 cent per kWh and interest and depreciation charges amount to 10%.

Calculate the most economical conductor size. Assume resistivity of conductor material to be 1.73 $\mu\Omega$ cm.

Solution.

Resistance of one conductor $= \frac{\rho l}{a} = \frac{1.73\times10^{-6}\times10^{5}}{a} = \frac{0.173}{a}\Omega$

Energy lost per annum $= \frac{2I^2Rt}{1000}kWh \quad = \frac{2\times(200)^2\times0.173\times8760}{1000\times a} = \frac{121238.4}{a}kWh$

Annual cost of energy lost = Cost per kWh X Annual energy loss

$$= RM\,\frac{5}{100}\times\frac{121238.4}{a} \qquad = RM\;6062/a$$

The capital variable cost of the cable is given to be RM 20a per metre. Therefore, for 1km

length of the cable, the capital variable cost is RM 20a X 1000 = 20,000a.

Variable annual charge = Annual interest and depreciation on capital variable cost of cab

= RM 0.1 X 20,000a = RM 2000a

According to Kelvin's law, for most economical CSA of the conductor,

Variable annual charge = Annual cost of energy lost ,   2000a   = 6062/a

$$a = \sqrt{\frac{6062}{2000}} = 1.74cm^2$$

Economic Choice of Transmission Voltage

It has been stated that if transmission voltage is increased, the volume of conductor material required is reduced i.e. decrease in the expenditure on the conductor material. As the transmission voltage is increased, the cost of insulating the conductors, cost of transformers, switchgear and other terminal apparatus also increases. Therefore, there is **optimum transmission voltage** beyond which its not economical to transmit. That transmission voltage for which the cost the elements is minimum is called economical transmission voltage.

To determine the economical transmission voltage assuming the power to be transmitted, generation voltage and length of transmission line to be known, the cost for the following can be worked out using standard transmission voltage.

(i) Transformers, for a given power the cost increases with the increases in transmission voltage.

(ii) Switch gear, the cost also increases with increase in transmission voltage.

(iii) Lightning arrestor, the cost increases rapidly with the increase in transmission voltage.

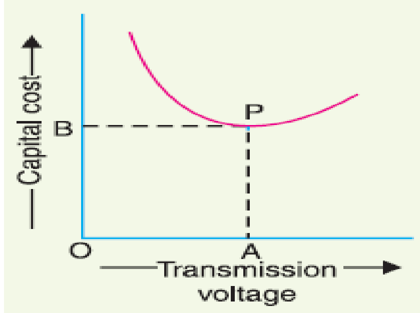
(iv) Insulation and supports, this cost increases sharply with the increase in transmission voltage

(v) Conductor, the cost decreases with the increase in transmission voltage.

The sum of all the above cost gives the total cost of transmission for the voltage considered. Similar are made for other transmission voltages. Then, a curve is drawn for total cost of transmission against voltage as shown in Fig 3.22. The lowest point (p) on the curve gives the economical transmission voltage.

In this case OA is the optimum transmission voltage. This method is rarely used as different cost cannot be determined with a fair degree of accuracy in practice for economic transmission of voltage.

Fig. 3.22



The trend is to follow certain empirical formulae according to American practice for finding the economic transmission voltage between lines in a 3-phase a.c. system and this is,

$$V = 5.5\sqrt{0.62l + \frac{3P}{150}}$$

Where, V = line voltage in kV

P = maximum kW per phase to be delivered to single circuit

l = distance of transmission line in km

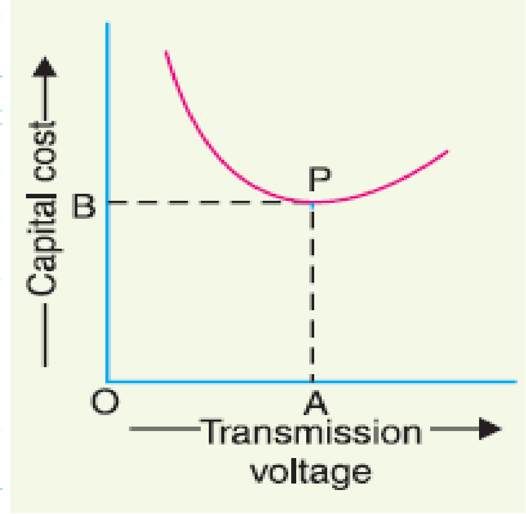


Fig. 3.22

In the above expression, **power to be transmitted** and distance of **transmission line** have been taken into account. This is because both factor influence the economic voltage of a transmission line. The explanation being that "if the distance of transmission line is increased, the cost of terminal apparatus is decreased, resulting in higher economic transmission voltage".

Also if the power to be transmitted is large, large generating and transforming units can be employed which reduces the cost per kW of the terminal station equipment.

Requirement of Satisfactory Electric Supply

The electric power system of Malaysia is 3-phase a.c. operating at a frequency of 50Hz. Power is delivered to consumers through transmission and distribution networks. The system is characterized by **constant** or **nearly constant voltage**, **dependability of service**, **balanced voltage**, **efficiency** so as to give minimum annual cost, sinusoidal waveform and freedom from inductive interference with telephone lines.

(i) Voltage regulation: A voltage that is too high or too low will result in a decrease in efficiency. If the fluctuations in the voltage are sudden it might cause tripping of circuit breakers and consequent interruptions to service so necessary voltage regulation measures are required to keep voltage variations sufficiently low.

(ii) Dependability: The cost of failure of electric power supply to industries, hospitals, crowded theatres and general consumer is huge , therefore, it is the duty of electric supply company to keep the power system going and to furnish uninterrupted service.

(iii) Balanced voltage: It is important that polyphase voltage are balanced so as the ensure the smooth operation of equipment and machinery. When terminal voltages are unbalanced three-phase devices are liable to considerable damage due to overheating.

(iv) Efficiency: The important economic feature of the transmission system design is that the layout of the system as a whole should be such as to perform the requisite function of generating and delivering power with a minimum overall annual cost. Measures are expected to be taken to ensure the efficiency of the system

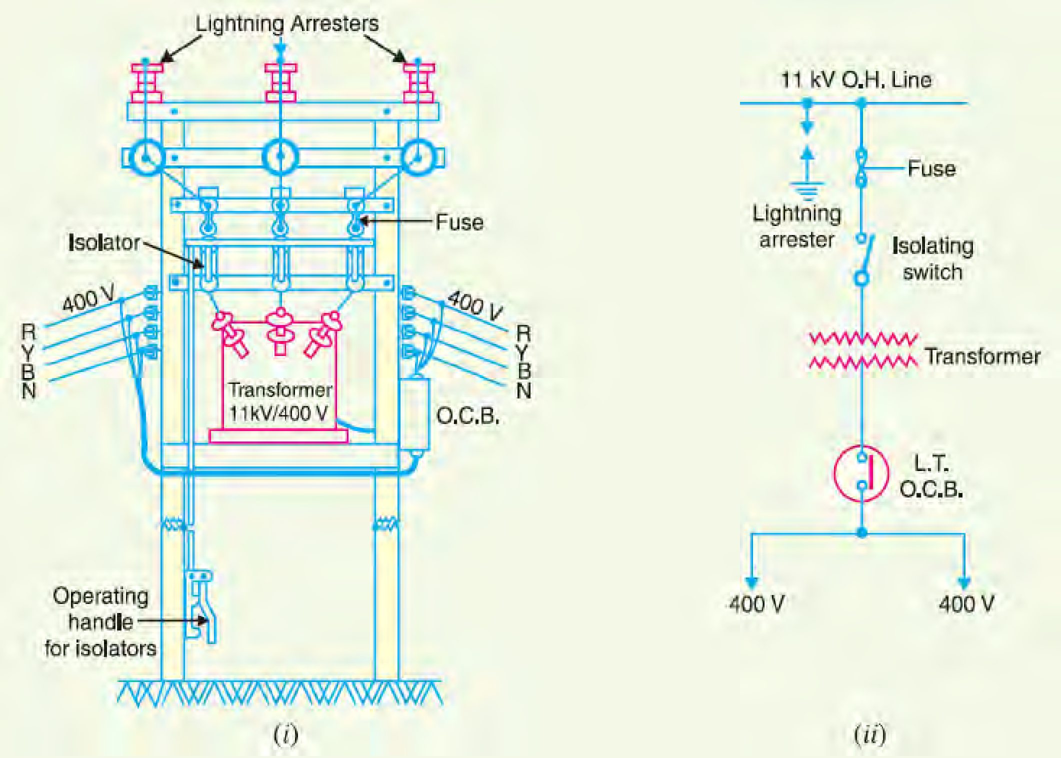
(v) Frequency: The frequency of the supply must be maintained constant. A change in frequency would cause the malfunction of equipment and devices.

(vi) Sinusoidal waveform: The supply to the consumers should have a sine waveform. Harmonics would have detrimental effect upon the efficiency and maximum power output of the connected equipment. Measures have to be taken to avoid harmonics by using appropriate practices.

(vii) Freedom from inductive interference: Power lines running parallel to telephone lines produce electrostatic and electromagnetic field disturbances which causes objectionable noise and hums in the apparatus connected to communication circuits. There are approved practices to avoid interference of power lines with communication devices.

SUBSTATION LAYOUT.

Substations are the points in the power network where transmission lines and distribution feeders are connected together through circuit breakers or switches via bus-bars and transformers. This allows for the control of power flows in the network and general switching operations for maintenance purposes.



Substation Design Considerations

(i) **Security of supply -** In an ideal situation all circuits and substation equipment would be duplicated such that following a fault or during maintenance a connection remains available. This would involve very high cost. Methods have therefore been adopted to achieve a compromise between complete security of supply and capital investment. A measure of circuit duplication is adopted whilst recognizing that duplication may itself reduce the security of supply by, for example, providing additional leakage paths to earth. Security of supply may therefore be considered in terms of the effect of this loss of plant arising from fault conditions or from outages due to maintenance. There are various established standard for substation design like the British Code of Practice for the Design of High Voltage Open Terminal substation (BS 7354).

(ii) Extendibility

The design should allow for future extendibility. Adding bays of switchgear to a substation is normally possible and care must be taken to minimize the outages and outage durations for construction and commissioning. Where future extension is likely to involve major changes (such as from a single to double busbar arrangement) then it is best to install the final arrangement at the outset because of the disruption involved. **When minor changes such as the addition of overhead line or cable feeder bays are required then busbar disconnectors may be installed at the outset (known as 'skeleton bays') thereby minimizing outage disruption.**

(iii) Maintainability

The design must take into account the electricity supply company system planning and operations procedures together with a knowledge of reliability and maintenance requirements for the proposed substation equipment. The need for circuit breaker disconnector bypass facilities may therefore be obviated by an understanding of the relative short maintenance periods for modern switchgear.

Portable earthing points and earthing switch/interlock requirements will also need careful consideration. **In a similar way the layout must allow easy access for winching gear, mobile cranes or other lifting devices if maintenance downtimes are to be kept to a minimum**. Similarly standard minimum clearances must be maintained for safe working access to equipment adjacent to operational live switchgear circuits or switchgear bays, bearing in mind that some safety authorities now resist the use of ladder working and require access from mobile elevated working platforms or scaffolding.

(iv) Operational flexibility

The physical layout of individual circuits and groups of circuits must permit the required power flow control. In a two transformer substation operation of either or both transformers on one infeed together with the facility to take out of service and restore to service either transformer without loss of supply would be a normal design consideration. In general a multiple busbar arrangement will provide greater flexibility than a ring busbar.

(v) Protection arrangements

The design must allow for the protection of each system element by provision of suitable CT locations to ensure overlapping of protection zones. The number of circuit breakers that require to be tripped following a fault, the auto-reclose arrangements, the type of protection and extent and type of mechanical or electrical interlocking must be considered.

E.g. a 1½ breaker substation layout produces a good utilization of switchgear per circuit but also involves complex protection and interlocking design which all needs to be engineered and thus increases the capital cost.

(vi) Short circuit limitations

In order to keep fault levels down parallel connections (transformers or power sources feeding the substation) should be avoided. Multi-busbar arrangements with sectioning facilities allow the system to be split or connected through a fault limiting reactor. It is also possible to split a system using circuit breakers in a mesh or ring type substation layout although this requires careful planning and operational procedures.

(vii) Land area

The cost of purchasing a plot of land in a densely populated area is considerable. Therefore there is a trend towards compact substation design.

This is made possible by the use of indoor gas insulated switchgear (GIS) substation designs or by using such configurations as the transformer-feeder substation layout. In addition compact design reduces civil work activities (site preparation, building costs, requirements for concrete cable trenches, surfacing and access roads).

Long multicore control cable runs and switchyard earth grid requirements are also reduced. The reduction in site work by using compact layouts and in particular by using modular elements results in an overall shorter substation project design and construction duration to the advantage of the client.

(viii) Cost

A satisfactory cost comparison between different substation layout designs is extremely difficult because of the differences in performance and maintainability.

It is preferable to base a decision for a particular layout on technical grounds and then to determine the most economical means of achieving these technical requirements.

ALTERNATIVE LAYOUTS

1. Single busbar

The single busbar arrangement is simple to operate, places minimum reliance on signalling for satisfactory operation of protection and facilitates the economical

addition of future feeder bays. It has the following features.

i) Each circuit is protected by its own circuit breaker and hence plant outage does not necessarily result in loss of supply.

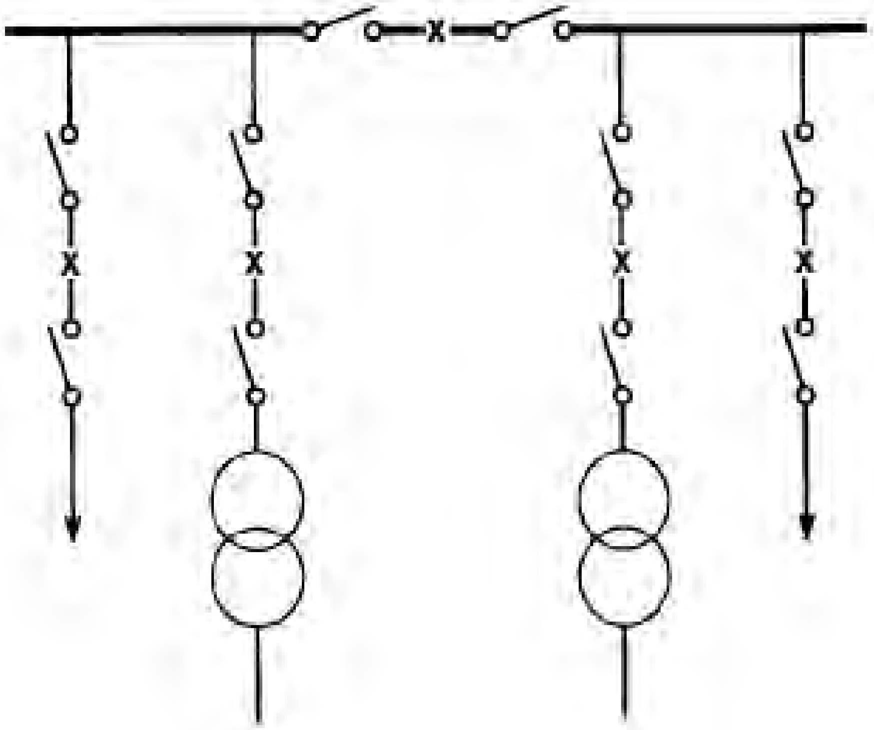
ii) A feeder fault or transformer circuit breaker causes loss of the transformer and feeder circuit one of which may be restored after isolating the faulty circuit breaker.

iii) A fault on a bus section circuit breaker causes complete shutdown of the substation. All circuits may be restored after isolating the faulty circuit breaker and the substation will be ‘split’ under these conditions.

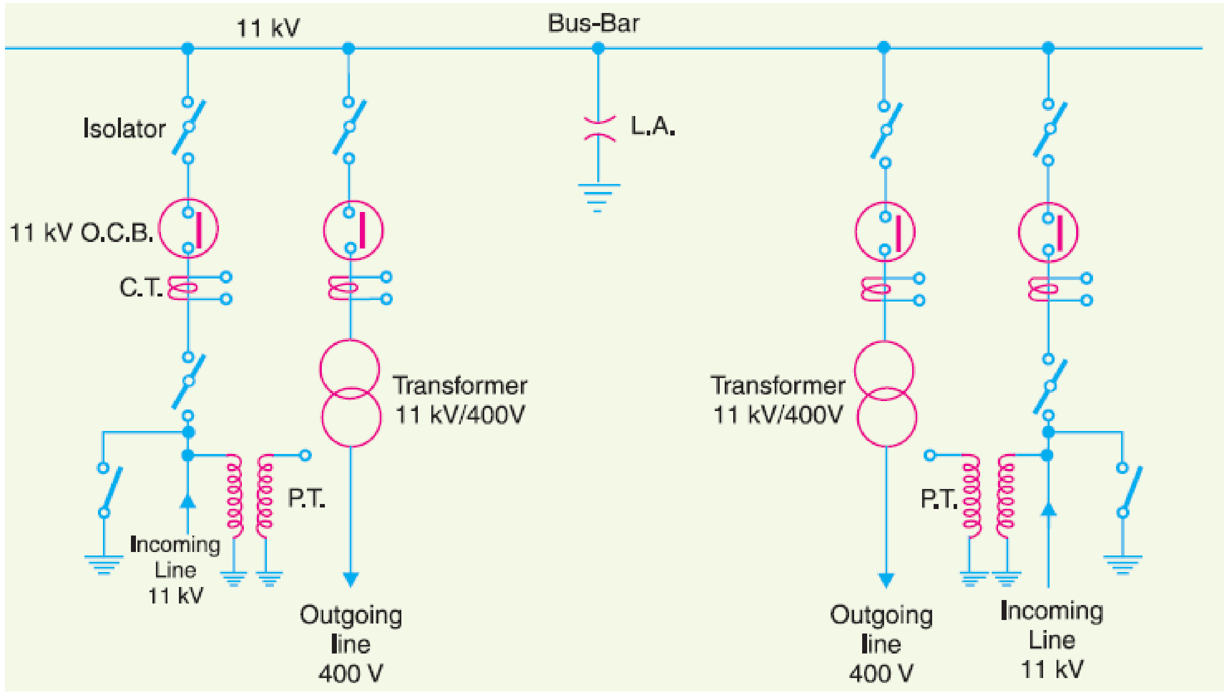
iv) A busbar fault causes loss of one transformer and one feeder. Maintenance of one busbar section or disconnector will cause the temporary outage of two circuits.

v) Maintenance of a feeder or transformer circuit breaker involves loss of that circuit.

vi) The introduction of bypass isolators between the busbar and circuit isolator allows circuit breaker maintenance facilities without loss of the circuit.

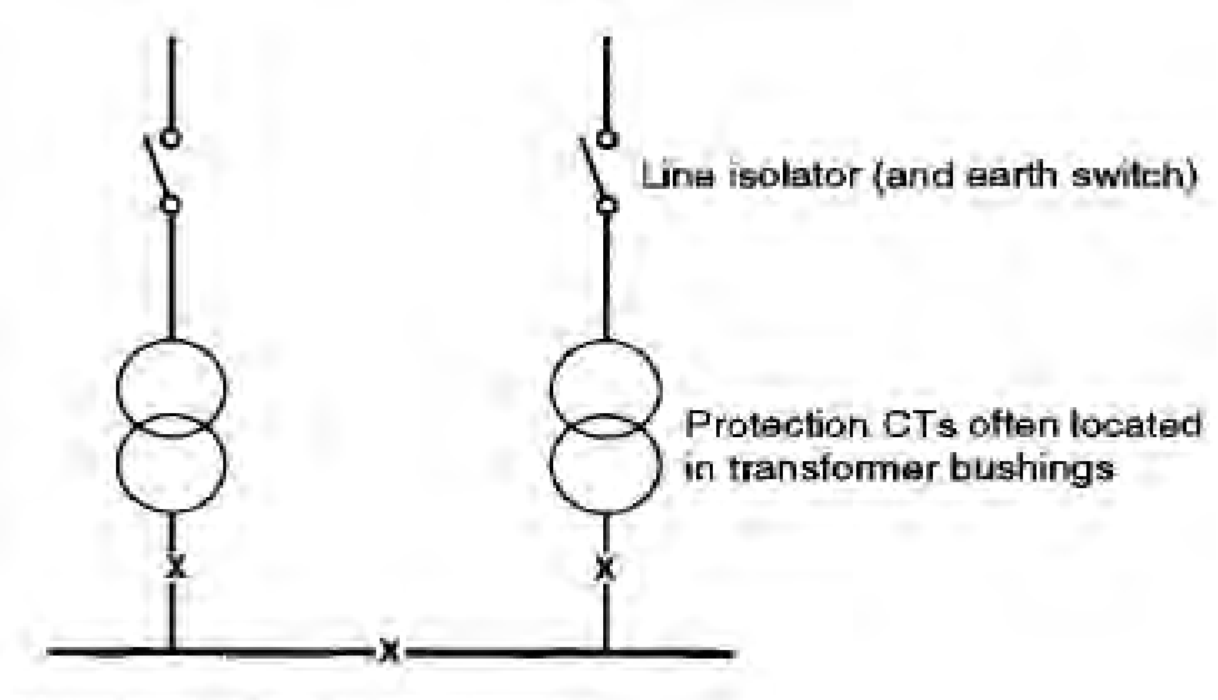


Five circuit breaker single busbar arrangement



2. Transformer feeder

The transformer-feeder substation arrangement offers savings in land area together with less switchgear, small DC battery requirements, less control and relay equipment, less initial civil works together with reduced maintenance and spares holding in comparison with the single busbar arrangement.



Transformer-feeder arrangement

3. Mesh

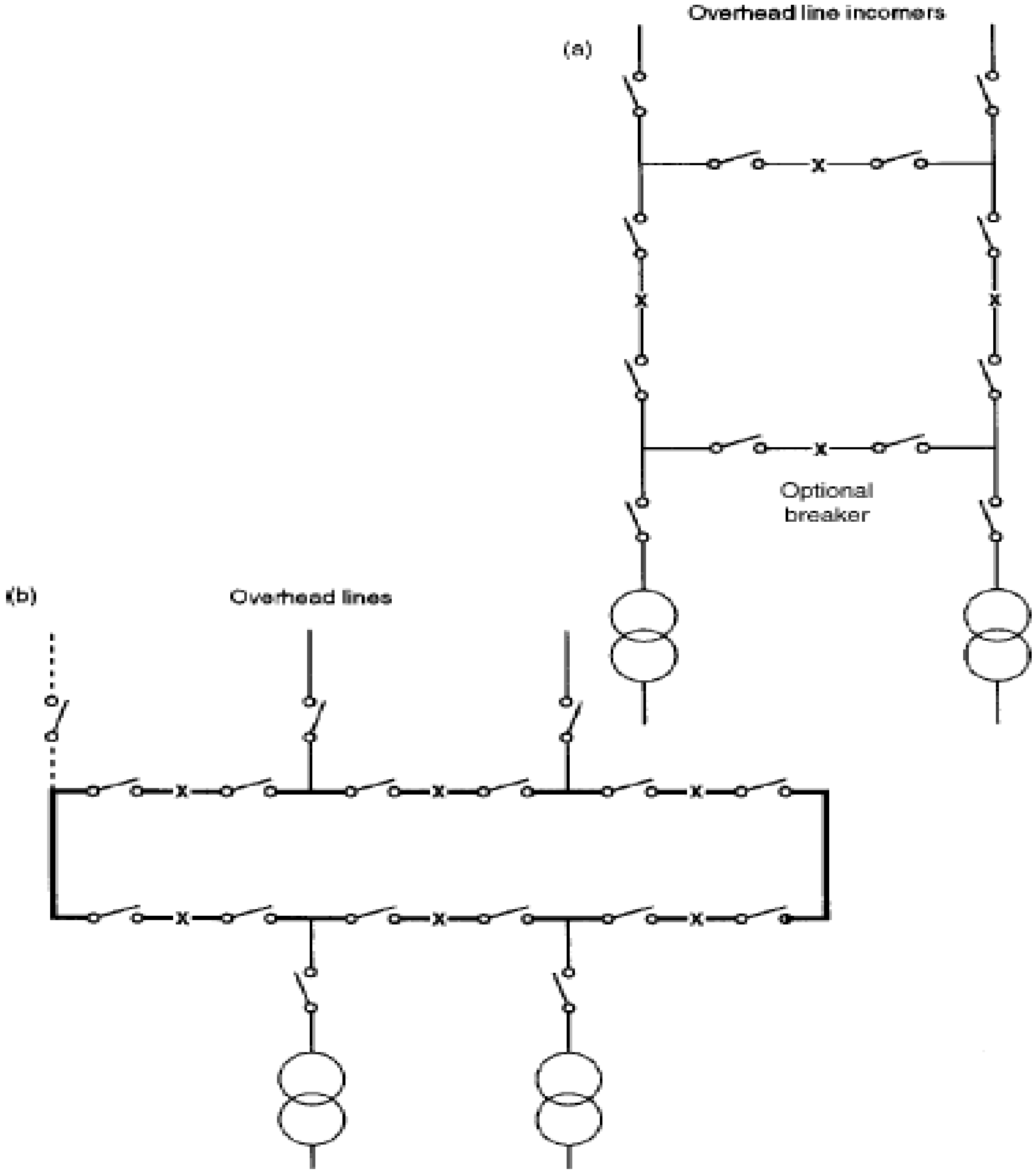
The scheme offers better features and facilities than the single busbar without a bus section switch:

i). Any circuit breaker may be maintained at any time without disconnecting that circuit. Full protection discrimination will be lost during such maintenance operations. In order to allow for all operating and maintenance conditions all busbars, circuit breakers and disconnectors must be capable of carrying the combined loads of both transformers and line circuit power transfers.

ii). Normal operation is with the bypass disconnectors or optional circuit breaker open so that both transformers are not disconnected for a single transformer fault.

iii). A fault on one transformer circuit disconnects that transformer circuit without affecting the healthy transformer circuit.

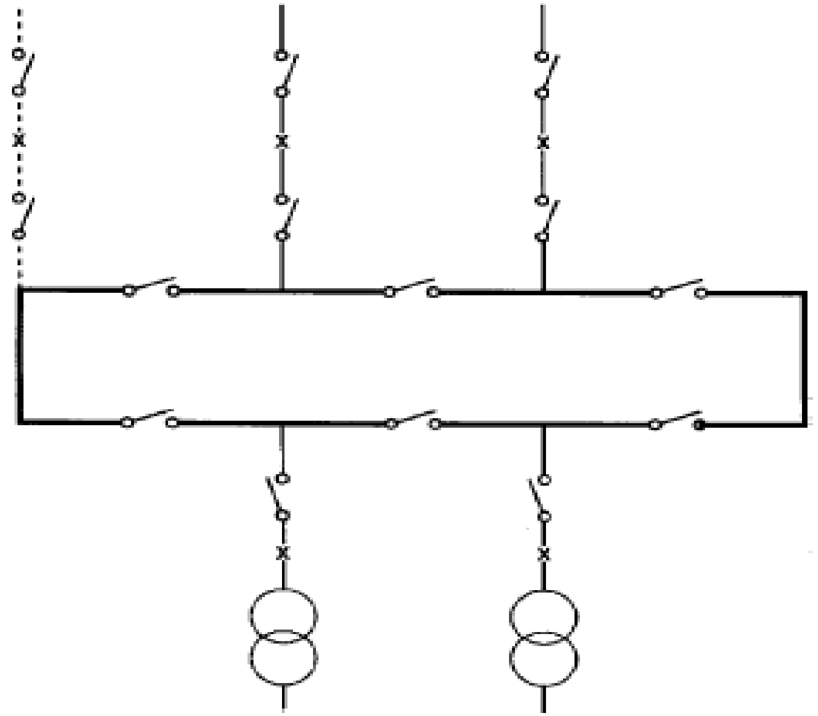
iv). A fault on the bus section circuit breaker causes complete substation shutdown until isolated and power restored.



(a) Three switch mesh. (b) Full mesh

4. Ring

The ring busbar offers increased security compared to the single busbar arrangement since alternative power flow routes around the ring busbar are available. The ring is not so secure as the mesh arrangement as a busbar fault causes all circuits to be lost until the fault has been isolated using the ring busbar isolators. Unless busbar disconnectors are duplicated maintenance on a disconnector requires an outage of both adjacent circuits. The inability of disconnectors to break load current is also an operational disadvantage.



Ring Busbar

5. Double busbar

Transfer bus - The double busbar arrangement is probably the most popular open terminal outdoor substation arrangement throughout the world. It has the flexibility to allow the grouping of circuits onto separate busbars with facilities for transfer from one busbar to another for maintenance or operational reasons

i). This is essentially a single busbar arrangement with bypass disconnector facilities. When circuit breakers are under maintenance the protection is arranged to trip the bus-coupler breaker.

ii). The system is considered to offer less flexibility than the full duplicate

double busbar arrangement

Duplicate bus

i). Each circuit may be connected to either busbar using the busbar selector disconnectors. On-load busbar election may be made using the bus-coupler circuit breaker.

ii). Motorized busbar selector disconnectors may be used to reduce the time to reconfigure the circuit arrangements.

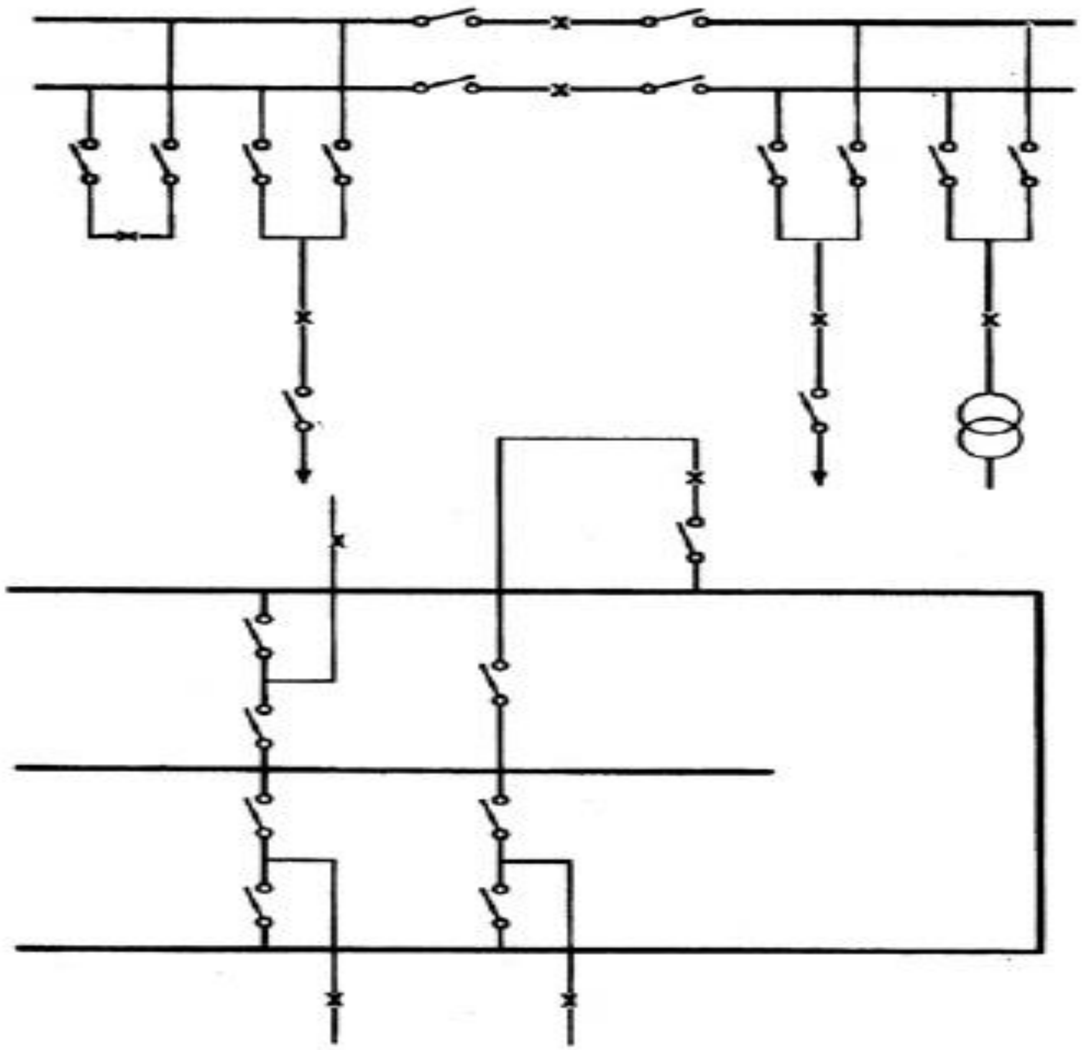
iii). Busbar and busbar disconnector maintenance may be carried out without loss of supply to more than one circuit.

iv). The use of circuit breaker bypass isolator facilities is not considered to offer substantial benefits since modern circuit breaker maintenance times are short and in highly interconnected systems alternative feeder arrangements

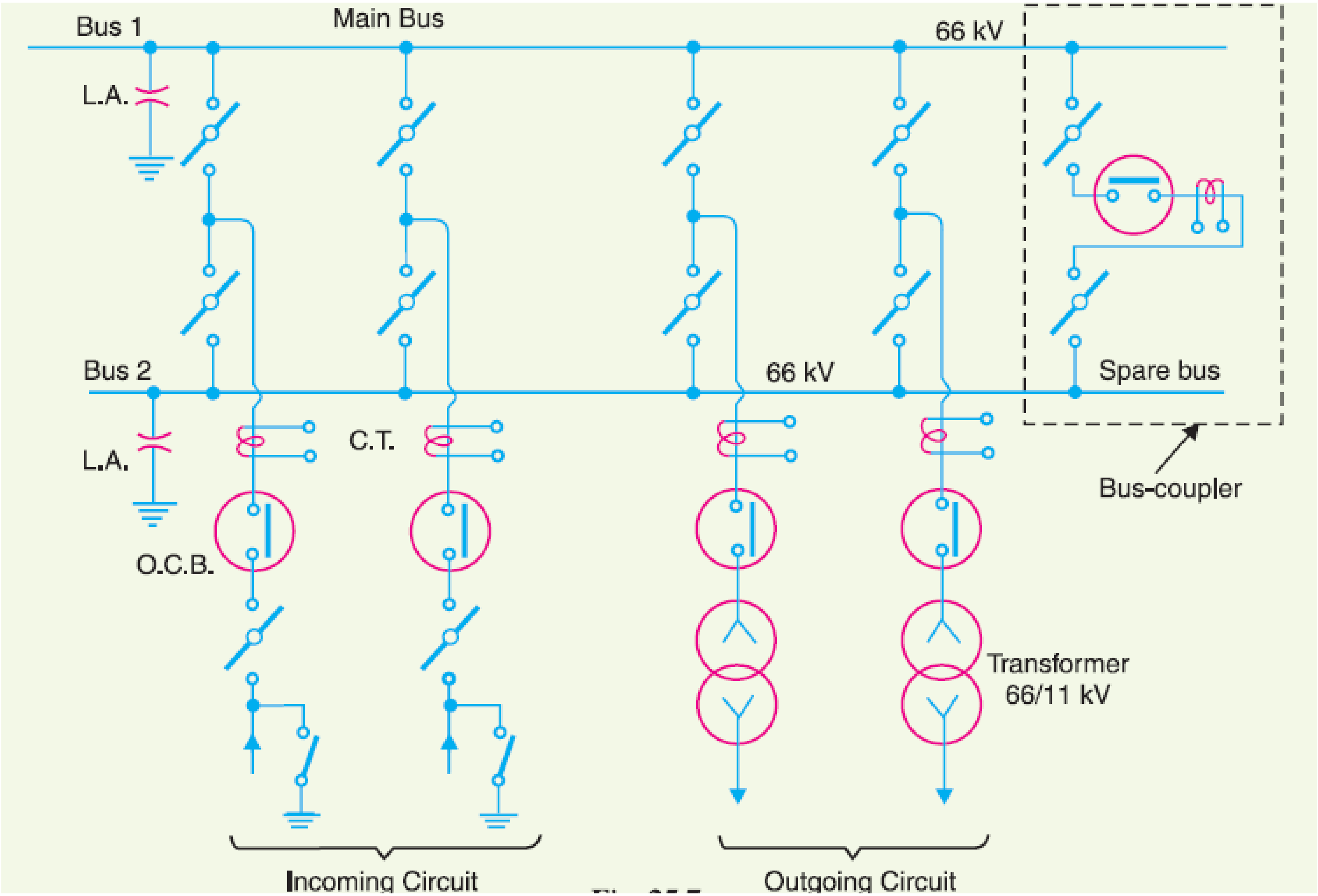
are normally possible.

v). A variant on the scheme uses a ‘wrap around’ busbar layout arrangement

in order to reduce the length of the substation.



Duplicate bus



Duplicate bus

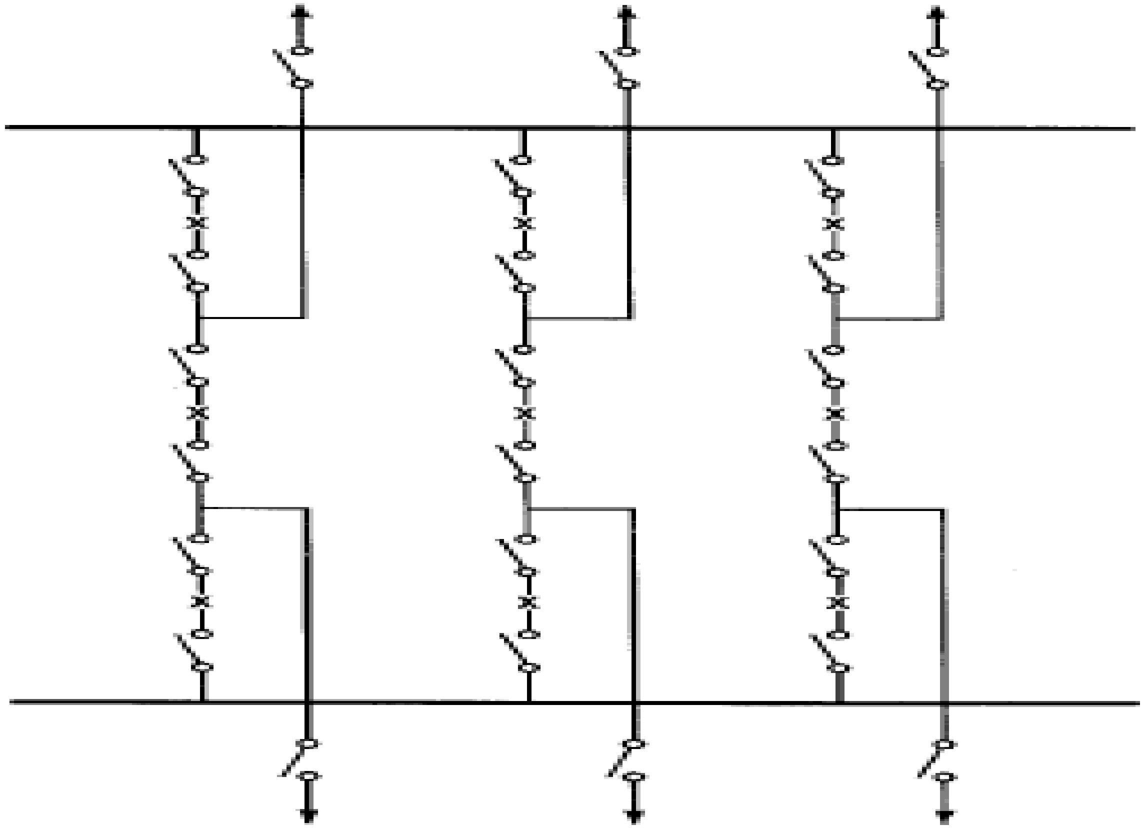
6. 1½ Circuit breaker

The arrangement is shown in Figure below. It offers the circuit breaker bypass facilities and security of the mesh arrangement coupled with some of the flexibility of the double busbar scheme. The layout is used at important high voltage substations and large generating substations where the cost can be offset against high reliability requirements. Essentially the scheme requires 1½ circuit breakers per connected transmission line or transformer circuit and hence the name of this configuration:

1. Additional costs of circuit breakers are involved together with complex protection arrangements.

2. It is possible to operate with any one pair of circuits, or group of pairs of circuits separated from the remaining circuits. The circuit breakers and other system components must be rated for the sum of the load currents of two circuits.

3. High security against loss of supply.



$1^{1/2}$ Circuit breaker

SPACE REQUIREMENTS

Having selected the required substation single line diagram arrangement it is then necessary to convert this into a practical physical layout. It is essential to allow sufficient separation or clearances between substation equipment to withstand voltage stresses and to allow safe operation and maintenance of the equipment. The designer will have to consider the following.

Actual site selection. The substation configuration and number of circuits involved (including any allowance for future expansion) will largely determine the land area requirements.

The ideal site will have the following characteristics:

1. Reasonably level and well drained so minimum surface dressing and civil ground works are required.

2. Low lying and not in a prominent position so that planning permission will be relatively easy to obtain.

3. Good access from public highways for easy transportation of materials and especially heavy items such as transformers to the site.

4. Good overhead line way leave substation entry routes.

5. Pollution-free environment.

High or low level, catenary or solid, busbar arrangements. A high busbar is exposed and must span complete switchgear bays. Low busbars are more shielded, may be more suitable for connection of portable earths but may need frequent supports. They may be considered to be more visually or environmentally acceptable

Space savings are also possible from the use of different types of switchgear, for example by using pantograph instead of horizontal swivel isolators.

Safety clearances

The safety distance means the minimum distance to be maintained in air between the live part of the equipment or conductor on the one hand and the earth or another piece of equipment or conductor on which it is necessary to carry out work on the other.

A basic value relates to the voltage impulse withstand for the substation. To this must be added a value for movements for *all* methods necessary to maintain and operate the equipment so that a safety zone may be determined. Note safety clearance must also be allowed to any necessary working platforms.

Phase–phase and phase–earth clearances

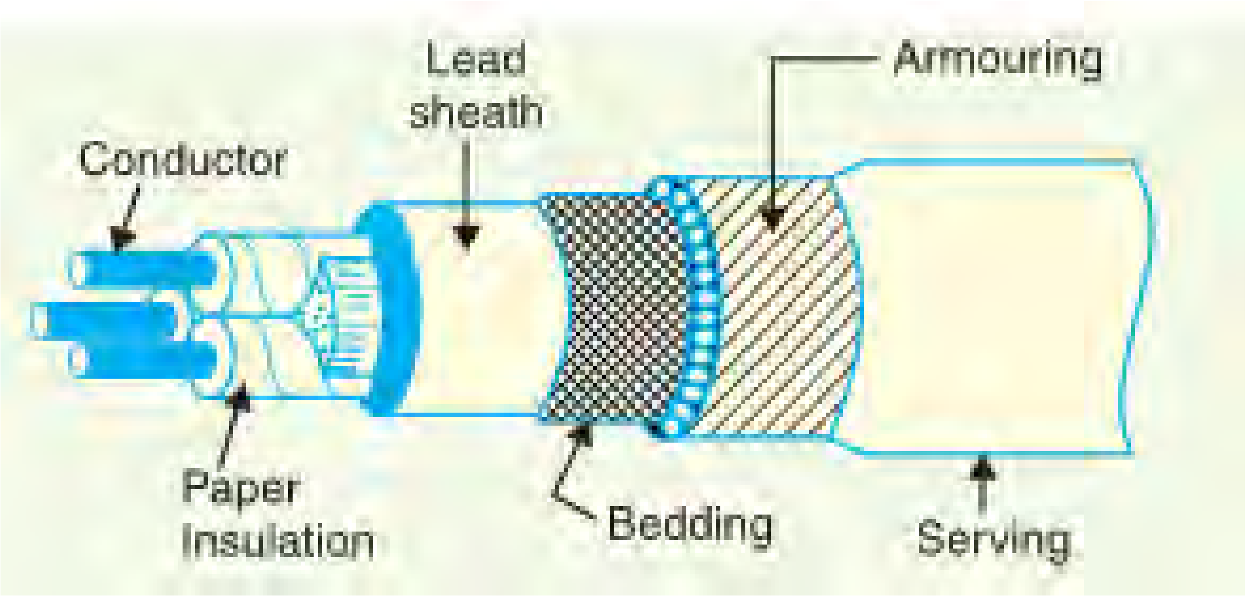
IEC 60071 deals with insulation co-ordination and proposes standard insulation levels and minimum air distances. BS7354 also specifies phase–phase and phase–earth clearances. Phase–phase clearances and isolating distances are usually specified as 10–15% greater than phase–earth clearances. The justification is that phase–phase faults or faults between equipment terminals usually have more serious consequences than phase–earth faults. It should be noted that the configuration of conductors and adjacent earthed structures and equipment also affects these clearances. Therefore care must be taken when applying these criteria. For example, the clearance required from an open contact on a disconnector to an adjacent structure will be greater than that from a continuous busbar to ground level in order to achieve the same insulation level.

Once the various minimum allowable phase–phase and phase–earth clearances have been chosen it is necessary to ensure that the design maintains these at all times. Allowance must be made for movement of conductors in the wind and temperature sag effects. Under short circuit conditions flexible phase conductors may first repel each other (reducing clearances to adjacent equipment) and then swing together (reducing phase–phase clearances). The coincidence of an overvoltage on one phase with an overvoltage or peak value of system voltage of opposite polarity on an adjacent phase can produce an increase in voltage between phases. The 10–15% margin in phase–phase clearances allows for a degree of protection against this occurrence. At high altitudes the reduced air density lowers the flashover voltage and clearances should be increased by approximately 3% for each 305 m (1000 ft) in excess of 1006 m (3300 ft) above sea level. Allowances must also be made for variations in the level of the substation site and the positioning of foundations, structures and buildings. At lower voltages an additional margin may be added to avoid flashovers from birds or vermin. A common mistake is not to take into account the substation perimeter fence and thereby infringe phase–earth clearances.

CABLES SELECTION CODES AND STANDARDS

The selection of cables for particular applications is best done with reference to the latest and specific manufacturer’s cable data and application guides. E.g. IEC 60183 used to designate appropriate cable voltage ratings.

The selection of cables with the appropriate voltage rating for a particular application is dependent upon the system voltage and earthing category.



The categories are defined as follows:

- **Category A** – A system in which, if any phase conductor comes in contact with earth or an earth conductor, it is automatically disconnected from the system.

- **Category B** – A system which, under fault conditions, is operated for a short time with one phase earthed. These conditions must not exceed 8 hours on any occasion with a total duration, during any 12 month period, not exceeding 125 hours.
- **Category C** – A system which does not fall into categories A and B.

General design criteria for cables

The following factors govern the design of power cables:

1. The cross-sectional area of the conductors chosen should be of the optimum size to carry the specified load current or short circuit short term current without overheating and should be within the required limits for voltage drop.

2. The insulation applied to the cable must be adequate for continuous operation at the specified working voltage with a high degree of thermal stability, safety and reliability.
3. All materials used in the construction must be carefully selected in order to ensure a high level of chemical and physical stability throughout the life of the cable in the selected environment.
4. The cable must be mechanically strong, and sufficiently flexible to withstand the re-drumming operations in the manufacturer’s works, handling during transport or when the cable is installed by direct burial, in trenches, pulled into ducts or laid on cable racks.
5. Adequate external mechanical and/or chemical protection must be applied to the insulation and metal or outer sheathing to enable it to withstand the required environmental service conditions.

Types of cables

Cables are mostly specified by describing the materials and their properties from the phase conductors to the outer covering. Manufacturers will provide a drawing showing a cross-section through the cable and the relevant technical parameters and guarantees associated with the design. Check a typical specification sheet, 19 000/33 000 XLPE power cable.

Cable construction

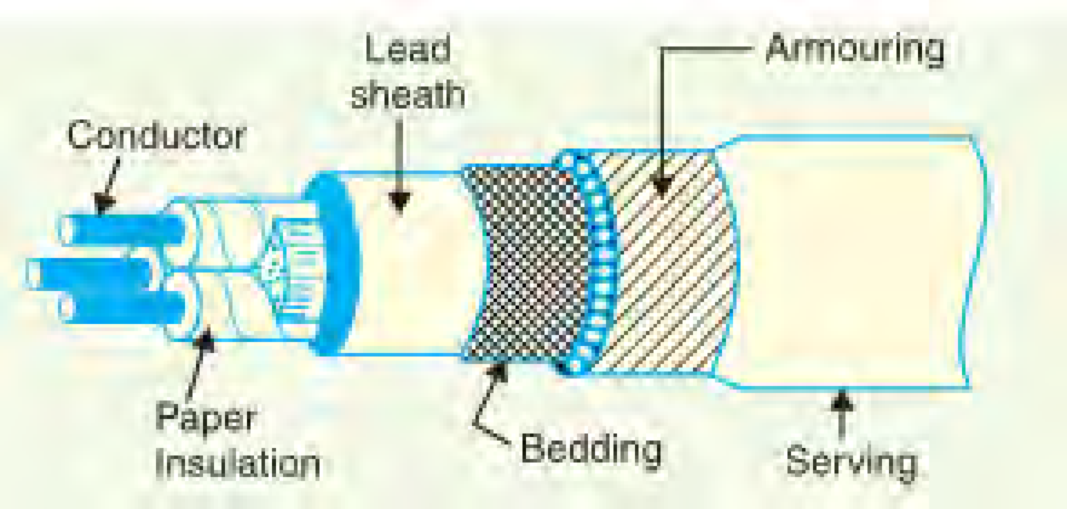
1. *Conductor materials* - Copper is still the predominant conductor material in stranded, shaped, segmental sectorial and milliken formats. Solid or stranded, shaped or segmental aluminium is also often specified on the basis of cost in the manufacturer’s country at the time of tender. Aluminium is also lighter and assists with ease of handling large cables. Additional care has to be taken when jointing aluminium cables. It is necessary to ensure that the contact surfaces are free from oxide and that when connecting to copper or brass terminals no corrosion cell is formed.

2. Insulation – There are a number of different insulator which are used to insulate the conductor. Mainly the type of insulator to be used for a particular conductor depends on a number of factor among which are; the current carrying capacity of the conductor, size of conductor, environmental factor, area of conductor application and so on. The most popular types are;

i). Paper Insulated cables

ii). Polypropylene Paper Laminate (PPL) cables

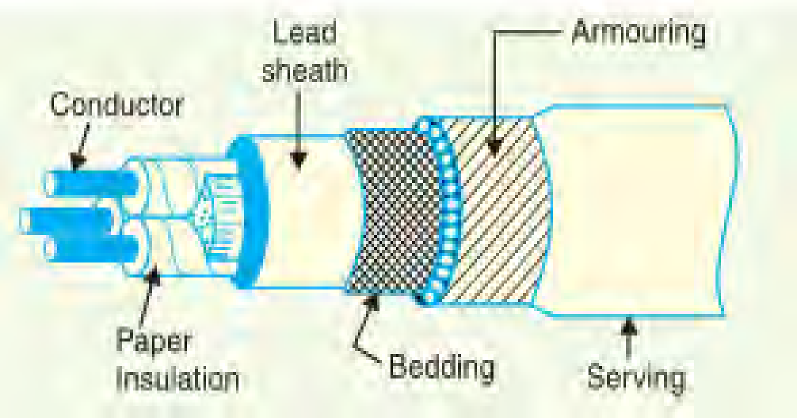
iii.) Polyvinyl Chloride (PVC) insulated cable



iv). Cross-Linked Polyethylene (XLPE) insulated cable

v). Ethylene propylene rubber Insulated (EPR) cables

vi). Mineral insulated copper conductor (MICC) cables



3. Sheaths - Lead and lead alloy sheaths are used to prevent the ingress of moisture into paper-insulated cables or other cables installed in particularly marshy conditions. Lead corrosion and fatigue resistance properties are important and improvements are obtained by the addition of other elements.

4. Insulation levels and screening - The correct selection of appropriate cable voltage designation depends upon the type of network and network earthing arrangements. Generally, if the network is solidly earthed the voltage will not rise above the maximum system phase-to-neutral voltage under fault conditions. However, if under fault conditions the earthing arrangement is such as to allow the voltage to neutral to rise to the line voltage then the cable insulation must be specified accordingly. To minimize the possibility of discharges at the inner surfaces of cable core dielectric a grading screen is introduced. This screen comprises of one or two layers of semiconducting tapes or compounds over the core insulation.

5. Armouring - In order to protect cables from mechanical damage such as pick or spade blows, ground subsidence or excessive vibrations cable armouring is employed. Galvanized steel wire armour (SWA) is preferred since it gives a more flexible construction, is easy to gland and gives better performance where the cable may be subjected to longitudinal stresses in service. In addition, the overall cross-sectional area of steel wire armour tends to be greater than that for the equivalent steel tape armour mechanical protection and therefore SWA presents a lower impedance if the armour is used as the earth return conductor. If armouring is required on single core cables aluminium should be used instead of steel wire in order to avoid losses.

6. Finish - One of the most important factors that can affect cable life is the degree of protection afforded by the cable finish against the harmful effects of chemical corrosion, electrolytic action, insect or rodent attack and mechanical damage.

Submarine cables

Submarine cables require additional tensile strength to permit laying on or under the sea or river bed under high tension conditions. Paper, PVC or XLPE insulation is used together with additional protection measures against water ingress and mechanical damage and with special sheath compositions to repel worm attack. Such cables are manufactured in the longest possible lengths in order to minimize the number of underwater cable joints. **When preparing the design for submarine cables an accurate knowledge of the prevailing currents and tidal variations is essential to assist in deciding the best cable route and most favourable times for the cable laying work.**

Joints and terminations

Important factors in the design of cable joints and terminations include:

- safe separation between phases and between phase and earth;
- capability to avoid dielectric breakdown at the interface and around reinstated jointing insulation under normal load and impulse surge conditions;
- adequate stress control measures to avoid high fields around screen discontinuities and cable/joint interfaces

In all cases great care should be taken to ensure dry clean conditions during the jointing process.

Structures, Towers and Poles

Open-terminal substation(is one in which the line supplying to the substation terminates or ends)

equipment support structures are nowadays being fabricated more and more from aluminium

alloy angle rather than from galvanized steel.

The structures may be welded up and drilled to tight tolerances in the factory.

The prefabricated structures are light weight and may be transported directly to site.

Although there is an initial higher capital materials cost this is largely offset by not having to provide special corrosion protection finishes. In addition the aluminium alloy material has a low resistivity.

Therefore earth connections from the substation earth mat to the base of the support structures are normally sufficient.

Additional copper tapes to the ‘earthy ends’ of the insulator supports are not specifically required.

Wide range of applicable for selection of overhead line design standards are shown in the Table below.

Reference	Description
IEC 60383	Insulators for overhead lines with a nominal voltage above 1000 V
IEC 60471	Dimensions of clevis and tongue couplings on string insulator units
IEC 60720	Characteristics of line post insulators
IEC 60797	Residual strength of string insulator units of glass or ceramic material for overhead lines after mechanical damage to the Dielectric
IEC 60826	Design criteria for overhead transmission lines
IEC/TR 60828	Loading and strength of overhead transmission lines
IEC/TR 61774	Meteorological data for assessing climatic loads for overhead Lines
EN 12465	Wood poles for overhead lines – durability requirements
EN 12479	Wood poles for overhead lines – signs, methods of measurement and densities
EN12509	Timber poles for overhead lines – determination of modulus of elasticity, binding strength, density and moisture content.

Reference	Description
EN12510	Wood poles for overhead lines – strength grading criteria
EN12511	Wood poles for overhead lines – determination of characteristic Values
EN14229	Wood poles for overhead lines – requirements
EN 12843	Precast concrete masts and poles
EN 50341	Overhead electrical lines exceeding AC 45 k V. Part 3 covers all the different National Normative Aspects (NNAs
EN50423	Overhead lines AC 1 to 45 k V – based on 50341 but provides specific simplifications or/changes
Eurocode 1 – EN1991	Basis of design and actions on structures; 1991-1-3 covers snow loads; 1991-2-4 covers wind loads
Eurocode 2 – EN1992	Design of concrete structures – 1992-3 covers concrete Foundations
Eurocode 3 – EN1993	Design of steel structures
Eurocode 7 – EN1997	Geotechnical design
Eurocode 8 – EN1998	Design provision for earthquake resistance of structures
BS1990	Wood poles for overhead power and telecommunication lines
BS3288 – 2	Insulator and conductor fittings for overhead power lines –specification for a range of fittings. Other parts of this standard are superseded, or becoming so.

Reference	Description
BS7354	Code of practice for the design of high-voltage open-terminal Stations
BS8100	Lattice towers and masts. Part 1 is a Code of practice for loading; Part 2 is a guide to Part 1; Part 3 is a CoP for strength assessment of tower and mast members; Part 4 covers the loading of guyed masts.

ENVIRONMENTAL CONDITIONS

In order to match both the mechanical and electrical characteristics of the overhead line conductor to the environmental conditions and climatic details must first be collected and analysed. The typical parameters required are;

• Maximum ambient shade temperature	°C
• Minimum ambient shade temperature	°C
• Maximum daily average temperature	°C
• Maximum annual average temperature	°C
• Maximum wind velocity (3-second gust)	km/hr

Minimum wind velocity (for line rating purposes)	km/hr
Solar radiation	mW/sq m
Rainfall	m/annum
Maximum relative humidity	%
Average relative humidity	%
Altitude (for insulation level)	m
Ice (for loading conditions)	
Snow (for loading conditions)	
Atmospheric pollution	light, medium, heavy, very heavy
Soil type	clay, alluvial rock, etc.
Soil temperature at depth of cable laying	°C
Soil thermal resistivity	°C m/W
Soil resistivity	ohm-m

• Isokeraunic level	thunderstorm days or lightning flashes to ground per km^2
• Seismic factor	

Effect on tower or support design

Wind load **-** The wind load is related to the wind speed in accordance with the code of practice applicable to the country where the work is being carried out. For instance in the EU the relevant information is set out in the NNAs of EN50341 and 50423. It describes procedures for calculating wind loads on both structures and conductors, with considerable variation in detail between individual countries. Using the UK NNAs as an example the site reference wind speed, V_r is the mean hourly wind speed at a level 10m above the effective height of obstructions ‘appropriate to the site terrain 'and is given by:

The effective height of obstructions ‘appropriate to the site terrain‘ and is given by:

$V_r = \gamma_v K_d K_R V_B$

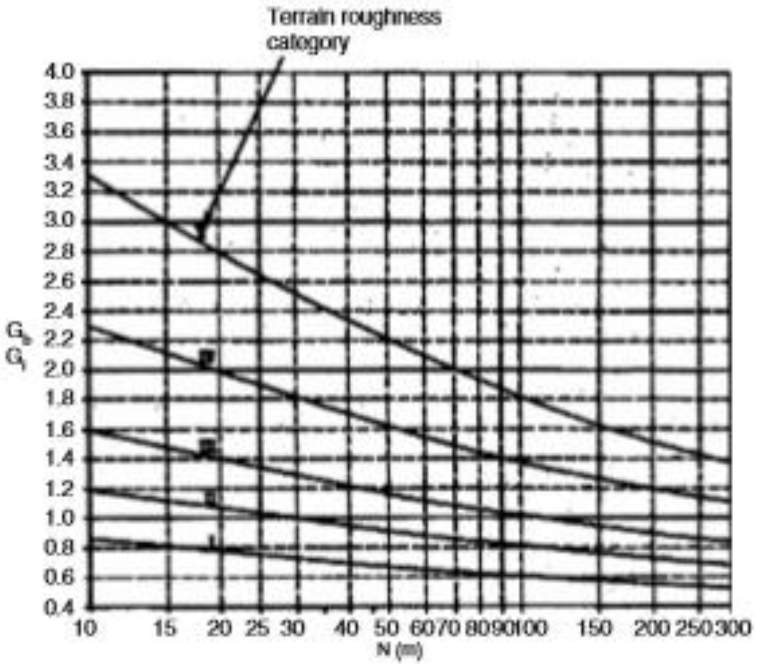
Where,

V_B(m/s) = Basic wind speed – obtainable from wind maps in BS8100 Part 1

K_d = Wind direction factor-Fig. 17.1

K_R = Terrain roughness factor-Table 17.2

γ_v = Partial safety factor on wind speed is1 for reliability level I (50 years)



The basic gust response for towers, G_b, Insulators and Fittings, G_I, is given by the maximum of G_x or G_y where

$$G_x = K_1 K_2 (3{,}976/K_R - 2{,}485)$$

$$K_1 = (1+\alpha/2)\,(10/H)^{\alpha}$$

$$K_2 = \{2/S_1 + 2/S_1^2\,(e^{-S1} - 1)\}^{0.5}$$

$$S_1 = (H/100{,}8)\,(10/H)^{\alpha}$$

$$G_y = K_3 K_4 K_5 (3{,}976/K_R - 2{,}485)$$

$$K_3 = (1+\alpha/2)\,(10/K_6)^{\alpha}$$

$$K_4 = \{2/S_2 + 2/S_2^2\,(e^{-S2} - 1)\}^{0.5}$$

$$K_5 = (K_6/H)^{\alpha}\,\{1-(1-K_6/H)^2\} / \{1-(1-K_6/H)^{\alpha+2}\}$$

$$S_2 = (K_6/100{,}8)\,(10/H)^{\alpha}$$

$$K_6 = H/10 \text{ but not less than } 10\text{m}$$

Figure 17.2 Basic gust response factor for towers (G_b) and insulators and fittings (G_i) (from BSEN 50341)

Table 17.2 **G_B terrain characteristics (from BSEN 50341-3-9)**

Category	*Terrain description*	*Terrain roughness factor* K_R	*Power law index of variation of wind speed with height* α	*Effective height* h_e *(m)*
I (Z_0 = 0.003 m)	Snow covered flat or rolling ground without obstructions; large flat areas of tarmac; flat coastal areas with off-sea wind	1.20	0.125	0
II (Z_0 = 0.01 m)	Flat grassland, parkland or bare soil, without hedges and with very few isolated obstructions	1.10	0.140	0
III (Z_0 = 0.03 m)	Basic open terrain, typical UK farmland, nearly flat or gently undulating countryside, fields with crops, fences or low hedges, isolated trees	1.00	0.165	0
IV (Z_0 = 0.10 m)	Farmland with frequent high hedges, occasional small farm structures, houses or trees	0.86	0.190	2
V (Z_0 = 0.30 m)	Dense woodland, domestic housing typically covering 10% to 20% of the plan area	0.72	0.230	10

Notes: 1. Z_0 is the terrain aerodynamic roughness parameter.
2. The lower (smoother) of any two possible categories should be adopted in case of doubt or where environs may change.
3. The terrain description should apply to environs extending several km upwind from the site.
4. Higher (rougher) categories that occur within only a few km upwind may not be sufficiently extensive to develop an 'equilibrium wind profile' and should generally be ignored.
5. In urban areas (Z_0 = 0.8 m) where towers rise above the general level of surrounding buildings, category V should be used. Specialist advice should be sought where adjacent high buildings could affect design.

The variation of wind speed with height for sites in level terrain is given by

$V_z = V_r(\{z - h_e\}/10)^{\alpha}$ for $z \geq 10 + h_e$ or $(V_r/2)(1+ z)/(10 + h_e)$ for $z < h_e$

where, V_z = Mean wind speed at height z in metres above ground level

α = Power law index of speed with height -Table 17.2

h_e = Effective height of surface obstructions -Table 17.2

The dynamic pressure q_z at height z shall be taken as:

$q_z = (\rho_a/2)Vz^2$

where ρ_a = The density of air, taken as 1.22 kg/m^3 for UK

It is considered good practice to apply a gust factor at this stage, to derive the ‘gust wind pressure’ $q_{z'}$, where: $q_z' = q_z(1 + K_{com} G_b)$

K_{com} = a combination factor to take account of the improbability of maximum gust loading on both conductors and towers occurring simultaneously. It may be conservatively taken as 1.0

G_b = the basic gust factor for the support, depending on the height of the support.-Fig. 17.2

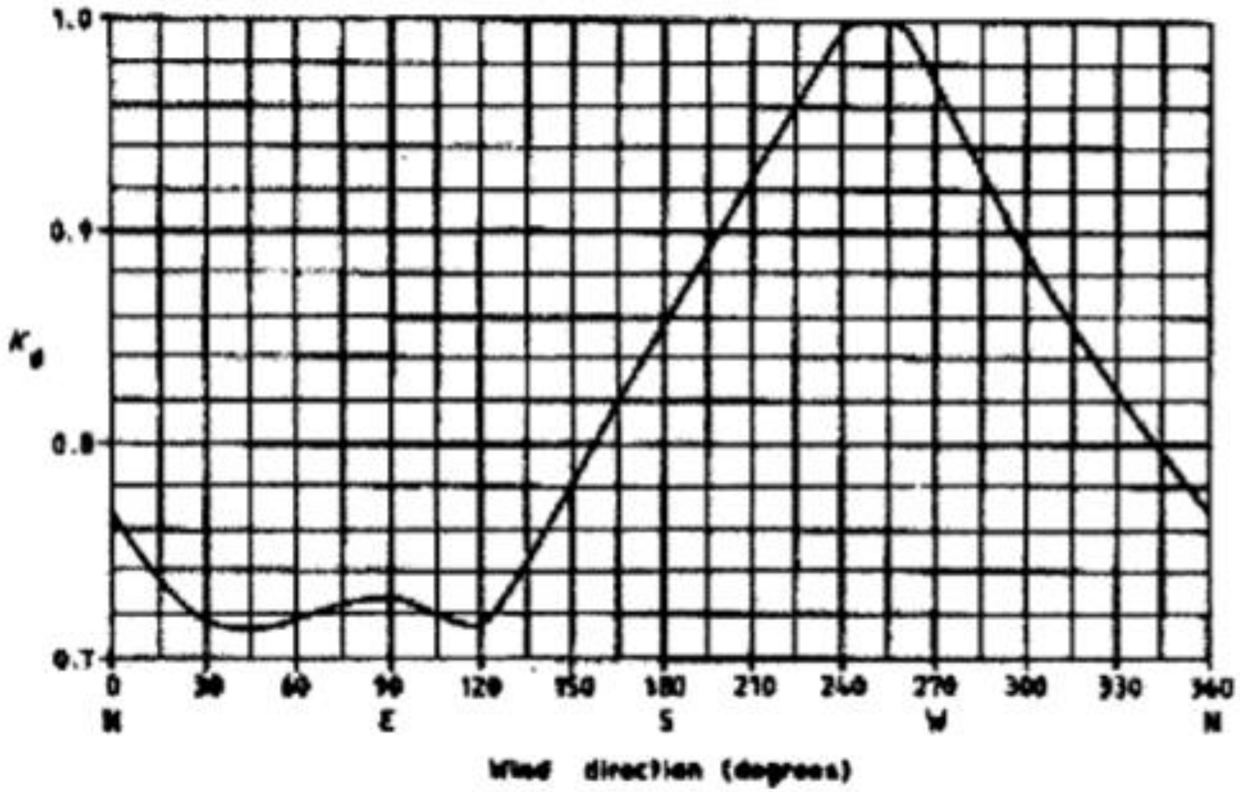


Figure 17.1 G_b Wind direction factor (from EN50341)

In planning the sag, tension and clearance of a given span, a maximum stress is selected.

It is then aimed to have this stress developed at the worst probable weather conditions.

Wind loading increases the sag in the direction of resultant loading but decreases the vertical component.

Conductor tensions - The starting point for all conductor sag/tension calculations is the clear definition of the bases and conditions upon which the minimum factor of safety at which the conductor is allowed to operate are set. The following are typical requirements with values given for UK conditions in respect of transmission lines:

Maximum working tension (MWT) - Conductor tension shall not exceed 50% of its breaking load (factor of safety of 2) at, say,

Temperature	- 6°C
Cross wind pressure	383 N/m^2
Radial ice thickness	12.7mm

Everyday stress (EDS) - Conductor tension shall not exceed 20% of its breaking load at, say,

Temperature	16°C
Cross wind pressure	–
Radial ice thickness	–

Normally either MWT or EDS will be the critical basis for calculations and the other condition will then automatically be met. Often there is a particular span length above which the one basis is critical and below which the other one is.

The tension, *T*, in the conductor for a given sag, *S*, is given by the formula:

$$T = \frac{W.g.L^2}{8S} N$$

Where W = weight of conductor per unit length (kg/m)

L = span of the conductor (m)

g = gravitational constant (1 kgf = 9.81 N)

S = sag (m)

This is based on the parabolic curve shape for the conductor which, for less than 300 m spans or high span-to-sag ratios (sag is less than 10% of span and generally level topography), is very close to the more mathematically correct catenary formula.

Ice loading - The build-up of ice on conductors will increase effective conductor weight, diameter and wind loading. Local experience must be used in the application of ice loads to structural design.

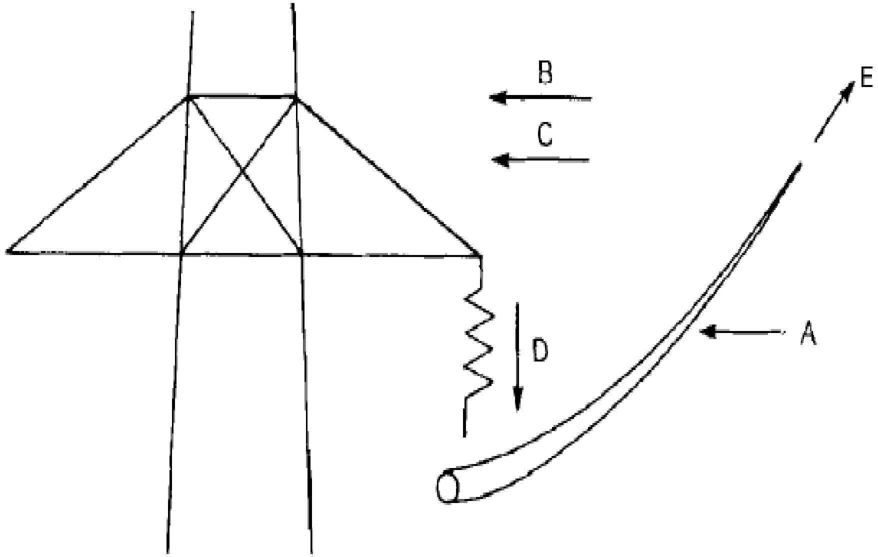
Seismic loads - The application of seismic loads in structural design is a specialist subject, but the following gives a simplistic overview.

The acceleration due to a seismic event is categorized as a fraction of the gravitational constant, g.

This may be given for both horizontal and vertical effects over a frequency spectrum.

Combined loads - The simultaneous application of individual worst case loads is unlikely to occur in practice and the simple arithmetic addition of all such load cases would lead to an uneconomic and over-engineered solution. The individual loads are therefore factored to arrive at a sensible compromise. For example, wind load plus ice load is often taken as full ice loading plus wind load at, say, 50% basic wind speed. Similarly, wind load plus seismic load is normally taken as full earthquake load plus 50% wind load.

Forces on an overhead line tower:

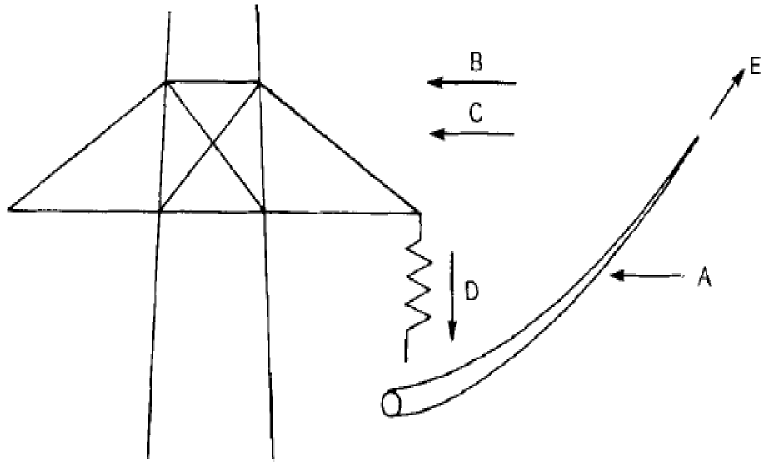


A = horizontal conductor wind load, wind span × wind pressure

B = horizontal structure wind load

C = component of wind loading due to direction of wind and effective structure area normal to the wind

Forces on an overhead line tower:



D = vertical conductor weight span × conductor weight, including weight of insulator strings and fixings

E = longitudinal loads due to conductor tension. This will occur under uneven loading, such as for broken wire conditions or at a terminal tower with a slack span on one side of the tower entering to a substation gantry. These forces will, in general, result in a turning moment causing compression on one side of a tower and tension (‘uplift’) on the opposite side.

Having calculated the forces on structure and conductors, standards such as EN50341 apply a ‘partial factor’, which depends on the selected reliability level and takes account of possible modelling inaccuracies and uncertainties in the disturbing ‘actions’. Such factors will depend on different national experience. Partial factors are also applied to the various material properties such as resistance of steel cross sections and of bucking of sections, compressive concrete strength, etc.

STRUCTURE DESIGN

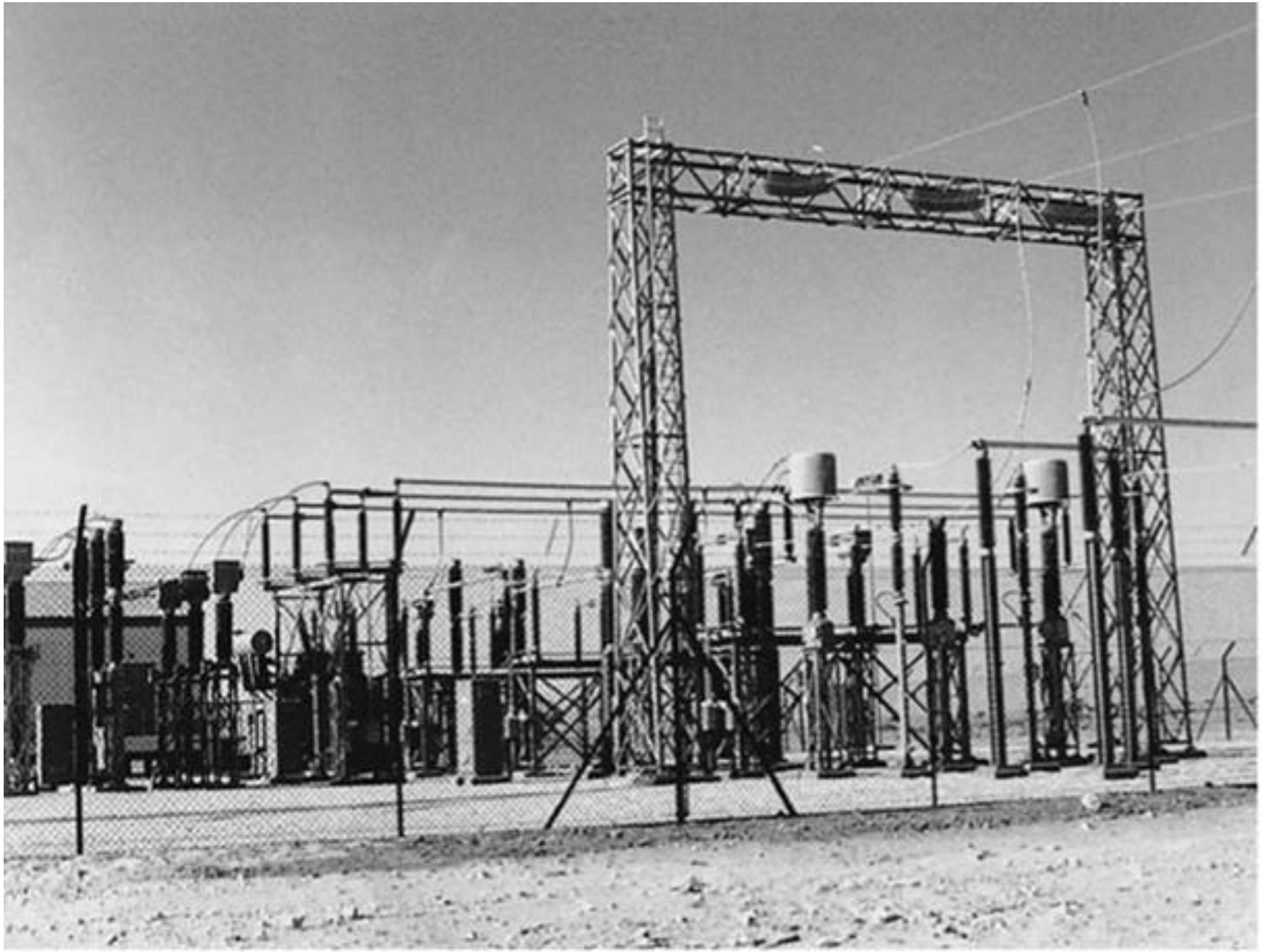
Lattice steel tower design considerations - structural design is not an exact science, but BS5950 covering the subject is comprehensive and will, in general, lead to an economic design. The standard is based on material yield strengths with factors to take account of dynamic and static loads.

Eurocode 3 (design of steel structures) is applicable, supplemented by EN50341, with different national criteria provided in EN50341 Part 3.

The *l*/*r* (*l* = length and *r* = radius of gyration) slenderness ratios for different steel member sections are obtained from tables in BS5950, Volume 1, Section – Properties Member Capacities. Obviously the longer and thinner the steel section the less load it will be able to take before failure along its axis. An equal steel angle will have a radius of gyration equal in both planes whereas an unequal angle will have different radius of gyration values in the *x* and *y* planes and for the design of a steel column the minimum value of '*r*' should normally be taken. This gives a higher *l*/*r* ratio and correspondingly lower design compressive strength to work with.

Steel lattice transmission tower design is based on compression formulae for leg members with different length/radius of gyration (*l*/*r*) values.

The self-supporting tower design uses steel angle columns supported by stress-carrying bracing and redundant members. Higher strength steels show their greatest advantage in the lower *l*/*r* range where it can be seen from the tables(pg.644-645) that the allowable stress is not so sensitive to the slenderness of the member involved. The equivalent area of the member and the radius of gyration are looked up in tables (pg.644-645) for standard steel sections. An accurate analysis procedure is necessary to take into account the tension in the conductors, ice and wind effects. In particular, account must be taken of broken wire conditions (unequal loading on either side of the tower) and also the effect of the insulator strings. Tower design is carried out by specialist structural engineers.



132 kV line entry gantry

132 kV gantry bolted connected

Bolted connections - There are basically three types of bolt connector in use:

- ISO metric black hexagonal bolts, screws and nuts to EN 24016 (st. grade 4.6).
- ISO metric precision hexagonal bolts, screws and nuts to EN 24016 (strength grade 8.8).
- High strength friction grip bolts and associated nuts and washers to EN143399 (grades 8.8 and 10.9 and 10.9 with wasted shank) – these are more usually considered for buildings and bridges rather than towers.

There are three main aspects of bolted joints to be considered:

- Bearing – the stress on the inner surface of the bolt hole imparted by the bolt. The thicker the plates being bolted together the larger the bearing area and the lower the bearing stress.
- Reduction in steelwork material and cross-sectional area due to the presence of the bolt holes.
- The bending and prying effects of tension in the bolts.

Checking the effect of bolt holes for connecting steel members together - If structural members are bolted together then an allowance has to be made for the reduction in steel bulk and therefore stiffness due to the holes required for the bolted connection. Steel plates may be connected together by bolted connections with forces acting in shear across the bolt diameter. Friction grip bolts are normally only used in rigid frame structures where high shear loads and moment loads are involved. In a pinned three dimensional truss structure, such as a steel lattice tower, the design will involve only very slight bending moments. High strength friction grip bolts would not therefore normally be used in a lattice tower structure to clamp the plates together.

There are standard edge distances and back marks for bolt drilling in standard section steel members. For example, a bolt centre should not be less than 1.4 X hole diameter from the edge of the member in the direction of the load, and a minimum distance of not less than 1.25 X hole diameter in the direction normal to the load **(BS5950)**.

The application of such precautions takes into account the reduction in steel bulk due to the bolt holes. More conservative guidelines are also given in EN50341, which takes account of whether or not the shear plane passes through the threaded portion of the bolt.

Bracing - The calculation to confirm the adequacy of a steel brace is similar to that

for the tower leg . A 3.5 m long mild steel, Y_s = 245N/mm^2, 60 X 60 X 6 mm angle brace, equivalent area 691mm^2 and $r_{\min}$=11.7 mm is to be designed to carry a maximum compressive force of 80kN. Experience would show that this is rather a slender steel section for the proposed load. Compressive stress = 80 X 10^3/691 = 116N/mm^2. From standard Table the *l*/*r* ratio must not be greater than 110. Therefore the maximum unsupported length of the brace must not exceed 110 X 11.7 = 940 mm and therefore the brace must have additional supports at 3500/940 ≈ four points along its length when using this type of steel in this application.

Analysis - The structural analysis may be carried out by:

- computer
- graphical methods

It is normal to use computer methods to carry out the analysis and often the complete design with simple hand calculations only to check certain results. The tower or gantry structure is designed to have members either in compression or tension. The computer checks each element to ensure that it is capable of withstanding the applied loads. The checks are carried out in accordance with standard codes of practice applicable to the country involved or as specified by the design or consulting engineer. A most useful reference is the *Steel Designers Manual.*

***Tower testing* -** New tower designs may be type tested at special open air laboratories.

POLE AND TOWER TYPES

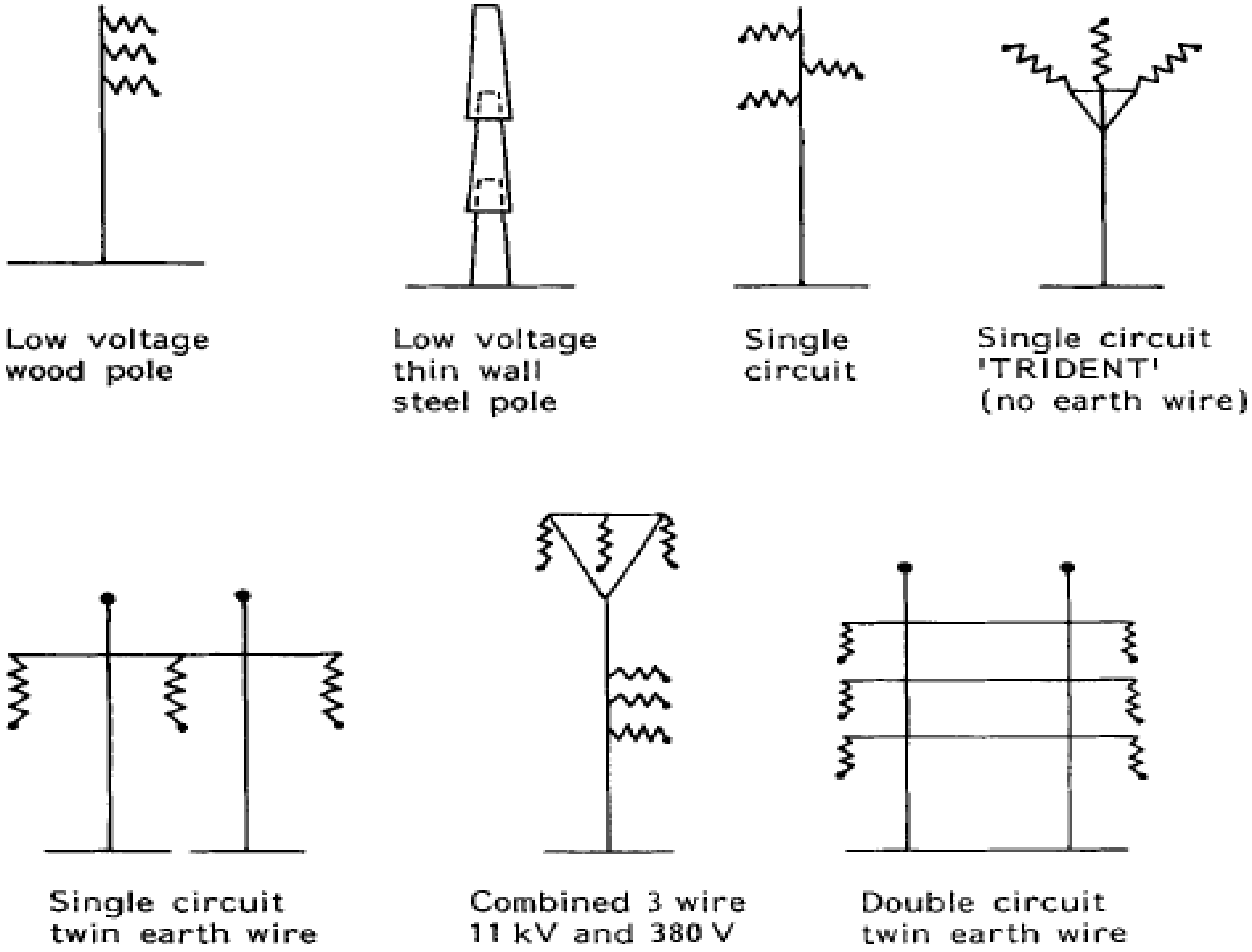
***Pole structures* -** Pole structures are especially used for economic household distribution at voltage levels of 240/415 V and 20/11kV where planning permission allows such arrangements in place of buried cables. Such pole structures are also used at the lower transmission voltage levels, typically at up to 33 kV but also with multi-pole and guyed (stayed) arrangements at voltages up to 330kV. Low-voltage designs are based on matching the calculated equivalent pole head load to the particular type and diameter of wood, steel or concrete to be employed. At higher voltages specific designs are used in order to select optimum size and relative cost. Some examples of different pole arrangements are given in Figure below. Wood poles must be relatively straight and defects such as splits and shakes are unacceptable. There are various national standards. Commonly used soft woods such as fir, pine and larch require impregnation with creosote, anti-termite repellents if to be used in tropical countries and similar chemicals to prevent decay.

Some hardwoods may not need chemical treatment but these are becoming very expensive and their use is considered by some to damage the environment. The poles are usually direct buried with a depth of burial normally equal to one sixth of pole length. If this is insufficient to resist the design turning moment, supplementary blocking or ‘Permasoil’ is used to provide further resistance to overturning.

Tubular poles are available in single column circular sections, octagonal shapes made from folded steel and stepped/swaged sections. Very thin steel wall sections, slightly conical in shape, are also available. The poles are shipped with the smaller sections inside the larger ones for compactness. They are then erected on site by sliding one section over the other to form the pole.

Concrete poles are available in prestressed spun or unstressed cast concrete.

Light fibre glass poles are also available for light head loads.



Low voltage wood pole

Low voltage thin wall steel pole

Single circuit

Single circuit 'TRIDENT' (no earth wire)

Single circuit twin earth wire

Combined 3 wire 11 kV and 380 V

Double circuit twin earth wire

Typical pole arrangements

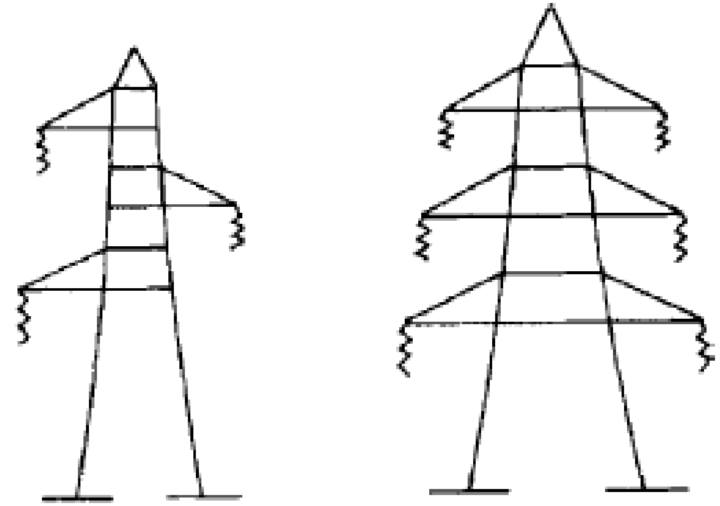
Tower structures **-** Steel lattice towers are generally used at the higher voltage levels where longer spans, high wind loads, ice loads and heavy conductors make the use of wood or light steel poles impractical. In order to standardize, towers are categorized typically to fulfil the following duties:

Suspension towers	straight line and deviation angles up to about 2°
10° angle or section tower	angles of deviation up to 2° or at section positions also for heavy weight spans or with unequal effective negative weight spans
30° angle	deviation angles up to 30°
60° angle	deviation angles up to 60°
90° angle	deviation angles up to 90°

Terminal tower terminal tower loading taking full line tension on one side of tower and none or slack span on other – typically at substation entry

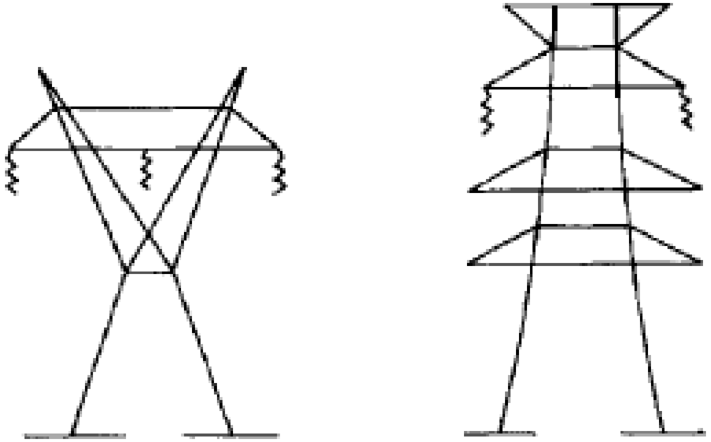
The terminology adopted to describe such towers varies and must be clearly described in order to avoid confusion. For example, a double circuit 30° angle tower for twin conductor use could be described in short form as D30T, but the ‘T’ can be confused between ‘twin’ and ‘triple’. Many users would restrict the description to D30. Similarly, a double circuit terminal tower for twin conductor use could be described as DTT, or more commonly just DT. Extensions are described with a further addition; for example D30E6 describes a dual circuit tower with a 30° maximum angle and a six metre body extension.

In addition to the conductor and insulator set loadings, tower design must take into account shielding angles (lightning protection). Further clearances must be maintained as the insulator sets swing towards the earthed tower structure under certain wind conditions.



Single circuit single earth wire

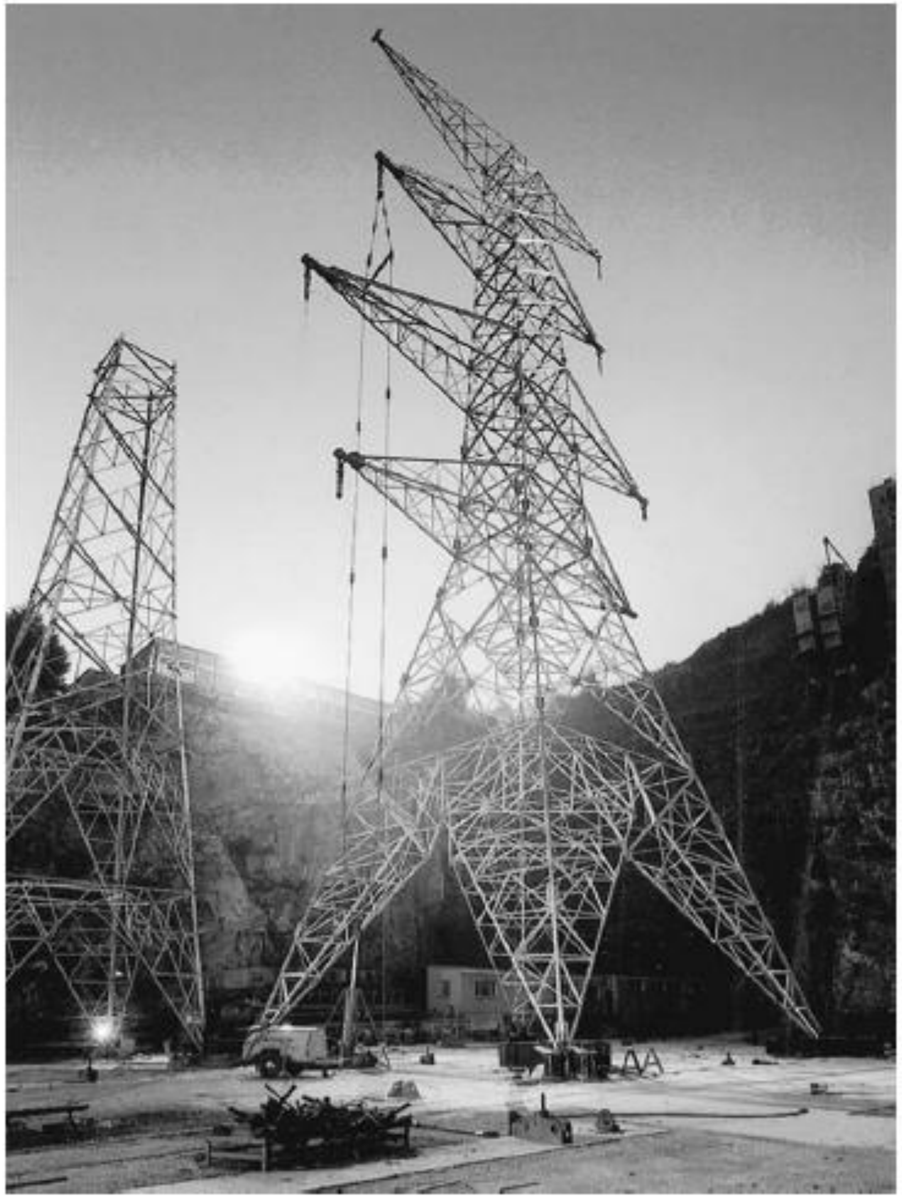
Double circuit single earth wire



Single circuit double earth wire

Double circuit double earth wire

Typical tower outlines



Double circuit 400 kV tower undergoing type tests

Overhead Line Conductor and Technical Specifications

Overhead lines are, air-insulated cables suspended from insulated supports with a power transfer capacity approximately proportional to the square of the line voltage. Overhead lines are cheaper in initial capital cost and are generally more economic than cable feeders. For the transmission of equivalent power at 11 kV a cable feeder would cost some 5 times the cost of a transmission line, at 132 kV 8 times and at 400 kV 23 times. Such comparisons must, take into account rights of way, amenity, clearance problems, planning permissions associated with the unsightly nature of erecting bare conductors in rural and urban areas, and ongoing maintenance requirements.

In order to match both the mechanical and electrical characteristics of the overhead line conductor to the environmental conditions climatic details must first be collected and analysed as itemised under environmental condition.

- *Temperature* - The maximum, minimum and average ambient temperature influences conductor current rating and sag. For temperate conditions typically 20°C with 55°C temperature rise. For tropical conditions 35°C or 40°C with 40°C or 35°C temperature rise. Maximum conductor operating temperature should not exceed 75°C for bare conductors to prevent annealing of aluminium. Conductor temperatures up to 210°C are possible with ‘GAP’ conductor.

- *Wind velocity* - Required for structure and conductor design. Electrical conductor ratings may be based on cross wind speeds of 0.5 m/s or longitudinal wind speeds of 1 m/s.

- *Solar radiation* - Required for conductor ratings but also for fittings such as composite insulators which may be affected by exposure to high thermal and ultraviolet (UV) radiation. Typical values of 850W/m^2 and 1200W/m^2 may be assumed for temperate and tropical conditions respectively.

- *Rainfall* - Important in relation to flooding (necessity for extension legs on towers), corona discharge and associated electromagnetic interference, natural washing and insulator performance.
- *Humidity* - Effect on insulator design.
- *Altitude* - Effect on insulation and conductor voltage gradient.
- *Ice and snow* - Required for design of conductor sags and tensions. Build-up can also affect insulation as well as conductor aerodynamic stability.
- *Atmospheric pollution* - Effect on insulation and choice of conductor material (IEC 60815-1 and -2 – Guide for the selection of insulators in respect of polluted conditions – drafts for public comment).
- *Soil characteristics* - Electrically affecting grounding requirements (soil resistivity) and structurally the foundation design (weights, cohesion and angle of repose).

- *Lightning* - Effect on insulation levels and also earth wire screening arrangements necessary to provide satisfactory outage performance.
- *Seismic factor* - Effect on tower and foundation design.
- *General loadings* - Refer also to IEC 60826 (Design criteria for overhead lines), EN50341 (Overhead lines exceeding AC45 kV – supersedes 60826 for European use) and BS8100 (Loading and strength of overhead transmission lines).

CONDUCTOR SELECTION

The selection of the most appropriate conductor size at a particular voltage level must take into account both technical and economic criteria as listed below:

1. The maximum power transfer capability must be in accordance with system requirements.
2. The conductor cross-sectional area should be such as to minimize the initial capital cost and the capitalized cost of the losses.
3. The conductor should conform to standard sizes already used elsewhere on the network in order to minimize spares holdings and introduce a level of standardization.
4. The conductor thermal capacity must be adequate.
5. The conductor diameter or bundle size must meet recognized international standards for radio interference and corona discharge.

6. The conductor must be suitable for the environmental conditions and conform to constructional methods understood in the country involved (such as IEC, BS, etc.)

Types of conductor

The international standards covering most conductor types are IEC 61089 and EN 50182 and 50183. For 36 kV transmission and above both aluminium conductor steel reinforced (ACSR) and all aluminium alloy conductor (AAAC) may be considered. Aluminium conductor alloy reinforced (ACAR) and all aluminium alloy conductors steel reinforced (AACSR) are less common than AAAC and all such conductors may be more expensive than ACSR. Historically ACSR has been widely used because of its mechanical strength, the widespread manufacturing capacity and cost effectiveness. For all but local distribution, copper based overhead lines are more costly because of the copper conductor material costs.

Copper (BS 7884 applies) has a very high corrosion resistance and is able to withstand desert conditions under sand blasting. All aluminium conductors (AAC) are also employed at local distribution voltage levels. From a materials point of view the choice between ACSR and AAAC is not so obvious and at larger conductor sizes the AAAC option becomes more attractive. AAAC can achieve significant strength/weight ratios and for some constructions gives smaller sag and/or lower tower heights. With regard to long-term creep or relaxation, ACSR with its steel core is considerably less likely to be affected. Jointing does not impose insurmountable difficulties for either ACSR or AAAC types of conductor as long as normal conductor cleaning and general preparation are observed. AAAC is slightly easier to joint than ACSR.

Relevant national and international standards

Number	Title	Comment
IEC 61089	Round wire concentric lay overhead electrical stranded conductors	Supersedes IEC 207 (AAC), 208 (AAAC), 209 (ACSR) and 210 (AACSR)
EN 50182	Conductor for overhead lines: round wire concentric lay stranded conductor	Supersedes IEC 61089 for European use. BSEN 50182 identical
EN 50183	Conductor for overhead lines: aluminium–magnesium–silicon alloy wires	
BS 183	Specification for general purpose galvanized steel wire strand	For earth wire
BS 7884	Specification for copper and copper–cadmium conductors for overhead systems	

The development of ‘Gap type’ heat-resistant conductors offers the possibility of higher conductor temperatures. The design involves an extra high strength galvanized steel core, and heat-resistant aluminium alloy outer layers, separated by a gap filled with heat-resistant grease. To maintain the gap, the wires of the inner layer of the aluminium alloy are trapezoid shaped. Depending on the alloys used, temperatures of up to 210°C are possible, with a current carrying capacity of up to twice that of hard-drawn aluminium. This offers particular value where projects involve upgrading existing circuits.

Characteristics of different conductor materials

Property	Unit	Annealed Copper	Hard-drawn Copper	Cadmium Copper	Hard-drawn Aluminium	Aluminium alloy (BS)	Galvanized steel
Resistance @ 20°C	($\Omega mm^2/km$)	17.241	17.71	21.77	28.26	32.2	-
Density	(kg/m^3)	8890	8890	8945	2703	2703	7780
Mass	($kg/mm^2/km$)	8.89	8.89	8.945	2.703	2.703	7.78
Resistance temperature coefficient @ 20°C	(per °C)	0.00393	0.00381	0.00310	0.00403	0.0036	-
Coefficient of linear expansion	(per °C)	17×10^{-6}	17×10^{-6}	17×10^{-6}	23×10^{-6}	23×10^{-6}	11.5×10^{-6}
Ultimate tensile stress (approx.) BS values	(MN/m2)	255	420	635	165	300	1350
Volumetric resistivity @ 20°C	($\Omega mm^2/m$)	0.01724 (std.)	0.01771 (average)	0.02177 (Max.)	0.02826 (Max.)	0.0322 (std.)	-
Mass resistivity @ 20°C	(Ω kg/km)	0.15328	0.15741	0.19472	0.07640	0.08694	-
Modulus of elasticity	(MN/m2)	100×10^3	125×10^3	125×10^3	70×10^3	70×10^3	200×10^3
Relative conductivity	(%)	100	97 (average)	79.2 (minute)	61 (minute)	53.5	-

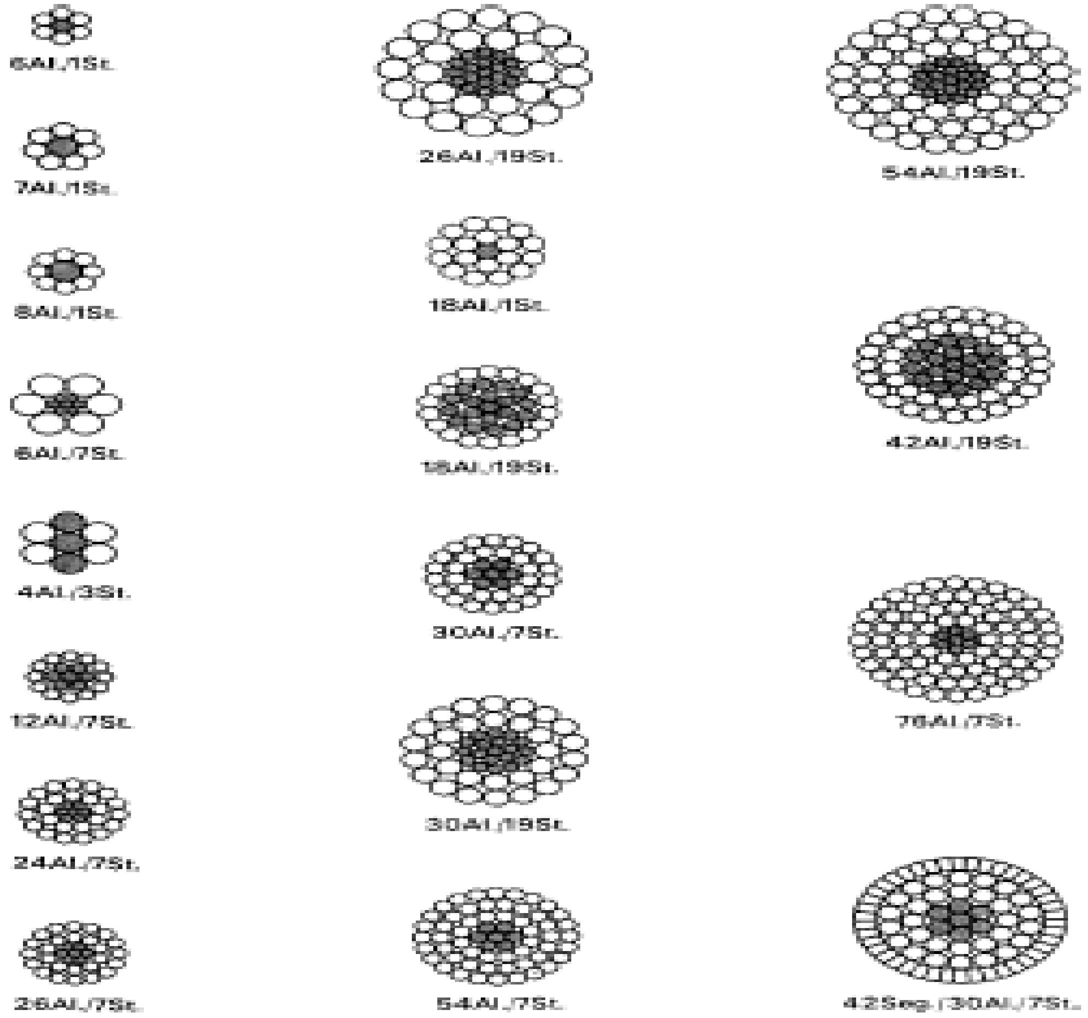
Aerial bundled conductor and BLX

Power failures on open wire distribution systems (up to 24 kV) under storm conditions led to various distribution companies investigating what steps could be taken to increase service reliability. At low voltage levels aerial bundled conductor (ABC) is now becoming rapidly more popular because of improved reliability and the low installation and maintenance costs compared to conventional open wire pole distribution. For short distribution lines, where voltage drop is not a limiting factor determined by the line reactance, the ABC installation is some 160% of the cost of the equivalent open wire construction at 24kV. For longer lines and higher currents where the line reactance is important the cost differential diminishes. The initial capital cost of the cable alone is, however, up to twice the cost of the equivalent open wire conductor.

Environmentally it could be argued that the ABC end product is marginally more pleasing. However, for the 10–14 kV distribution levels the use of ABC is more problematic due to the requirement of employing underground cable joining techniques at high level (especially difficult in maintenance situations).

There are two distinct ABC systems in use. One system uses a self-supporting bundle of insulated conductors where all conductors are laid up helically and where tension is taken on all conductors which are of hard-drawn aluminium. An alternative system is where all conductors are insulated and the hard-drawn aluminium phase conductors are laid up around an aluminium alloy neutral

which has greater tensile strength and acts as a catenary wire to support the whole bundle. The insulation material may be polyvinylchloride (PVC), linear polyethylene (PE) or cross-linked polyethylene (XLPE).



Conductor arrangements for different CSR combinations

Conductor breaking strengths - It may come as a surprise to many readers that the declared breaking strength (sometimes referred to as the ultimate tensile strength) of a conductor has no unique value. The value depends upon the method of calculation employed as stipulated in the National or IEC Standards to which the conductor material is supplied. Differences quoted in breaking strengths for a given conductor configuration are *not* due to the material itself but to this calculation methodology.

The calculation of conductor behaviour under changing loading conditions (wind, ice) and temperature is related to breaking strengths, and the design of fittings (tension clamps, repair sleeves, etc.) must also be related to these values. Hence it is necessary in any overhead line specification to state clearly which standard calculated breaking strengths are to be based on in order to avoid disputes at a later date. If in doubt it is suggested that the IEC values should be used.

Bi-metal connectors - Where an aluminium conductor is terminated on a copper terminal of, say, an isolator a special copper/aluminium joint is necessary to prevent the formation of a corrosion cell. A termination of this type usually comprises of an aluminium sleeve compressed onto a copper stalk with an insulating disc separating the two surfaces which are exposed to the atmosphere. The two dissimilar materials are generally welded together by friction welding as this process ensures a better corrosion resistance at the interface. An additional protection is afforded by the use of an anticorrosion varnish. When using such fittings it is always recommended that the aluminium component is above the copper one. Even slight traces of copper on aluminium have a disastrous effect on the aluminium material.

Corrosion - Since overhead lines are erected in different climatic conditions throughout the world a knowledge of their performance has been built up over the years. Aluminium conductors have good corrosion behaviour essentially resulting from the formation of an undisturbed protective surface oxide layer which prevents further corrosion attack. ACSR is known to suffer from bi-metallic corrosion which is noticeable as an increase in conductor diameter due to corrosion products in the steel core known as ‘bulge corrosion’. Early problems associated with deterioration of the steel cores used in ACSR conductors have been resolved over the years by the use of high temperature greases. These greases prevent the onset of any galvanic corrosion between the galvanized steel core and the outer aluminium wires. They have a high drop point which allows continuous operation of the conductor at 75°C and full service life protection. AAAC will obviously offer superior corrosion resistance than ungreased ACSR. Conductors that are not fully greased are not recommended for corrosive areas. The resistant properties of ACSR also depend upon the number of layers of aluminium surrounding the steel core.

Previous researches have shown that;

i). Pure aluminium had the best corrosion resistance under the majority of environmental conditions.

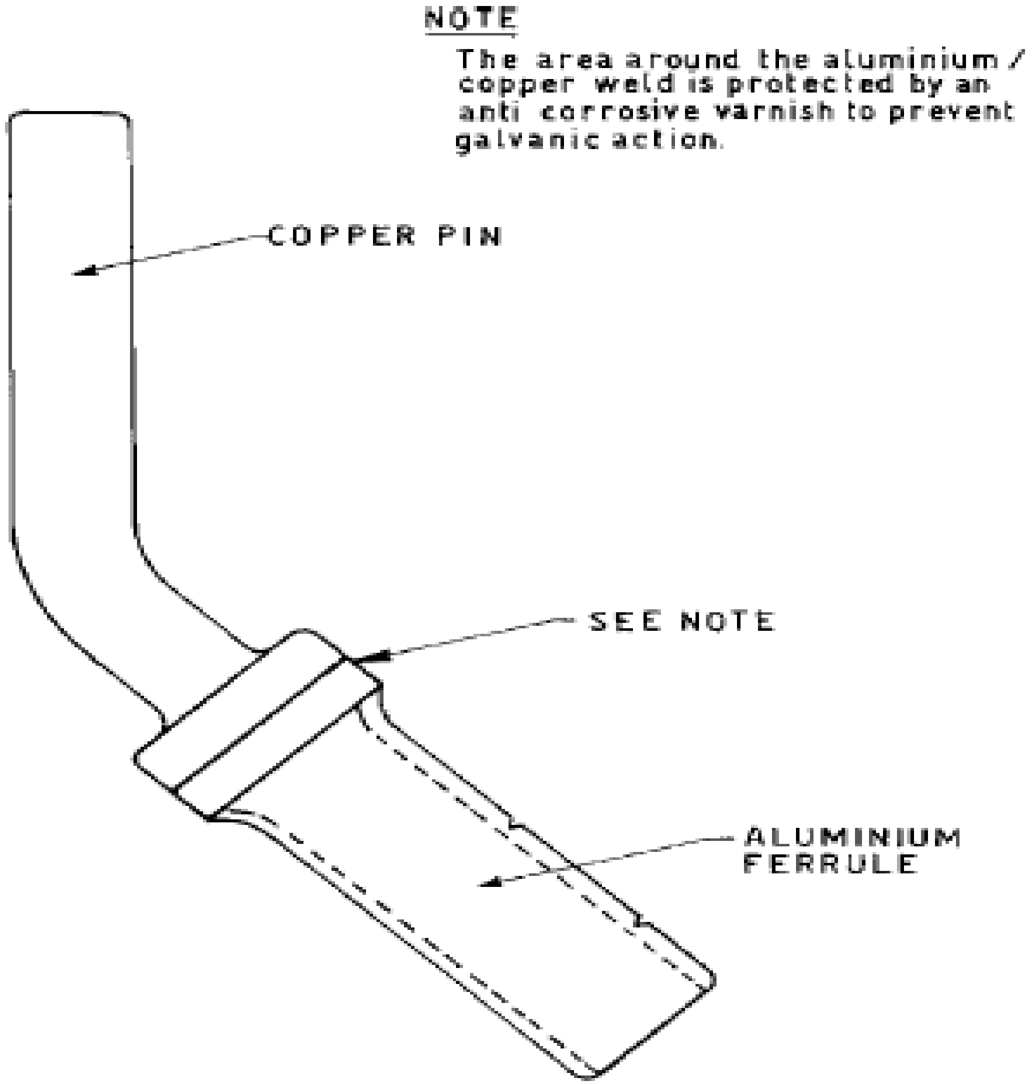
ii). Smooth body conductors were the most corrosion resistant, especially if the inner layers were greased.

iii). Small diameter wires were most susceptible to corrosion damage and to failure. Thus for a given conductor area it is preferable to have fewer larger diameter strands.

iv). The overall corrosion performance of aluminium alloy conductors depends upon the type of alloy used.

For very aggressive environments the following order of preference is suggested:

- Aluminium conductor fully greased.
- Aluminium conductor with alumoweld core fully greased.
- ACSR fully greased.
- Aluminium alloy conductor fully greased.



Bi-metal connector

- Aluminium conductor with alumoweld core ungreased.

- ACSR with greased core.

CALCULATED ELECTRICAL RATINGS

Heat balance equation **-** A conservative approach to the conductor thermal current rating in wind, ignoring any voltage regulation considerations, is given by the following simplified heat balance equation as valid for stranded conductors:

Heat generated (I^2R conductor losses) = heat lost by convection (watts/km)

+ heat lost by radiation (watts/ km)

- heat gained by solar radiation (watts/km)

$$= H_C + H_R - H_S$$

$$I^2R_{20}\{1 + \alpha (t + \theta)\} = 387 (V . d)^{0.448} . \theta + \Pi . E_C . s . d\{(t + \theta + 273)^4 - (t + 273)^4\} - \alpha_S . S \; d \text{ (watts/km)}$$

where I = current rating, amps

R_{20} = resistance of conductor at 20°C

α = temperature coefficient of resistance per °C (for ACSR at 20°C,0.00403)

t = ambient temperature, °C

θ = temperature rise, °C (t_1 initial temperature and t_2 final temperature)

α_S = solar absorption coefficient – depends upon outward condition of the conductor and varies between 0.6 for new bright and shiny conductor to 0.9 for black conditions or old conductor. Average value of 0.8, say, may be taken for initial design purposes.

S = intensity of solar radiation, watts/m^2

d = conductor diameter, mm

V = wind velocity normal to conductor, m/s

E_C = emissivity of conductor – differs with conductor surface brightness.

Typical values are 0.3 for new bright and 0.9 for black aluminium, ACSR or AAAC conductor. Average value 0.6, say.

s = Stefan–Boltzmann's constant = 5.7×10^{-8} watts/m^2

Π = pi, constant (22/7) = 3.141592654…

***Power carrying capacity* -** Approximate economic power transfer capacity trends for different line voltages are based on power transfer being proportional to the square of the line voltage.

In practice, the capacity will be limited over long distances by the conductor natural impedance (voltage regulation) as well as by conductor thermal capacity. Depending upon the required electrical load transfer, the number of overhead line conductors of a particular type used per phase may vary. Calculated ratings for typical ACSR conductors at lower voltage levels of 11, 33 and 66 kV overhead lines using different conductors over different distances are given in Table below.

Corona discharge - High voltage gradients surrounding conductors (above about 18 kV/cm) will lead to a breakdown of the air in the vicinity of the conductor surface known as corona discharge. The effect is more pronounced at high altitudes. Generally, the breakdown strength of air is approximately 31 kV peak/cm or 22kV rms/cm. This is a useful guide for the selection of a conductor diameter or conductor bundle arrangement equivalent diameter. Corona discharge and radio interference noise generated cause problems with the reception of radio communication equipment and adversely affect the performance of power line carrier signals. At higher voltage levels, and certainly at voltages of 400 kV and above, interferences due to the corona effect can be the dominant factor in determining the physical size of the conductor rather than the conductor thermal rating characteristic.

Increasing the conductor diameter may be necessary in order to reduce the surface stress to acceptable levels. Obviously there is a limit with regard to the practical size, strength and handling capability for conductors. The bundling of conductors assists in the effective increase in overall conductor diameter and hence leads to lower stress levels.

The surface voltage gradient may be determined from Gauss's theorem showing that an increase in radius or equivalent radius leads to a reduction in surface voltage gradient:

$$V_g = \frac{Q}{\left(2 \cdot \pi \cdot \in_0 \cdot r\right)}$$

where V_g = voltage surface gradient (volts/cm)

Q = surface charge per unit length (coulomb/m)

r = equivalent radius of smooth conductor (cm)

$\in_0$ = permittivity of free space = $1/\{36 . \pi . 10^9\}$(F/m)

Typical load carrying capacity of distribution lines

Line voltage (kV)	Conductor equivalent configuration spacing (mm)	ACSR conductor code	AAC conductor code	MW capacity based upon 5% regulation			
11				8 (km)	16(km)	24(km)	32(km)
	1400	Sparrow	Iris	0.95	0.49	0.33	0.25
		Raven	Poppy	1.4	0.7	0.47	0.35
		Linnet	Tulip	3.00	1.5	1.00	0.75
33				16(km)	32(km)	48(km)	64(km)
	1500	Quail	Aster	5.00	2.50	1.70	1.25
		Penguin	Oxlip	6.70	3.35	2.20	1.70
		Linnet	Tulip	8.35	4.18	2.80	2.10
		Hen	Cosmos	11.50	5.75	3.80	2.90
66				32(km)	64(km)	96(km)	128(km)
	3000	Quail	Aster	12.50	6.25	4.18	3.14
		Linnet	Tulip	16.00	8.00	5.32	3.99
		Hen	Cosmos	18.40	9.18	6.12	4. 59

In practical terms this may also be expressed as follows:

$$V_g = \frac{U_p}{\left[(d/2)\log_e(2D/d)\right]} kV/cm$$

where V_g = voltage surface gradient (kV/cm)

U_p = phase voltage (kV)

d = diameter of single conductor (cm)

D = distance between phases for single phase line or equivalent spacing

for three phase lines (cm)

For the three phase line configuration, $D = \sqrt[3]{D_{ry} \cdot D_{yb} \cdot D_{br}}$ where D_{ry}, D_{yb} and D_{br} are the spacings between the different phases r, y & b.

DESIGN SPANS, CLEARANCES AND LOADINGS

***Design spans* -** In order to design suitable tower dimensions for an overhead line it is necessary to calculate the conductor sags and tensions. The maximum conductor tension (which will occur at minimum temperature) is evaluated in order to ensure a sufficient mechanical strength margin for the particular conductor. The sag is calculated in order to fix the tower height. The ruling condition for the conductor has to be determined based on either the maximum working tension (MWT), the everyday stress (EDS) or, potentially, the maximum erection tension (MET). The conductor has to be designed such that the maximum anticipated loads do not exceed

50% of the breaking load at 6°C (MWT condition) and 20% at, say, an everyday temperature of 16°C (EDS condition).

Basic span **-** The optimum spacing of towers and their height becomes a financial exercise. With short spans and low towers the total number of towers and associated fittings will be large to cover a certain route length but less steel per tower will be necessary. If long spans are used then the conductor sag between tower points becomes greater and fewer stronger, higher towers and fittings, but with correspondingly more steel, are necessary to ensure correct clearances. The extent of labour associated with a variable number of towers for a given route length will also be important. The overall height of the tower is given by;

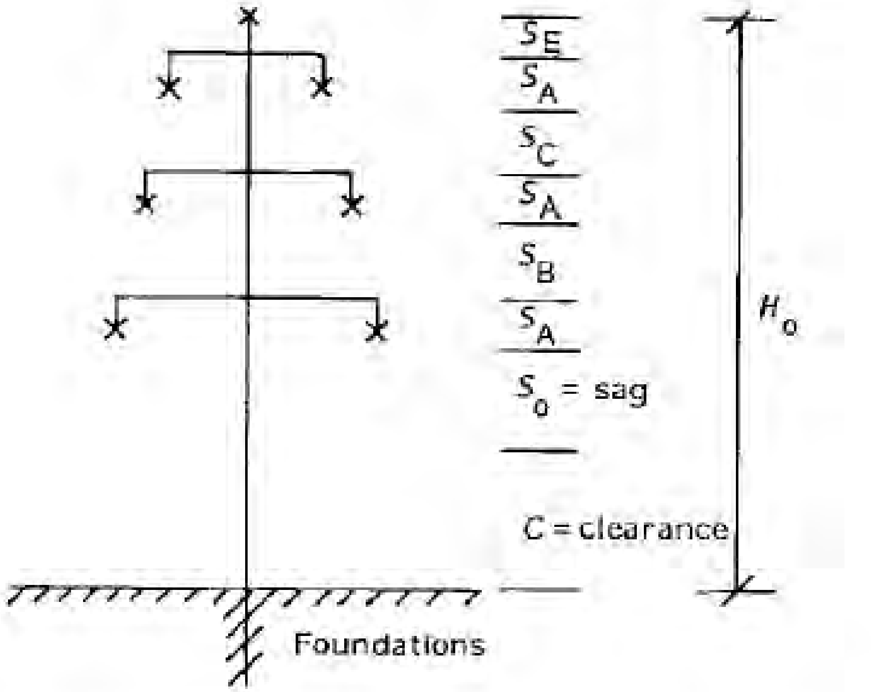
$$H = C + S_{\mathrm{O}} + 3S_{\mathrm{A}} + S_{\mathrm{B}} + S_{\mathrm{C}} + S_{\mathrm{E}}$$

where C = statutory clearance to ground

S_{A} = length of insulator suspension set

S_{B}, S_{C}, S_{E} = vertical distances between cross arms and conductor above or to earth wire.

S_O = sag of conductor (proportional to square of span)



Overall tower height $H_o = C + S_o + 3S_A + S_B + S_C + S_E$

Figure 18.7(a) Basic span – overall tower height and clearances

Given the mechanical loading conditions and phase and earth wire conductor types an evaluation of the basic span may be made as follows. Assume an arbitrary length in a flat area over, say, 100 km. Inevitably there will be some angle/section towers whose positions will be fixed beforehand. From experience let this number be N_0. If L is the basic span and l the span length then the number of suspension towers will be the next integer from $[(100 . L/l) + l - N_0]$.

1. Conductors and earth wire – costs for supply and installation.

2. Insulators – selection depending upon mechanical loading and pollution levels such that S_A may be defined.

3. S_B, S_C, S_E – a function of the still air clearance co-ordinated with the insulation level.

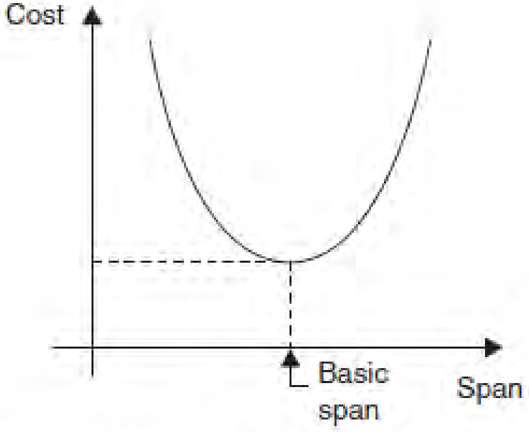
4. Tower weight (W)

5. Foundations – depends upon soil properties

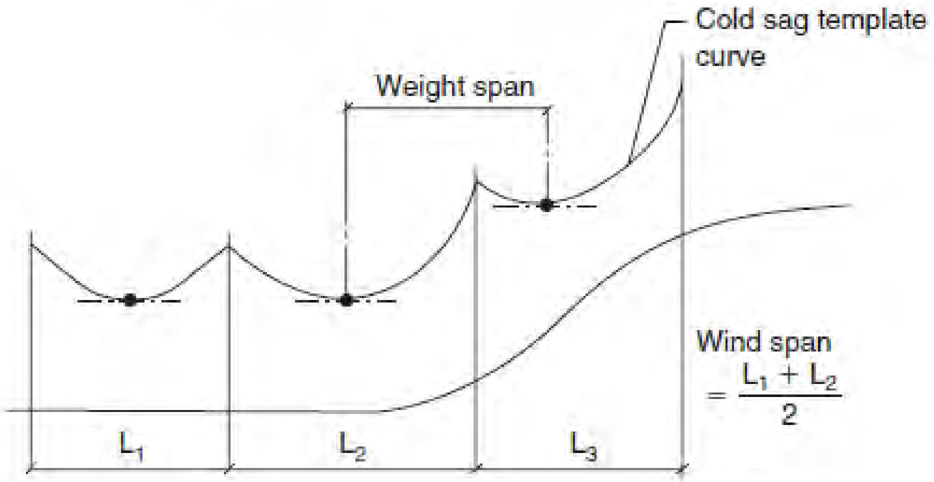
In addition, an allowance has to be made for the routing survey, land clearance, erection and similar incidentals. Basic spans might be approximately 365 m at 230 kV and 330 m at 132kV. The minimum allowable ground clearance between phase conductors and earth is derived from specified conductor clearance regulations for the country involved, in still air at maximum conductor temperature. Survey figures for the proportion of tower costs compared to the overall line costs ranged from 8% to 53% with ACSR, but from 25% to 45% with AAAC.

***Wind span* -** The wind span is normally taken as half the sum of the adjacent span lengths. At 230 kV this might be 400 m under normal conditions and 300m under broken wire conditions. Correspondingly, at 132 kV typical values are 365 m and 274 m respectively.

Weight span - The weight span is the distance between the lowest points on adjacent sag curves on either side of the tower. It represents the equivalent length or weight of conductor supported at any one tower at any time.

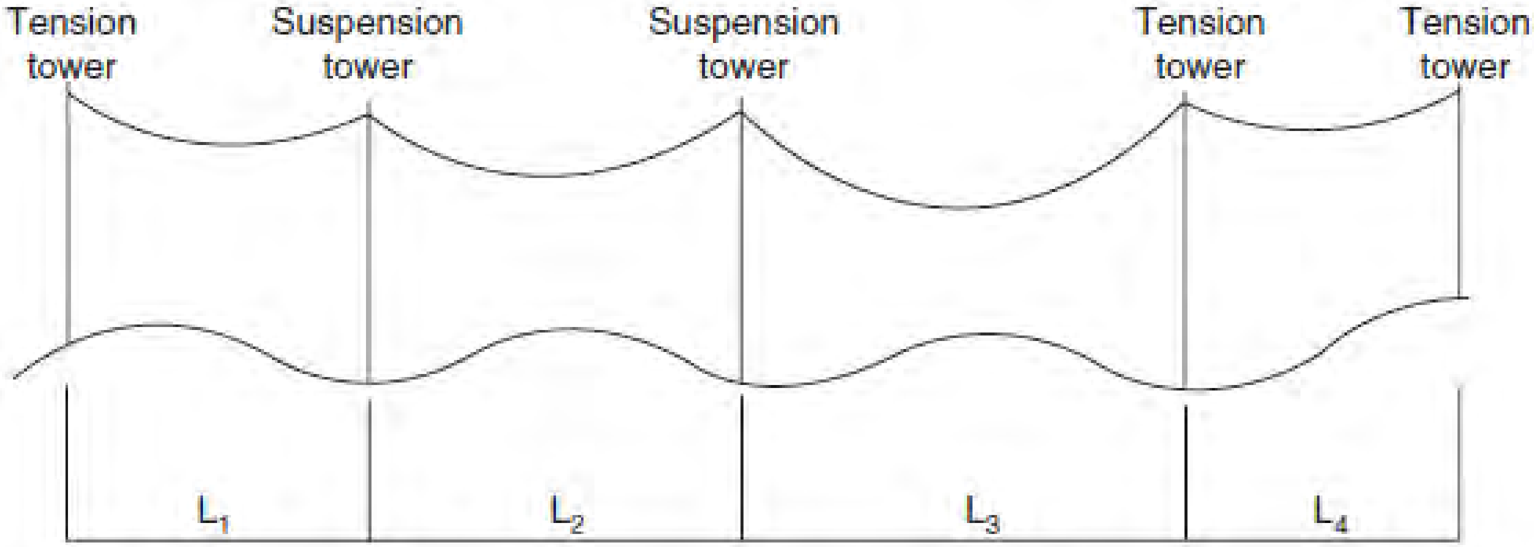


(a) Cost/span plot to determine most economic basic span. The basic span is the horizontal distance between centres of adjacent supports on level ground.



The wind span is half the sum of adjacent horizontal span lengths supported on any one tower.

The weight span is the equivalent length of the weight of conductor supported at any one tower at minimum temperature in still air.



$$\text{Equivalent span} = \sqrt{\frac{L_1^3 + L_2^3 + L_3^3 + L_4^3 + \quad \text{-----} L_n^3}{L_1 + L_2 + L_3 + L_4 + \text{-----} L_n}}$$

The equivalent span is used for determination of sag in spans for which the tension in any section length is that which would apply to a single span equal to the equivalent span.

(c) Equivalent Span

For design purposes, it is the value under worst loading conditions (minimum temperature in still air) which gives the greatest value. A tower at the top of a hill may be heavily loaded and it is usual to assume a weight span which can reach up to twice the value of the basic span. In fairly level terrain a value of 1.6 to 1.8 may be adopted. The ratio of weight span to wind span is also important since insulators on lightly loaded towers may be deflected excessively thus encroaching electrical clearances. A ratio of weight span to wind span of approximately 1.5–2 is often considered acceptable. This ratio is easily computed with the use of the ‘cold’ template. When plotting tower positions, the engineer must be aware of the maximum weight span and of such ratios. Typical weight span values at 230 kV and 132 kV are given below:

230 kV	132 kV
Suspension tower - 750m Normal conditions 565m Broken wire conditions	680m Normal conditions 510m broken wire conditions
Tension towers 750m Normal conditions 750m Broken wire conditions	680m Normal conditions 680m broken wire conditions

Equivalent span - The equivalent span is defined as a fictitious single span in which tension variations due to load or temperature changes are nearly the same as in the actual spans in a section. The mathematical treatment to obtain the equivalent span is based on parabolic theory and there is no similar concept using full catenary equations. For sagging the overhead line conductors the tension appropriate to the equivalent span and the erection temperature as shown in Fig. 18.8c is used.

Erection tensions are calculated from final tensions making an allowance for creep. This is equated to a temperature shift which is applied to final tensions.

Creep - Creep is a phenomenon which affects most materials subjected to stress. It manifests itself by an inelastic stretch (or permanent elongation) of the material in the direction of the stress. Certain materials such as aluminium are more susceptible than others. For example steel suffers only a limited amount of creep.

The increase in conductor length resulting from inelastic stretch produces increased sags which must be taken into account in the overhead line design and installation process so as not to infringe clearances.

When applying the technique of creep evaluation the designer must forecast reasonable conductor history. Typical conditions might be that which represent the periods for which compensation should be made.

As an illustration of the steps to be followed consider the following example.

1. The EDS is to be 20% of the UTS of the conductor at 20°C.

2. The maximum stress occurs when the conductor is subjected to a wind of 50 kg/m^2 at 0°C, no ice.

3. The maximum operating temperature is 70°C.

4. Accept a span length of 400 m. (In practice, three values should be taken: a maximum and a minimum span both deduced from the profile, and a basic span. The span which gives the highest value of creep strain is selected as a basis for creep compensation.)

5. Creep strain to be calculated for a period of 30 years.

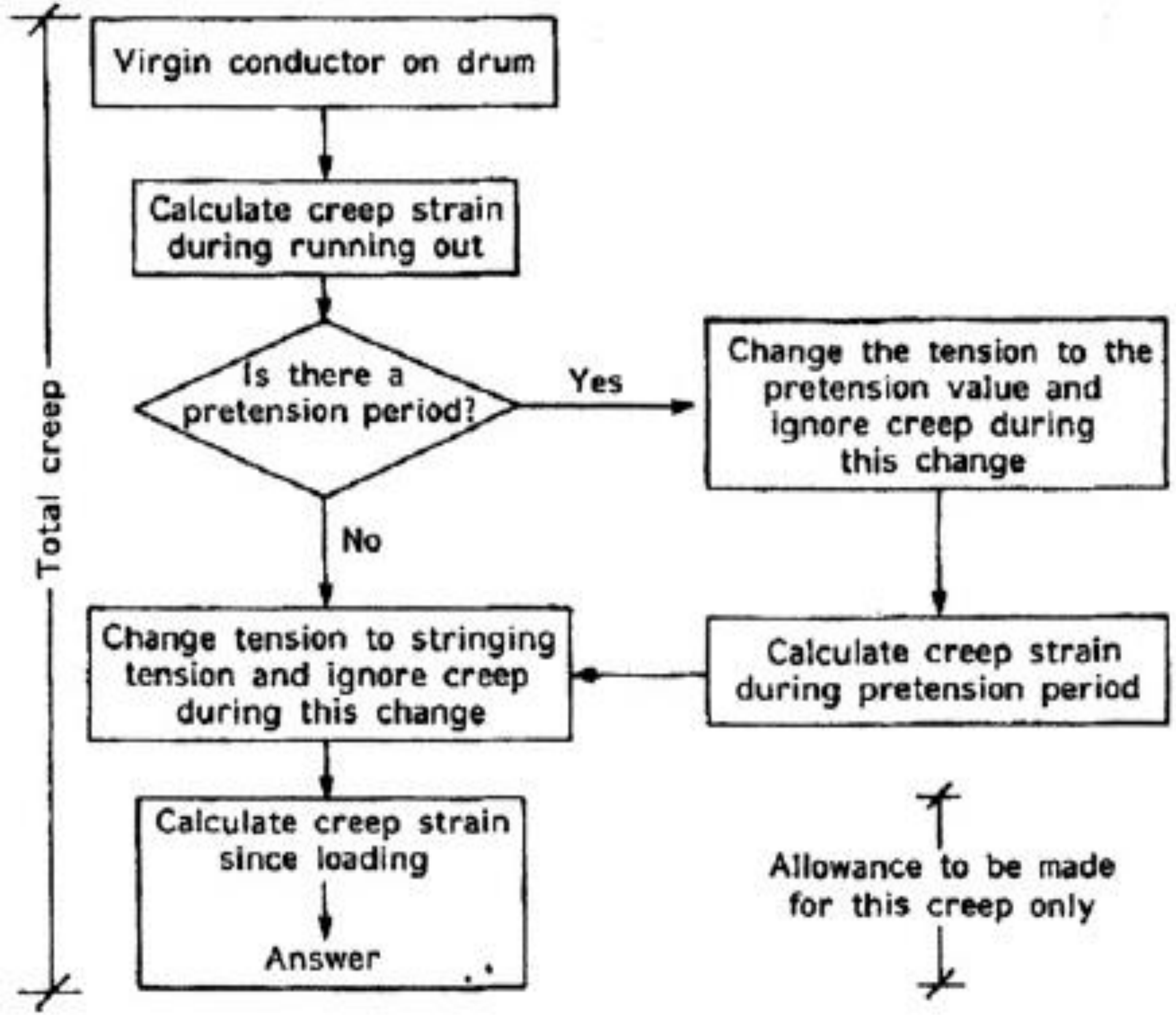
6. Conductor is manufactured from aluminium rod obtained by the Properzi method.

Some decisions based on experience are necessary regarding the duration of the maximum and minimum stresses, these values are then used in the calculation.

The Figure below illustrates an acceptable procedure for creep assessment. This concept is equally applicable if lifetime creep is predicted using other techniques.

For example:

- Using creep values from conductor creep tests made at actual mechanical and temperature conditions over a long time(normally more than 2 months) and extrapolating the creep curve up to 10, 30 or 50 years. Normally the final sag calculation is made using the 10 year figure, because the additional creep between 10 to 50 years is relatively small and a reasonable part of that may have elapsed from the time of stringing up to the time of clamping the conductor.



Creep assessment procedure

- Using creep values from accelerated conductor creep tests made at higher mechanical tension. The creep value at a certain time will then correspond to what is known to apply under real conditions after (say) 30 years.

- Using creep compensations made with the help of sag and tension charts.

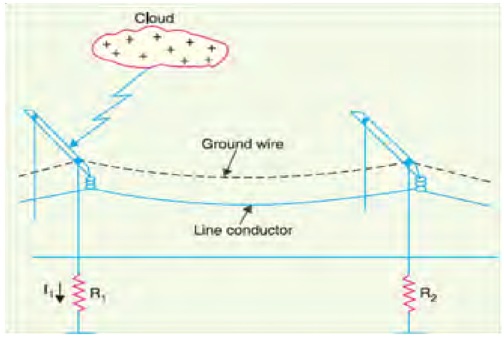
- maximum design temperature of conductor = 50°C, say

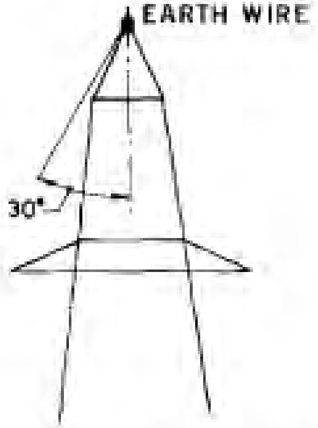
- equivalent temperature corresponding to creep, $\Delta\theta_e = 32°C$

- temperature for evaluating sag at time, *t*, and corresponding to the maximum design temperature of the conductor when no pretension or over tension regime are applicable, $\theta + \Delta\theta_e = 82°C$ Clearly, this will result in a penalty in the height of all towers. An alternative would be to reduce the sag at sagging time resulting in a temporary over tension in the conductor, resulting in an overdesign penalty on the angle towers. By applying several combinations of temperature correction or pretension you would be able to aim for the least onerous solution.

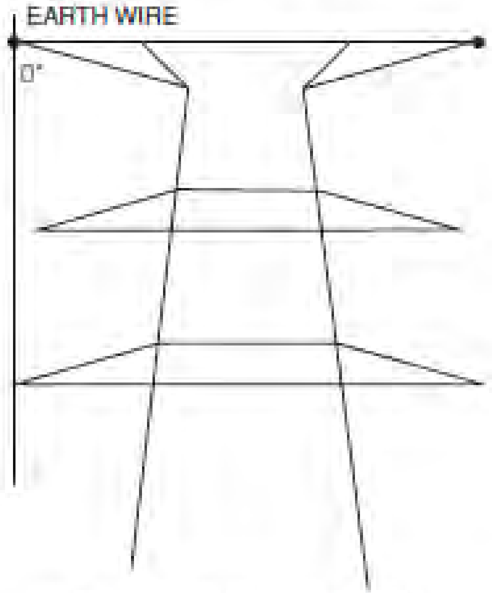
Conductor and earth wire spacing and clearances

Earth wires - Where there is a risk of a direct lightning strike to the phase conductors, transmission lines are provided with overhead earth (or ground) wires to shield them and also to provide a low impedance earth return. The degree of shielding of the overhead line phase conductors from lightning strikes is determined by the shielding angle afforded by the earth wire(s) running over the overhead line. Where lines are erected in areas of high lightning activity, or with supporting structures with wide horizontal spacing configurations, two earth wires may be provided to permit a lower shielding angle and superior protection.





(a) TYPICAL 132 kV DOUBLE CIRCUIT TOWER WITH 30° SHIELD ANGLE



(b) TYPICAL 230 kV TOWER WITH 0° SHIELD ANGLE

Figure 18.10 Protections from lightning strikes by overhead earth wires

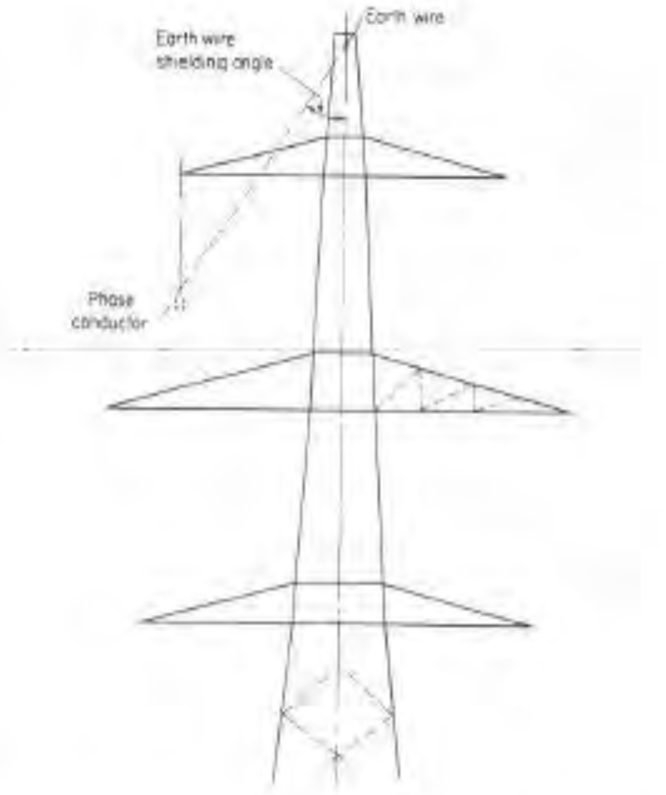
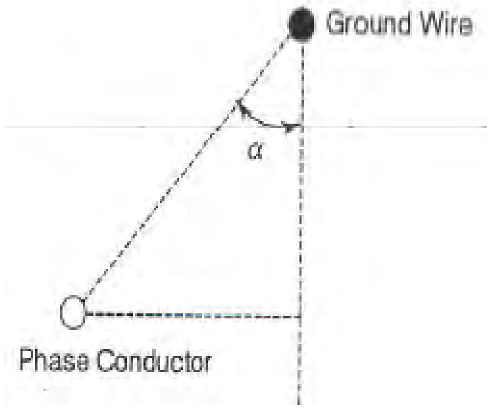


Figure 10.10 Single earth wire protection; shielding angle α normally 35°



The vertical spacing between the earth and phase conductors must be such as to ensure sufficient clearance to prevent mid-span flashovers under transient conditions. The sagging should be arranged so as to ensure that the vertical mid-span clearance between the phase and earth conductors is about 20% greater than at the supports. Galvanized stranded steel presents a low cost earth wire material. Where severe pollution exists or where protection schemes demand a low impedance earth path, ACSR or other materials may be used. In the UK the original 132 kV overhead lines were designed with a 45° angle of protection and gave satisfactory cover. When this angle was applied to the higher 400 kV overhead lines it was found advantageous to reduce the angle of protection to 30° in order to reduce the number of strikes. The calculation of lightning behaviour of overhead lines is complex but the electro-geometric model is a convenient way of visualizing the process.

Earthing counterpoise - A lightning strike on the earth wire will be dissipated into the ground after passing through the transmission tower structure and foundations. Wave propagation along electrical lines obeys classical wave propagation theory. Wave reflections will occur at points of discontinuity such as points of changing impedance.

Distribution voltage level clearances - For open wire construction at distribution voltage levels (380 V–24 kV) the earth or neutral wire is normally placed at the bottom (nearest the ground) of the conductor set so as to minimize the danger caused by poles, ladders, etc. touching the wires from underneath. Clearances for conductors are usually the subject of statutory regulations (e.g. in the UK the Statutory Instruments 2002, No. 2665, The Electricity Safety, Quality and Continuity Regulations). Because of the insulated nature of ABC, ground clearances may be reduced in comparison with open wire construction under certain circumstances

***Transmission voltage level clearances* -** There are no universally agreed clearances as they depend upon insulation level, pollution, span, type of overhead line construction, etc.

***Broken wire conditions* -** It is essential that the structures supporting the overhead line are capable of withstanding unequal loads. Suspension and tension structures must be designed for the vertical and transverse loadings plus the unbalanced longitudinal forces due to the simultaneous breakage of up to two complete phase conductors or one earth wire, whichever is the more onerous. The towers themselves are usually designed such that no failure or permanent distortion occurs when loaded with forces equivalent to 2 X the maximum simultaneous vertical, transverse or longitudinal working loadings for suspension towers and 2.5 X for tension towers. Under broken wire conditions the towers must be capable of withstanding typically 1.25 X the maximum simultaneous resulting working loadings.

***Conductor tests/inspections* - ** Conductors from a reputable manufacturer’s standard product range should already have full type test certification for electrical and mechanical properties (e.g. to IEC 61089 or EN 50182 for ACSR and BS183 for galvanized earth wire). Tests at the manufacturer’s works, in addition to any routine requirements in standards, may typically include those shown in Table Below.

Overhead line conductor test requirements

	Hard drawn aluminium wire	Complete ACSR or AAAC	Steel wires	Earth wires
Appearance and finish	Yes	Yes	Yes	Yes
Diameter	Yes	Yes	Yes	Yes
Resistivity	Yes			
Tensile test	Yes		Yes	
Wrapping test	Yes		Yes	
Lay ratio		Yes		Yes
Weight per metre		Yes		Yes
Grease weight per metre		Yes		
Breaking strength and resistance		Yes	Yes	Yes
Stress determination at 1% elongation			Yes	
Torsion test			Yes	
Thickness of galvanizing			Yes	Yes

Design Concept and Line Structure

There are various types of overhead transmission line structures available.

The tower is normally constructed from concrete, steel, and timber.

In Malaysia, the towers are commonly constructed from lattice steel. The structure is very strong and relatively lighter and simple to erect.

However, the design and fabrication stages are complicated and time consuming while the base for the tower requires significant land area.

In determining a suitable structure and type of tower to be used, several factors need to be considered:

i. Soil and surrounding conditions.
ii. Cost to design, fabricate, and construct the tower.
iii. Power capacity and voltage level of the line.
iv. Clearance : right-of way.

A single circuit line consists of three phase conductors.

Normally, HVAC line consists of double circuit three phase conductors in parallel to each other.

Conductors for each phase of the lines are bundled in a group of two to four, depending on the voltage levels, and separated by spacers.

On top of the tower is a conductor which is connected directly to earth via the tower configuration.

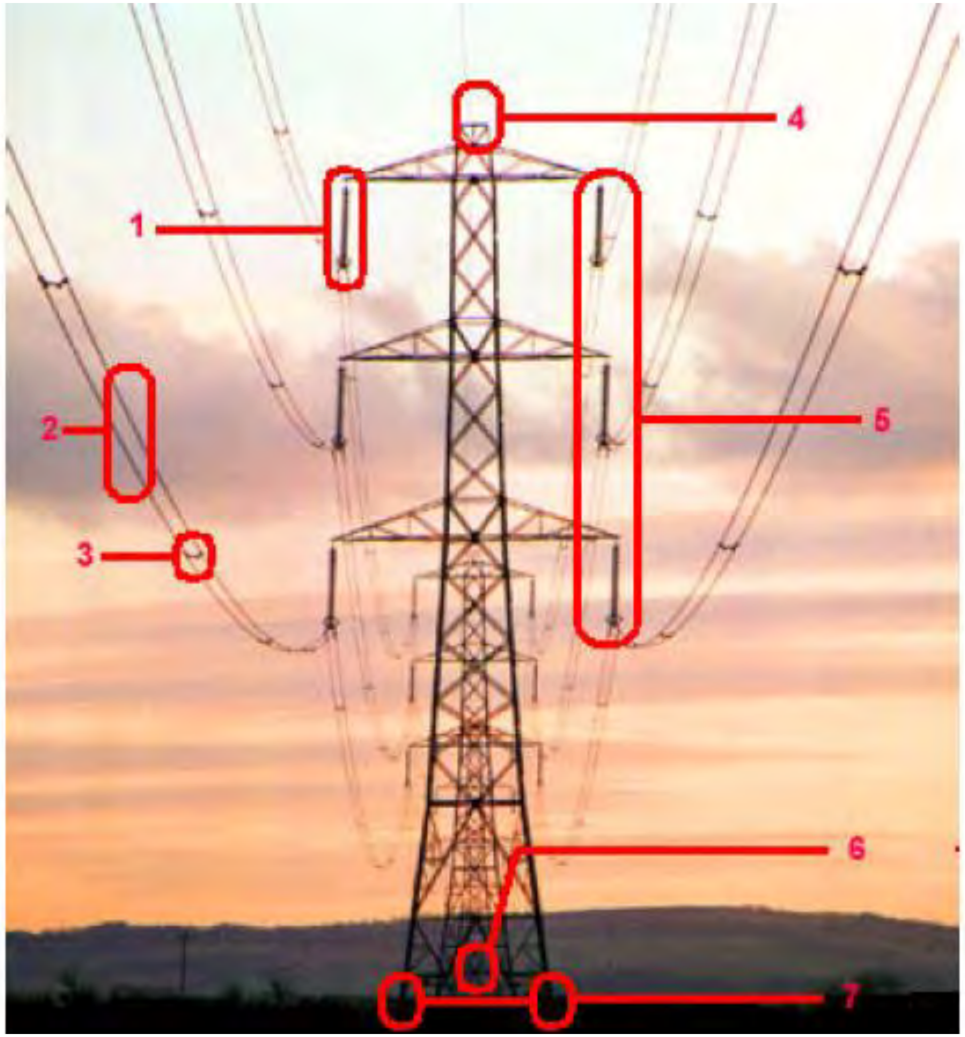
The conductor functions as a shield for the phase conductors from direct lightning strike.

In areas commonly plied by airplanes, the shield conductor is fixed with bright red spheres that can guide the pilots on the location of the tower.

There are four effects on power transmission lines : **resistance, inductance, capacitance**, and **leakage resistance**.

Voltage differences between points move electrons, hence current flows in the line.

The electrons encounter resistance along the line and this effect contributes to power loss and, to some extent, voltage drop in the line.



The main components :

1. Suspension insulator set.
2. Phase conductor.
3. Spacer between two conductors of the same phase.
4. Shield conductor.
5. A set of three phase conductors on a tower.
6. Identification plate for the line.
7. Security feature against unauthorized climber.

The transmission line also develops two types of fields, namely **magnetic** and **electric fields**.

Magnetic field is developed when current induces flux around the conductor.

Alternating current continuously changes the flux and resulting into induced voltage along the line.

The effect forms inductance which causes voltage drop in the line and requires constant supply of reactive power.

Inductance is the property of the circuit that relates the voltage induced by changing flux to the rate of change of current

Capacitance exist between the conductors and is the charge on the conductors per unit of potential difference between them.

The resistance and inductance uniformly distributed along the line form the series impedance. The conductance and capacitance existing between conductors of a single phase line or from a conductor to neutral of 3 phase line form the shunt admittance.

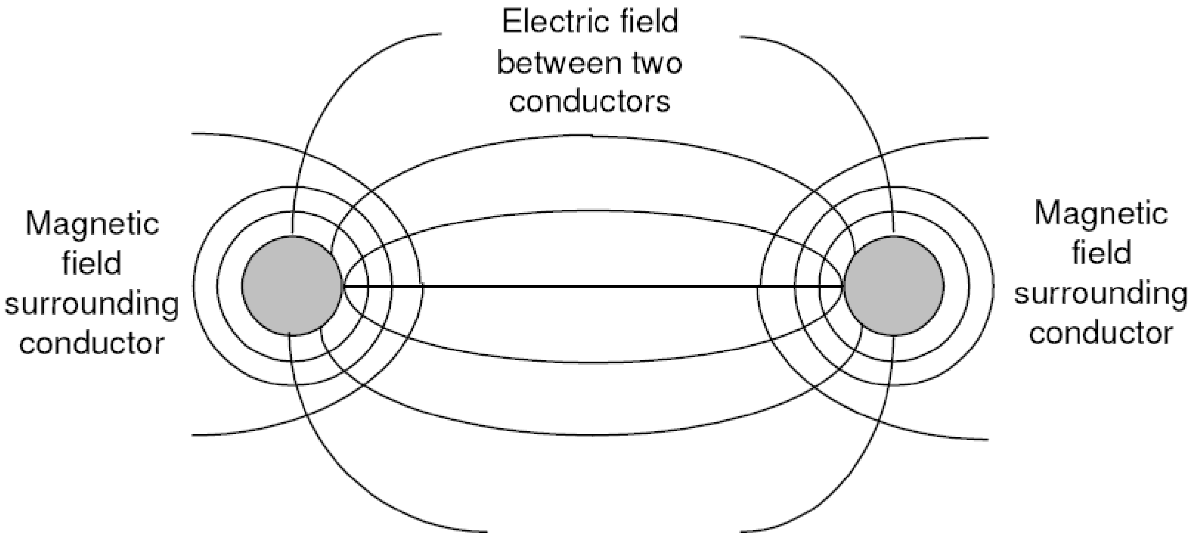
Although the R, L and C are distributed, the equivalent circuit of line is made up of lumped parameters.

The lines of magnetic flux form closed loops linking the circuit, and the lines of electric flux originate on the +ve charges on one conductor and terminate on the –ve charges on the other conductor.

Only flux line external to the conductors are shown. Some of the magnetic field exist inside the conductors.

The changing lines of flux inside the conductors also contribute to the e of the circuit and therefore to the L.

The correct value of L due to internal flux can be computed as the ratio of flux linkages to current by taking into account the fact that each line of internal flux links only a fraction of the total current.



Cross-sectional view of two conductors (shaded circle) with imaginary lines showing magnetic and electric fields

Conductance between conductors that are in touch with each other or between any conductor to earth through suspension insulator contributes to the flow of leakage current in transmission lines.

However, since the leakage in normal operating condition is quite negligible, the leakage reactance to represent the conductance **is not taken into account** in the following discussion.

Direct current resistance, R_{dc} for a conductor can be obtained using

$$R_{dc} = \frac{\rho l}{A} \quad \Omega$$

where : A cross-sectional area (m^2),

p resistivity (Ω.m),

l length (m) of the conductor.

Effective resistance=dc resistance only if the distribution of current throughout the conductor is uniform

$$R = \frac{power\ loss\ in\ conductor}{|I^2|}\ \Omega$$

Resistivity of any conductor depends on the type of material used and the ambient temperature (temperature surrounding the conductor).

Each conductor is normally in the form of strands, : several tiny wires twisted together, to strengthen the line structure.

The stranded arrangement results into higher line resistance since the effective length ***of the stranded conductor*** increases(spiraling of the strands) compared to a solid arrangement.

For example,

consider a one km conductor, all strands except the one in the middle have a length of more than 1 km.

In general, the resistances are estimated to be increased by 1% and 2% for three-stranded and concentrically stranded conductor, respectively.

The effect of ambient temperature is linear.

The point of intersection of the extended line with temperature axis with zero resistance value is a constant of the material.

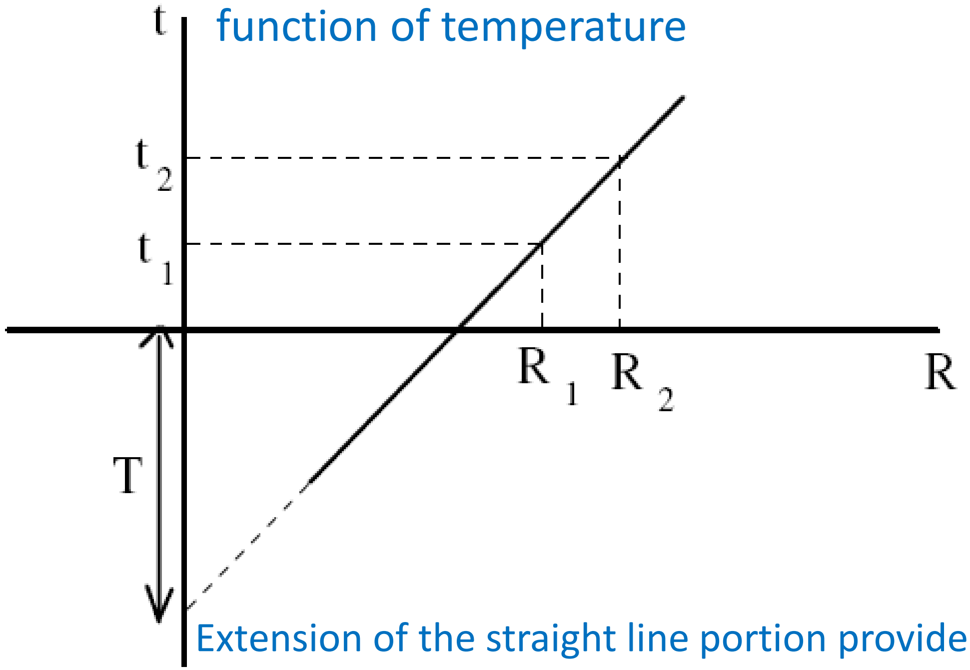
a temperature constant (T) for the given conductor is obtained.

$$\frac{R_2}{R_1} = \frac{T + t_2}{T + t_1}$$

Where : R_1 and R_2 direct current resistances (in Ohm) for the conductor at temperatures of t_1 and t_2 (in degree Celcius)

T is the temperature constant for the conductor

Resistance of a metallic conductor as a function of temperature



Extension of the straight line portion provides a method of correcting resistance for changes in temperature

The values of T for typical metals are:

(i) 234.5, for annealed copper with 100% conductivity,

(ii) 241, for hard drawn copper with 97.3% conductivity,

(iii) 228, for hard drawn aluminum with 61% conductivity.

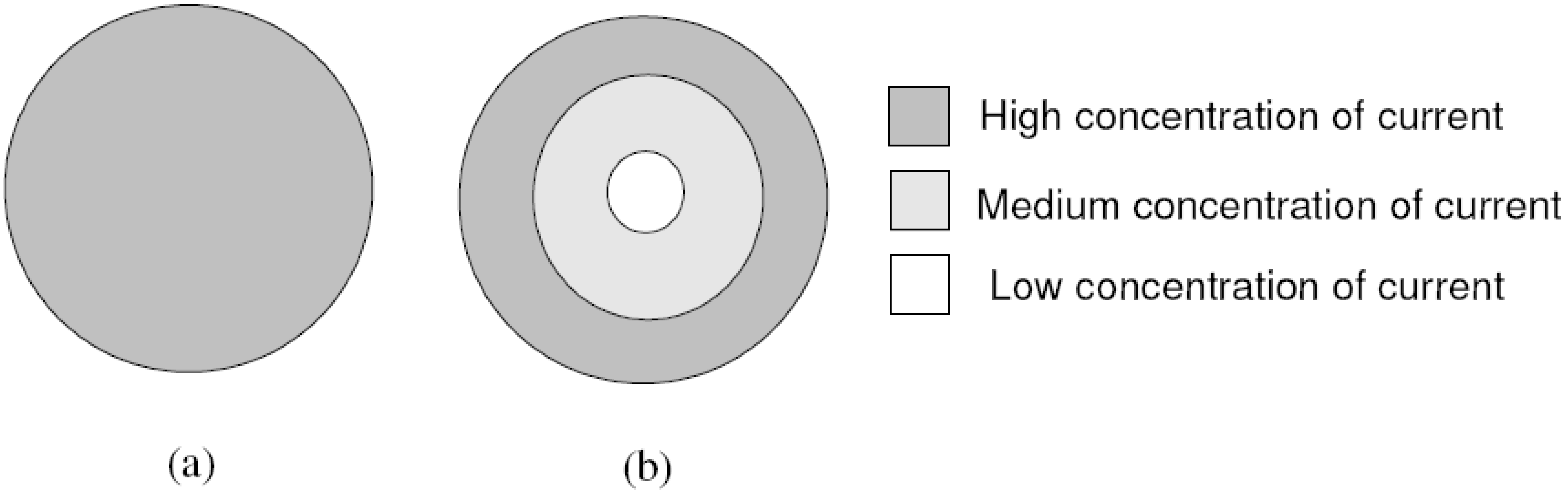
Conductors for ac applications suffer from the non-uniformity of the current distribution throughout the cross section of a conductor.

This phenomenon is known as ***skin effect***

The non-uniformity of current distribution is more apparent if the source frequency is higher. An increase of frequency causes non-uniform current density.

For cylindrical type conductor, skin effect results into higher current density near the surface compared to that at the centre of the conductor.

This effect increases the actual resistance of the conductor since current flow is limited to a smaller cross-sectional area of the conductor.



Current distribution across conductor with (a) direct current source and (b) alternating current source

Example:

An aluminum conductor consists of 24 strands, each with diameter of 0.508 cm. The conductor is used as a 3.22 km single phase line. For the aluminum conductor, assume that the temperature constant and resistivity are 228 and 3.6 x 10^{-8} Ωm (at 20° C),respectively. Calculate direct current resistance for the line at temperature of 70°C. Next, obtain the resistance value if stranding effect of 2% is taken into account.

Solution:

Cross sectional area for 24 strands = $24\pi(0.508 \text{ x } 10^{-2}/2)^2 = 4.9 \text{ x } 10^{-4} \text{ m}^2$.
At 70 °C resistivity of the conductor is

$$\rho = 3.6 \text{ x } 10^{-8}\left[\frac{228+70}{228+20}\right] = 4.33 \text{ x} 10^{-8}\ \Omega\text{m}$$

Direct current resistance at 70°C is

$$R_{\text{dc, }70^{o} C} = \frac{4.33 \text{ x } 10^{-8} \text{ x } 3.22 \text{ x } 10^{3}}{4.9 \text{ x } 10^{-4}} = 0.29\ \Omega$$

Taking into consideration the effect of stranding, the actual dc resistance is

$$R_{\text{line}} = 0.29 \text{ x } 1.02 = 0.296\ \Omega.$$

Self-assessment Question

Obtain the value of current resistance per km at temperature of 40°C for a three-strand copper conductor for which each stand has a diameter of 0.508cm. Use 2.3×10^{-8} Ωm for resistivity of copper at 20°C and 241.5 as temperature constant. Also account for 1% increase of resistance for the conductor due to the 3-strand configuration.

[0.318 Ωkm]

The effect of inductance in transmission line can be described by two electromagnetic induction phenomena on a conductor.

(i) flux changes induce voltage in a circuit, $e = \frac{d\tau}{dt}$

e : induced voltage (V)

τ : flux linkages on the circuit in weber-turns (Wbt)

(ii) change of current in the circuit that alters the flux linkages.

If permeability of the surrounding medium can be assumed constant, then the flux linkage is directly proportional to the current

$$e = L\frac{di}{dt}$$

L : constant known as inductance (H),

$\frac{di}{dt}$: rate of change of current against time (A/s).

The solution for both equations results into

$$L=\frac{d\tau}{di}$$

Flux linkages change linearly with respect to current(magnetic circuit has a constant μ)

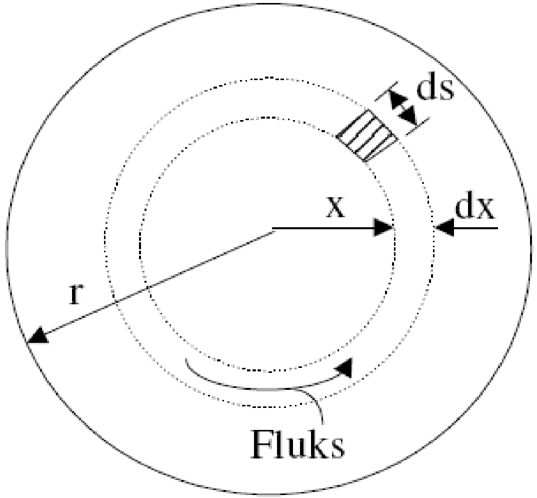
$$L = \frac{\tau}{i}$$

Inductance for a conductor consists of two parts

1. internal inductances(due to internal flux) : developed due to the current in the conductor
2. external inductances (due to flux external to a conductor): resulted from the flux linkages of the other conductor.

To obtain the internal inductance of the conductor, one needs to assume that the return path for the conductor is far away such that there is no effect from current in the return conductor.(not affect the magnetic field of the conductor)

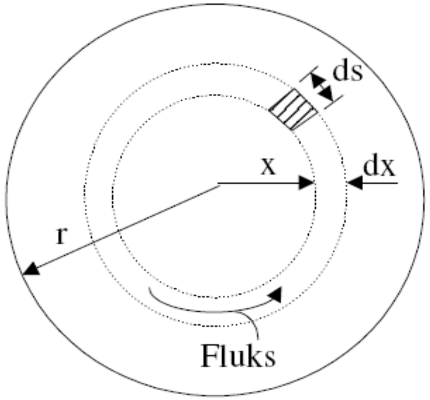
Thus, all fluxes to be considered are contained inside the conductor.



Cross section of a cylindrical conductor

Given current I flows in the conductor, then by applying Ampere’s Law, the magnetomotive force for concentric closed circular path of radius x,

$$\oint H_X ds = I_X$$



where H_x : magnetic field intensity at a distance x meters from the center of conductor (Ampere-turns/m)

I_x : enclosed current (A).

s: distance along path (m)

Since the field is symmetrical, H_x is constant at all points equidistant from the center of the conductor. If the integration is performed around a circular path concentric with the conductor at x meters from the center, H_x is constant over the path and tangent to it. Therefore,

$$2\pi x H_X = I_X$$

Assuming uniform current density,

$$I_X = \left(\frac{\pi x^2}{\pi r^2}\right) I = \left(\frac{x^2}{r^2}\right) \underset{\text{Total current}}{I}$$

Then, we can obtain

$$H_X = \frac{xI}{2\pi r^2} \qquad \text{At/m}$$

The flux density B_x , x (m) from the center of the conductor is

$$B_X = \mu H_X = \frac{\mu xI}{2\pi r^2} \qquad \text{Wb/m}^2$$

μ is the permeability of the conductor

For conductor length of 1 (m), the flux in the tubular element of thickness dx, the flux

dø is B_X times the cross sectional area of the element normal to the flux lines, the

area being dx times the axial length.

The flux per meter of length is

$$d\phi = \frac{\mu x I}{2\pi r^2} dx \quad Wb/m$$

The flux linkages *dλ* per meter of length, which are caused by the flux in the

tubular element, are the product of the flux per meter of length and the fraction

of current linked.

$$d\lambda = \left(\frac{x^2}{r^2}\right) d\phi = \left(\frac{x^2}{r^2}\right) \frac{\mu x I}{2\pi r^2} dx \quad \text{Wbt/m}$$

Integrating from the center of the conductor to its outside edge to find the total flux linkages inside the conductor

$$\lambda_{int} = \int_0^r \frac{\mu I}{2\pi r^4} x^3 dx = \frac{\mu I}{8\pi}$$

the internal inductance L_i in (H/m) is

$$L_i = \frac{\mu}{8\pi} \text{ H/m}$$

where,

$\mu = \mu_o \mu_r$

μ_o : permeability of free space (4π x 10^{-7} H/m)

μ_r : relative permeability of the given conductor material .

The value of μ_r is equal to 1 for aluminum, copper, and air.

For metallic conductor made of copper or aluminum, the internal inductance is equal to

$$L_i = \frac{4\pi \text{ x } 10^{-7}}{8\pi} \text{ H / m} = \frac{1}{2} \text{ x } 10^{-7} \text{ H / m}$$

Inductance per unit length (H/m) of a round conductor attributed only to the flux inside the conductor

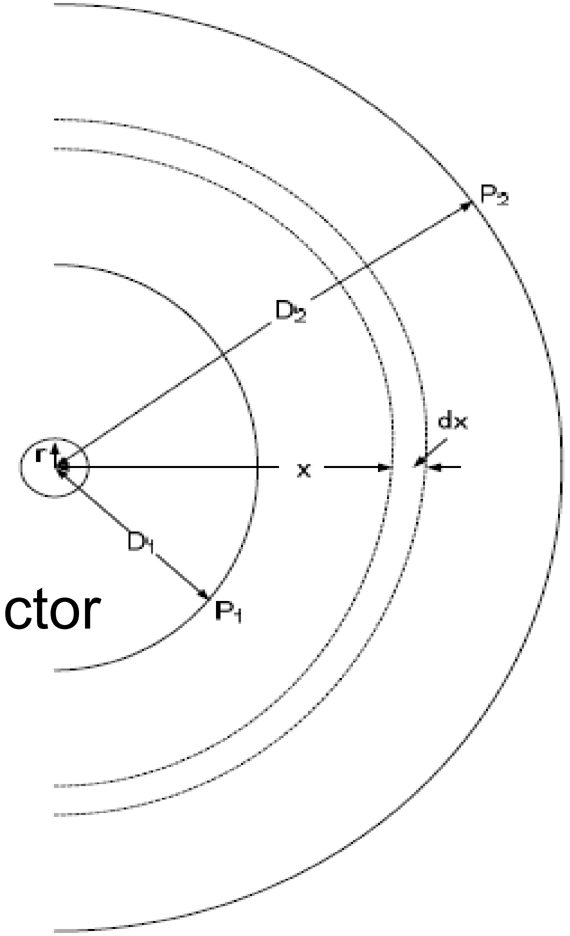
The external inductance for a conductor is due to the flux linkages from current of the other conductor for a given transmission line.

Points P_1 and P_2 are at distances D_1 and D_2 from the conductor which carries current I.

Assuming that the return path is far removed from the conductor, thus the magnetic field external to the conductor(flux path) is concentric circles around the conductor and all the flux between P_1 and P_2 lies within the concentric cylindrical surfaces passing through P_1 and P_2.

At the tubular element which is x meters from the center of the conductor the field intensity is H_x.

The mmf around the element, $2\pi x H_x = I$



A conductor and external points P_1 and P_2

Magnetic field intensity at distance x from the conductor is

$$H_X = \frac{I}{2\pi x} \quad (\mathrm{AT/m})$$

The flux dø contained in the tubular element of thickness dx is

$$d\phi = \frac{\mu I}{2\pi x} dx \quad (\mathrm{Wb/m})$$

Flux linkages per meter are numerically equal to the flux dø, since flux external to the conductor links all the current in the conductor only once

$$d\lambda = 1 \times d\phi = \frac{\mu I}{2\pi x} dx$$

Therefore, the total flux linkages of the conductor due to flux between P_1 and P_2 is

$$\lambda_{12} = \int_{D_1}^{D_2} \frac{\mu I}{2\pi x} dx = \frac{\mu}{2\pi} I \ln \frac{D_2}{D_1} \quad \text{Wbt/m}$$

For μr = 1

$$\lambda_{12} = 2\times10^{-7}\,I\ln\frac{D_2}{D_1}\quad\text{(Wb-turn/m)}$$

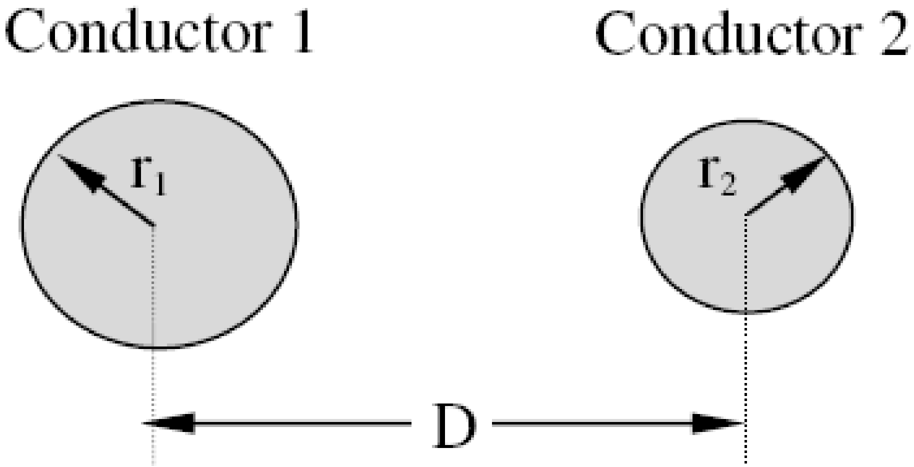
The external inductance between D_1 and D_2 is

$$L_{12} = \frac{\lambda_{12}}{I} = 2\text{ x }10^{-7}\ln\frac{D_2}{D_1}\quad\text{(H/m)}$$

Inductance due only to the flux included between P_1 and P_2

Inductance for Single Phase Line(2-wire line composed of solid round conductor)

Figure gives a cross-sectional view of two conductors in a single phase alternating current transmission line, both separated by a distance D and with radius of r_1 and r_2, respectively. One conductor is the return circuit for the other.



A circuit having 2 conductors of different radii and the magnetic field due to current in conductor 1 only

The inductance of both line(circuit) due to current in conductor 1 is determined by L_{12}, with the distance D between conductors 1 and 2 substituted for D_2 and the radius r_1 of conductor 1 substituted for D_1.

$$L_{12} = \frac{\lambda_{12}}{I} = 2 \times 10^{-7} \ln \frac{D_2}{D_1} \quad \text{(H/m)}$$

$$L_{1,ext} = 2 \times 10^{-7} \ln \frac{D}{r_1}$$

The inductance of conductor 1 is

$$L_1 = L_{1i} + L_{1o} = \frac{1}{2} \times 10^{-7} + 2 \times 10^{-7} \ln \frac{D}{r_1}$$

$$= 2 \times 10^{-7} [\frac{1}{4} + \ln \frac{D}{r_1}] \quad \text{(H/m)}$$

$$L_i = \frac{4\pi \times 10^{-7}}{8\pi} \text{ H/m} = \frac{1}{2} \times 10^{-7} \text{ H/m}$$

Since $\ln(e^{\frac{1}{4}}) = \frac{1}{4}$, thus

$$L_1 = 2 \times 10^{-7} [\ln(e^{\frac{1}{4}}) + \ln \frac{D}{r_1}]$$

$$= 2 \times 10^{-7} \left[\ln \frac{D}{e^{-\frac{1}{4}} r_1} \right] = 2 \times 10^{-7} \left[\ln \frac{D}{r_1'} \right] \quad \text{(H/m)}$$

Inductance per conductor

The radius r'_1 is that of a fictitious conductor assumed to have no internal flux but with the same inductance as the actual conductor of radius r_1.

This eq. omits the term to account for internal flux but compensates for it by using an adjusted value for the radius of the conductor.

Multiplying factor of 0.7788 to adjust the radius in order to account for internal flux applies only to solid round conductor.

where $r_1' = e^{-\frac{1}{4}} r_1 = 0.7788 r_1$.

Assuming that the return path is far removed from the conductor,

Where $r_1' = e^{\frac{1}{4}} r_1 = 0.7788 r_1$

The inductance due to current in conductor 2 is

$$L_2 = 2 \times 10^{-7} \left[ln \frac{D}{r_2'} \right] \text{(H/m), where } r_2' = 0.7788 r_2.$$

Thus, the total inductance for the line(complete circuit) is

$$\underset{\substack{\big\downarrow \\ \text{Inductance per loop meter}}}{L} = L_1 + L_2 = 4 \times 10^{-7} \left[in \frac{D}{\sqrt{r_1' r_2'}} \right] \text{(H/m)}$$

The inductance of the 2-wire line taking into account the flux linkages caused by current in both conductors, one of which is the return path for current in the other.

For line with both conductors have similar diameter, i.e. $r_1' = r_2'$ inductance is

$$L = 4 \times 10^{-7} \left[\ln \frac{D}{r'} \right] \text{ (H/m)}, \text{ where } r' = 0.7788r$$

Inductive reactance is obtained by multiplying the inductance by frequency

$$X_L = 2\pi f L = 8\pi \times 10^{-7} f \ln \frac{D}{R'} \quad (\Omega / m)$$

Self-assessment Question

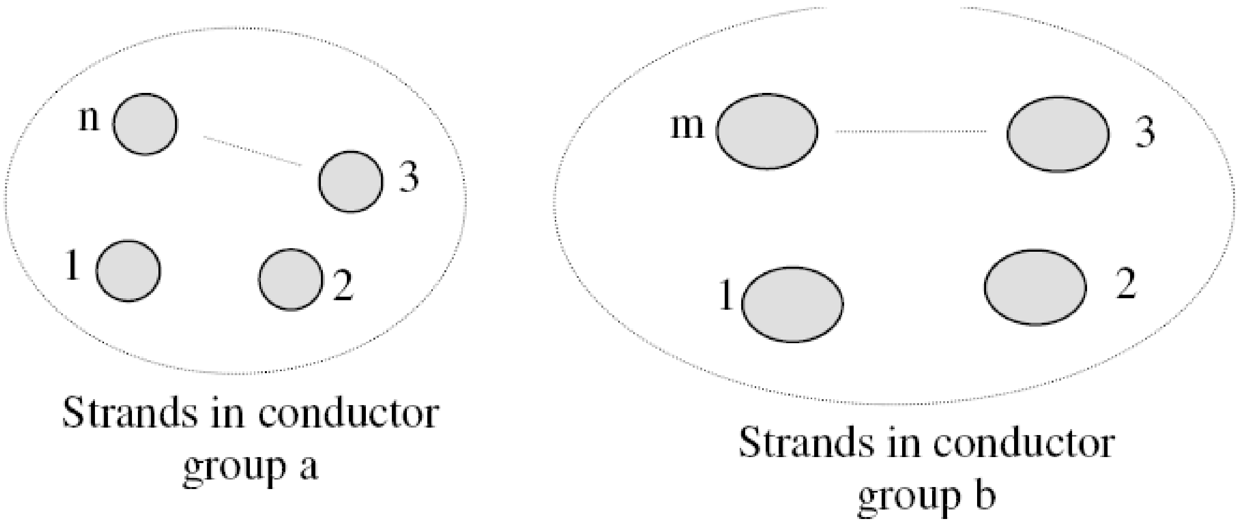
Both conductors for a single phase line has a radius of 0.1cm and separated from each other by 2 metre. Calculate the inductance per metre for each conductor and total inductance for the line.

$[1.57 \times 10^{-6}\ H/m,\ 3.14 \times 10^{-6}\ H/m,]$

Inductances of Stranded Conductors

Stranded conductors come under the general classification of composite conductors, which means conductors composed of two or more elements or strands electrically in parallel.

All strands are identical and share the current equally.

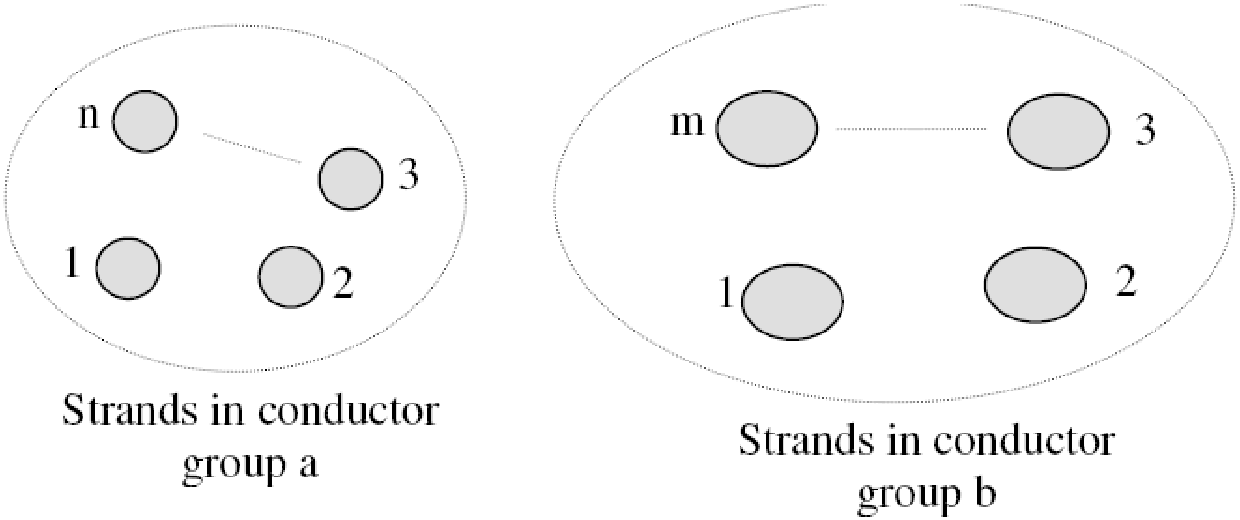


Single phase line consisting of two composite conductors(Double Circuit Single phase line)

Inductances of Stranded Conductors

Conductor group a is composed of n identical, parallel filaments, each of which carries the current I/n. Conductor group b, which is the return circuit is composed of m identical, parallel filaments, each of which carries the current –I/m.

Distance between the elements will be designated by the letter D with appropriate subscripts.



Single-phase line consisting of two composite conductors(Double Circuit Single phase line)

Inductances of Stranded Conductors

Typically, a conductor is made of several strands of wire .

To simplify analysis, the following assumptions are normally taken into consideration:

i. Current I, is assumed uniformly distributed among the strands of the conductors.

ii. Radius for each strand is assumed equal with other strands for each group of the conductor, i.e. $r_{a1}=r_{a2}=.....=r_{an}$ and $r_{b1}=r_{b2}=......=r_{bm}$.

Conductor group a is composed of n filaments electrically in parallel.

If all the filaments had the same inductance, the inductance of the conductor would be 1/n times the inductance of one filament.

Here all the filaments have different inductances, but the inductance of all of them in parallel is 1/n times the average inductance.

The average inductance for conductor a is

$$L_{average} = \frac{L_{a1} + L_{a2} + L_{a3} + \dots\dots\dots + L_{an}}{n}$$

Since L_{a1}, L_{a2}, L_{a3}, ...L_{an} are in parallel and $L_{average}$ is taken as inductance in each parallel branch, thus

$$\underset{\big\downarrow}{L_a} = \frac{L_{average}}{n} = \frac{L_{a1} + L_{a2} + L_{a3} + \dots\dots\dots + L_{an}}{n^2}$$

Inductance of conductor group a

Substituting the logarithmic expression for inductance of each filament in L_a and combining terms,

$$L_a = 2 \times 10^{-7} \times \ln \frac{\sqrt[mn]{(D_{a1b1}D_{a1b2}D_{a1b3}\cdots D_{a1bm})(D_{a2b1}D_{a2b2}D_{a2b3}\cdots D_{a2bm})\ldots\ldots(D_{anb1}D_{anb2}D_{anb3}\cdots D_{anbm})}}{\sqrt[n^2]{(D_{a1a1}D_{a1a2}D_{a1a3}\cdots D_{a1an})(D_{a2a1}D_{a2a2}D_{a2a3}\cdots D_{a2an})\ldots\ldots(D_{ana1}D_{ana2}D_{ana3}\cdots D_{anan})}}$$

where $D_{aiai} = r_i'$ bagi i =1,2,.......n.

In general, it can be deduced that:

i. Geometric Mean Distance, GMD (or D_m) between conductor a and b is the numerator of Equation 3.31.

ii. Geometric Mean Radius, GMR (D_S or also known as *self GMD*) is the denominator of Equation 3.31.

iii. Thus, $L_a = 2 \times 10^{-7} \ln \frac{D_m}{D_S}$ H/m.

GMD-the products of the distances from all the n filaments of conductor group a to all the m filaments of conductor group b

GMR-the product of the distances from every filaments in the conductor to itself and to every other filament.

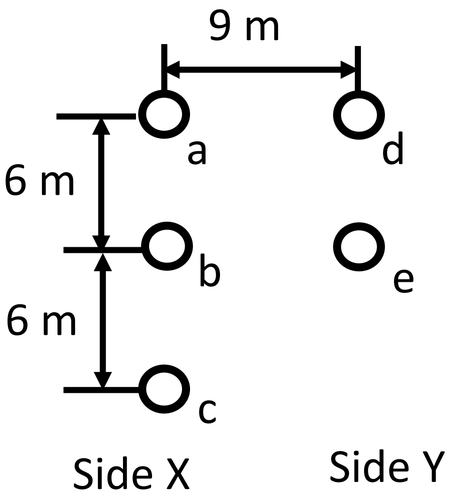
The inductance of L_b is determined in a similar manner, and the inductance of the line is

$$L = L_a + L_b$$

Example Problem

One circuit of a single-phase transmission line is composed of three solid 0.25 cm radius wires. The return circuit is composed of two 0.5 cm radius wires.

Find the inductance per conductor per meter and loop inductance per km of the line.

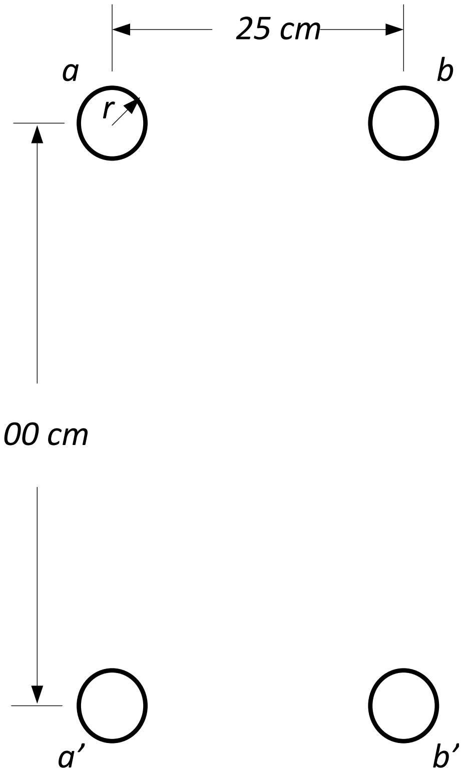


Ans:

(GMD between sides X and Y, D_m =10.743 m, GMR for side X, D_s = 0.481 m, GMR for side Y, D_s = 0.153 m, L_X= 6.212 X 10^{-7} H, L_Y= 8.503 X 10^{-7} H, L = 1.4715 mH)

Example Problem

Determine the inductance per km of double circuit single phase line. The conductor radius, r = 0.5 cm



Ans:

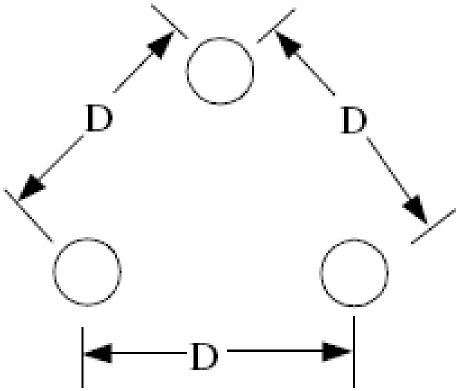
(D_m =50.74 cm, D_s = 6.23 cm, L=0.84 mH)

Inductance of three –phase lines with equilateral spacing

In order to obtain the inductance for a three phase line, the system is assumed balanced, i.e. the total current phasor for all phases is equal to zero.

In this case, the effect of neutral line can neglected since it does not carry any current. For line with symmetrical configuration, the inductance of each phase is :

D=spacing of conductors

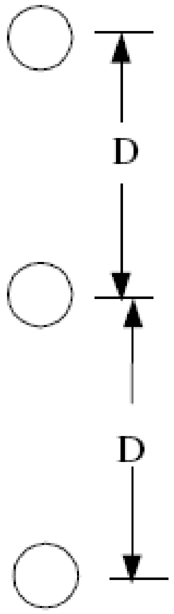


$$D_m = (D \times D \times D)^{1/3}$$

$$D_s = 0.7788r$$

$$L_a = 2 \times 10^{-7} \ln \frac{D}{D_s} = Lb = Lc$$

Inductance per phase of the three phase line



Symmetrical spacing

Inductance of three –phase lines with unsymmetrical spacing

However, three phase transmission lines are normally arranged in unsymmetrical manner.

The inequalities of the distances between phase conductors result into differences in flux linkages and inductances of the lines.

For short transmission lines, the unbalanced condition can be neglected.

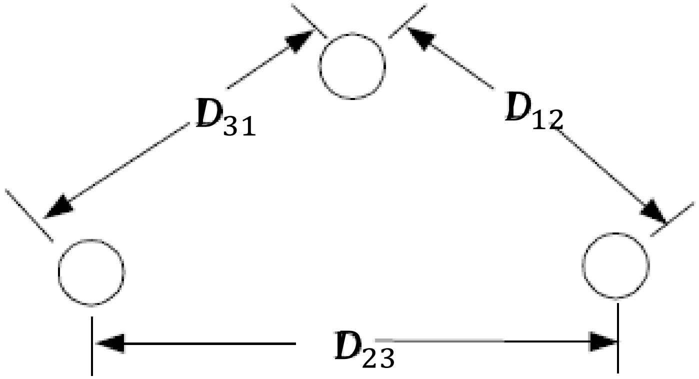
However, for long lines, the differences in line inductances can affect the line performances.

Thus, typically for these lines, the conductors are transposed at several switching stations at regular intervals.

This is to ensure that the total inductances of all lines are the same.

Equivalent equilateral spacing, $D_{eq} = (D_{12} \times D_{23} \times D_{31})^{1/3}$

D_s =0.7788r



Unsymmetrical spacing

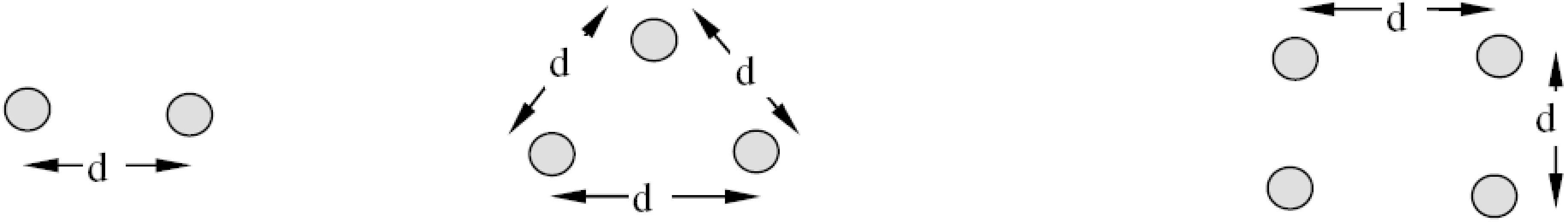
With this arrangement, the average inductance per phase of the lines can be obtained using equation below.

$$L_a = 2 \times 10^{-7} \ln \frac{D_{eq}}{D_s} \text{ H/m} \qquad D_{eq} = \sqrt[3]{D_{12} D_{23} D_{31}}$$

$$D_s = 0.7788r$$

Inductance for Bundled Conductor

For high voltage transmission line over approximately 100 kV, a bundled arrangement is normally used.



Bundle arrangements

Bundled arrangement for phase conductors consisting of (a) two (b) three and (c) four conductors.

Among **advantages** of the lines in bundled formation are:

i.The inductive reactance is lower.
ii.Voltage gradient is reduced.
iii.Critical level for corona is increased ,resulting into reduced power loss caused by corona, noise, and also reduced radio frequency interference.
iv.More power per unit mass of the conductor can be transported by the lines.

Disadvantages:

i. Increase of mechanical loading to the line due to wind or snow.

ii. The technique to suspend the conductors to transmission towers becomes much more complicated due to the weight of the additional conductors.

iii. The conductors are easily sway when blown by the wind.

iv. Increase of construction cost.

v. Significant effect from reactive power charging.

For the transposed conductor group in bundled arrangement, values of D_S,

D_{bS} (GMR of a bundled conductor)

D_S (GMR of individual conductors composing the bundle)

Bundled with 2 conductors

$$D_{bS} = \sqrt[2^2]{D_s \times d \times D_s \times d} = \sqrt{D_s \times d}$$

For the transposed conductor group in bundled arrangement, values of D_S,

Bundled with 3 conductors

$$D_{bS} = \sqrt[3^2]{(D_s \times d \times d)^3} = \sqrt[3]{D_s \times d^2}$$

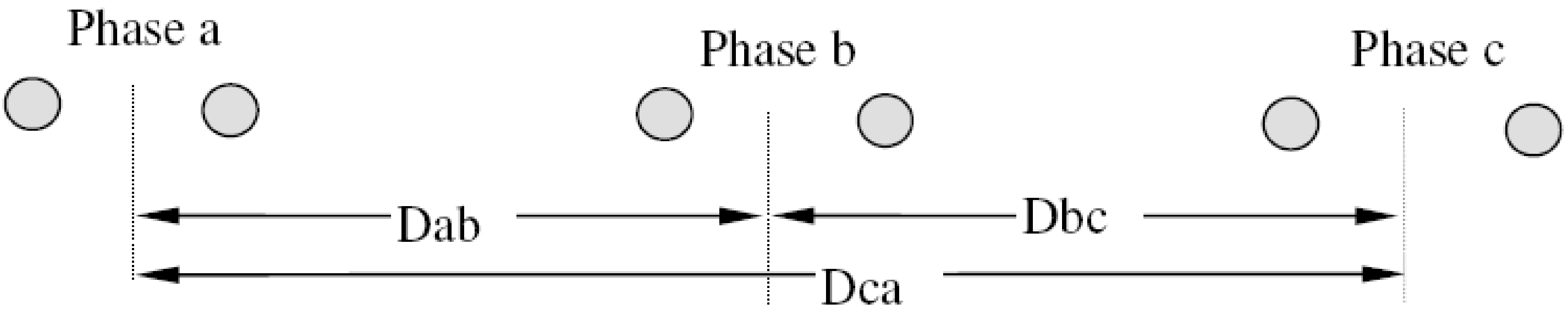
Bundled with 4 conductors

$$D_{bS} = \sqrt[4^2]{(D_s \times d \times d \times \sqrt{d^2 + d^2})^4}$$

$$= \sqrt[4]{D_s \times d^3 \times \sqrt{2}} \qquad = 1.09\sqrt[4]{D_s \times d^3}$$

For D_m (GMD) between the groups of conductors, the distance between center points of the groups are taken into account.

$$D_m = \sqrt[3]{D_{ab} D_{bc} D_{ca}}$$



Example:

A 50 Hz three phase transmission line is arranged as a three-conductor bundled line for each phase, as shown in Figure 3.17(b) while the three phase arrangement is in horizontal manner. Given that the GMR for each conductor of every phase is 6.767 mm, the distance d between the centre of adjacent conductor of each phase is 30 cm, and the distance between the centre of adjacent phase conductors is 15 m. Calculate the inductive reactance in Ω per km per phase for the line.

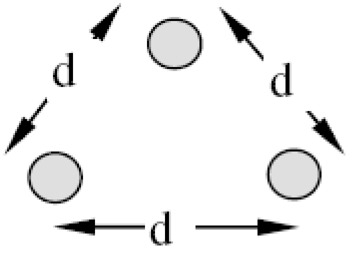


Figure 3.17(b)

Solution: GMR = $D_S = 6.767 \times 10^{-3}$ m.

$d = 30$ (cm) x 0.01 (m/cm) = 0.3 m.

$$D_{Sb} = \sqrt[3]{D_S \times d^2} = 0.085\,\text{m}.$$

$$D_m = \sqrt[3]{15 \times 15 \times 30} = 18.9\text{m}.$$

Thus, $L = 2 \times 10^{-7} \ln\left(\dfrac{18.9}{0.085}\right) = 1.08 \times 10^{-6}$ H/m.

$X_L = 2\pi(50)L = 0.34 \times 10^{-3}$ Ω/m per phase.

In per km term, the reactance becomes

$X_L = 0.34 \times 10^{-3} \times 1000 = 0.34$ Ω/km per phase.

Inductance for two Three-Phase Line In Parallel (Double Circuit 3 Phase line)

A paired three phase line arrangement in which each phase consists of two parallel lines.

Typically each line has the same value of GMR.

All conductors for each phase is considered as strands for that phase.

To simplify analysis, the line is considered to be properly transposed.

The steps to obtain GMD between phases of conductors (D_m) are as follows:

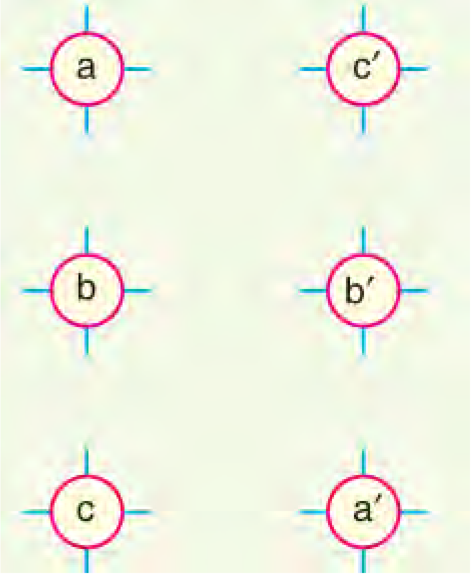
$$D_{m\text{-}ab} = \sqrt[4]{D_{ab} D_{ab'} D_{a'b} D_{a'b'}}$$

$$D_{m\text{-}bc} = \sqrt[4]{D_{bc} D_{bc'} D_{b'c} D_{b'c'}}$$

$$D_{m\text{-}ca} = \sqrt[4]{D_{ca} D_{ca'} D_{c'a} D_{c'a'}}$$

$$D_m = \sqrt[3]{D_{m\text{-}ab} D_{m\text{-}bc} D_{m\text{-}ca}}$$

Dij : geometric distance between conductors i and j



Conductor arrangement of the double circuit

The procedure to calculate phase GMR (D_S) is as follows:

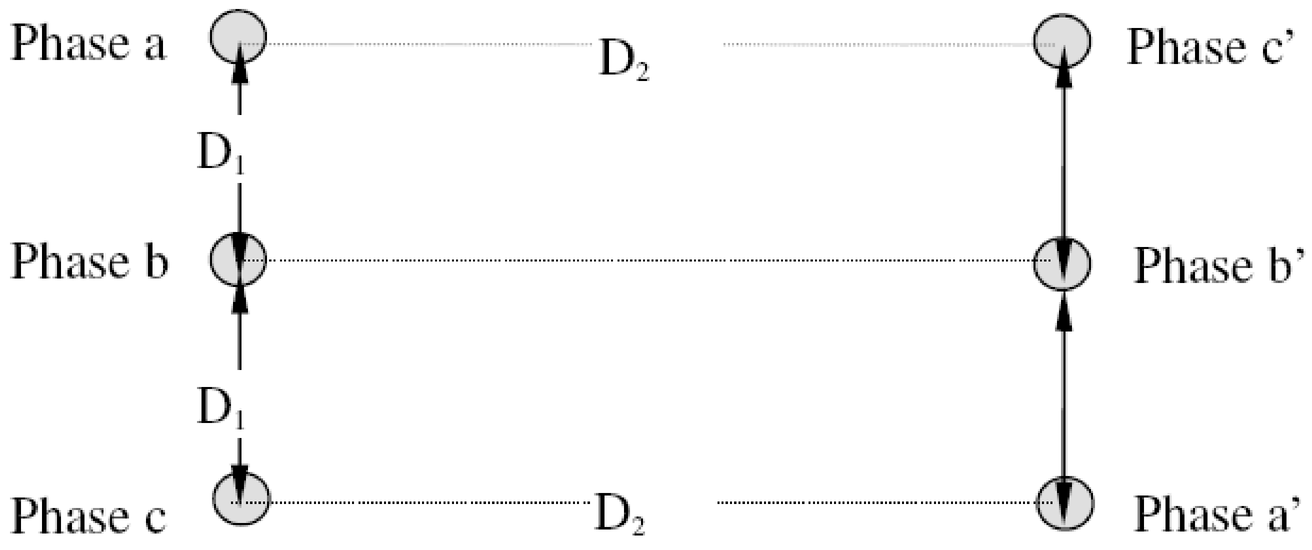
$$D_{sa} = \sqrt{D_{s\text{-conductor}} D_{aa'}}$$

$$D_{sb} = \sqrt{D_{s\text{-conductor}} D_{bb'}}$$

$$D_{sc} = \sqrt{D_{s\text{-conductor}} D_{cc'}}$$

$$D_S = \sqrt[3]{D_{sa} D_{sb} D_{sc}}$$

D_s : conductor is obtained similar to that for deriving GMR. Dii : distance between two conductors of the same phase.

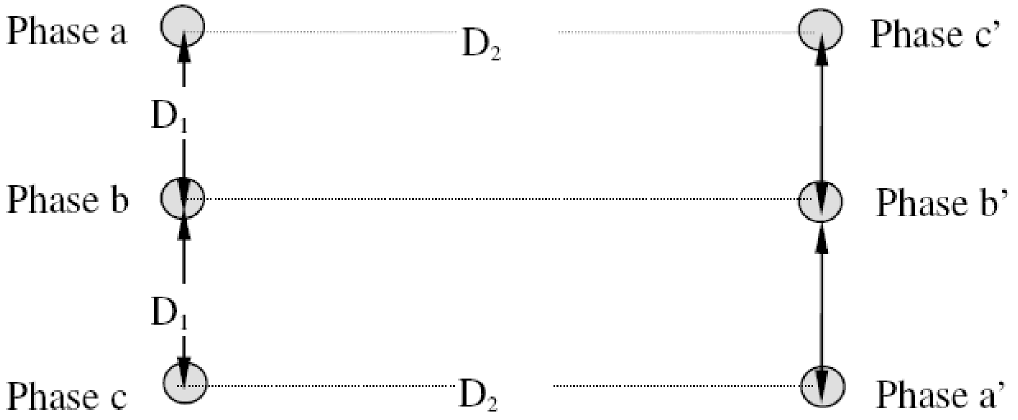


three phase line arranged in parallel

The inductance of the line is

$$L = 2\times10^{-7}\ \ln\frac{D_m}{D_S}\quad \text{H/m per phase}\quad .$$

Example: A three phase line is arranged as below. The GMR for each conductor is 6.62 mm. The distance D_1 and D_2 are 3.1 m and 4.6 m, respectively. If the line frequency is 50 Hz, calculate the inductive reactance of the line in Ω per km per phase.



Solution:

$\text{GMR} = D_S = 6.62 \text{ mm} = 6.62 \text{ x } 10^{-3} \text{ m.}$

$\text{Distance ab'} = \text{Distance bc'} = \sqrt{3.1^2 + 4.6^2} = 5.6 \text{ m.}$

GMD is obtained as follows:

$$D_{m\text{-}ab} = \sqrt[4]{(3.1 \text{ x } 5.6)^2} = 4.2 \text{ m}$$

$$D_{m\text{-}bc} = \sqrt[4]{(3.1 \text{ x } 5.6)^2} = 4.2 \text{ m}$$

$$D_{m\text{-}ca} = \sqrt[4]{(6.2 \text{ x } 4.6)^2} = 5.3 \text{ m}$$

$$D_m = \sqrt[3]{4.2 \text{ x } 4.2 \text{ x } 5.3} = 4.5 \text{ m}$$

$\text{Distance aa'} = \sqrt{6.2^2 + 4.6^2} = 7.7 \text{ m}$

GMR is calculated as follows:

$$D_{sa} = \sqrt{6.62x10^{-3}\ x\ 7.7} = 0.23\ m$$

$$D_{sb} = \sqrt{6.62x10^{-3}\ x\ 4.6} = 0.18\ m$$

$$D_{sc} = \sqrt{6.62x10^{-3}\ x\ 7.7} = 0.23\ m$$

$$D_S = \sqrt[3]{0.23\ x\ 0.18\ x\ 0.23} = 0.21\ m$$

$$L = 2\times10^{-7}\ \ln\frac{D_m}{D_S} = 2\times10^{-7}\ \ln\frac{4.5}{0.21} = 0.62\ x\ 10^{-6}\ \text{H/m per phase.}$$

$$X_L = [2\pi(50)\ x\ 0.62\ x\ 10^{-6}]x\ 1000 = 0.20\ \Omega/\text{km per phase.}$$

Capacitance forms shunt admittance in transmission line.

It exists when there is potential difference between two lines.

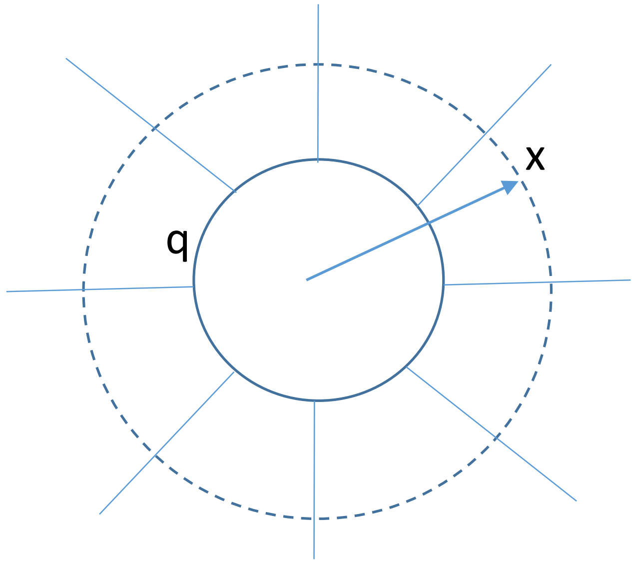
Charges in the conductor create lines of electric flux, which originate from positive to negative charges.

The flow of charge is current, and the current caused by the alternate charging and discharging of a line due to an alternating voltage is called charging current of the line.

The flux results into charging current flowing through the space between the lines, the reason on current flows through open-circuited transmission line.

It affects the voltage drop along the line as well as the efficiency and power factor of the line and the stability of the system of which the line is a part.

Consider the round conductor shown in Fig. below. The conductor has a radius of r and carries a charge of q coulombs.



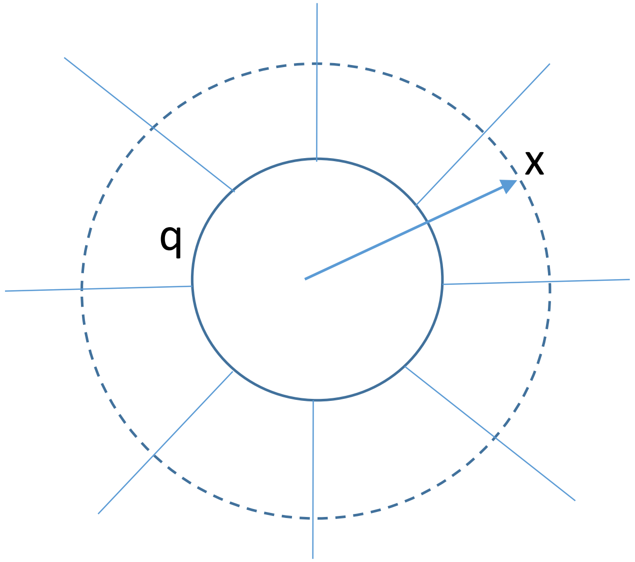
The capacitance C is the ratio of charge q of the conductor to the impressed voltage, $C = \frac{q}{V}$

The charge on the conductor gives rise to an electric field with radial flux lines where the total electric flux is equal to the charge on the conductor.

The following are general steps in deriving capacitance formula for transmission line.

Using Gauss Law : Electric flux density, D (C/m^2) at a cylinder of radius x when the conductor has a length of 1 m is

$$D = \frac{q}{A}$$



Where : *q : the charge per unit length on the conductor (C/m)*

A : the effective area taken by electric flux (in m^2).

Electric field intensity, E $$E = \frac{D}{\varepsilon} \quad \text{V/m}$$

where ε is permittivity of medium between conductors (in F/m).

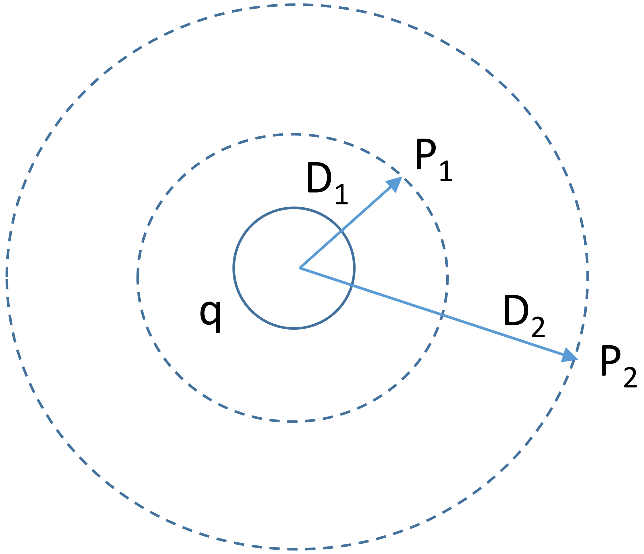
$$\varepsilon = \varepsilon_o \varepsilon_r$$

where ε_o : permittivity of free space (8.85×10^{-12} F/m)
ε_r : relative permittivity of the medium. For air, $\varepsilon_r = 1$.

Consider the long straight conductor that is carrying a +ve charge q C/m.

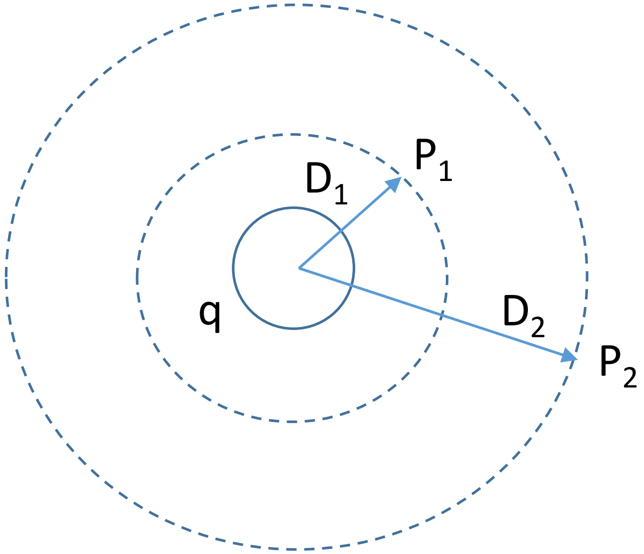
Let two points P_1 and P_2 be located at distances D_1 and D_2 respectively from the centre of the conductor.

The conductor is an equipotential surface in which we can assume that the uniformly distributed charge is concentrated at the centre of the conductor.



The potential difference V_{12} between the points P_1 and P_2 is the work done in moving a unit of charge from P_2 and P_1.

Therefore the voltage drop between the two points can be computed by integrating the field intensity over a radial path between the equipotential, surface,

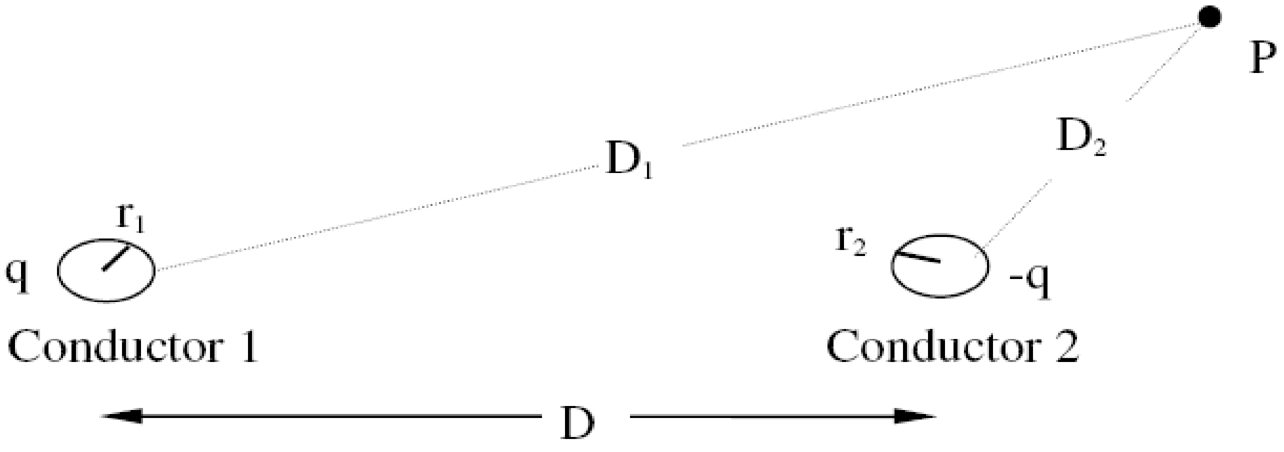


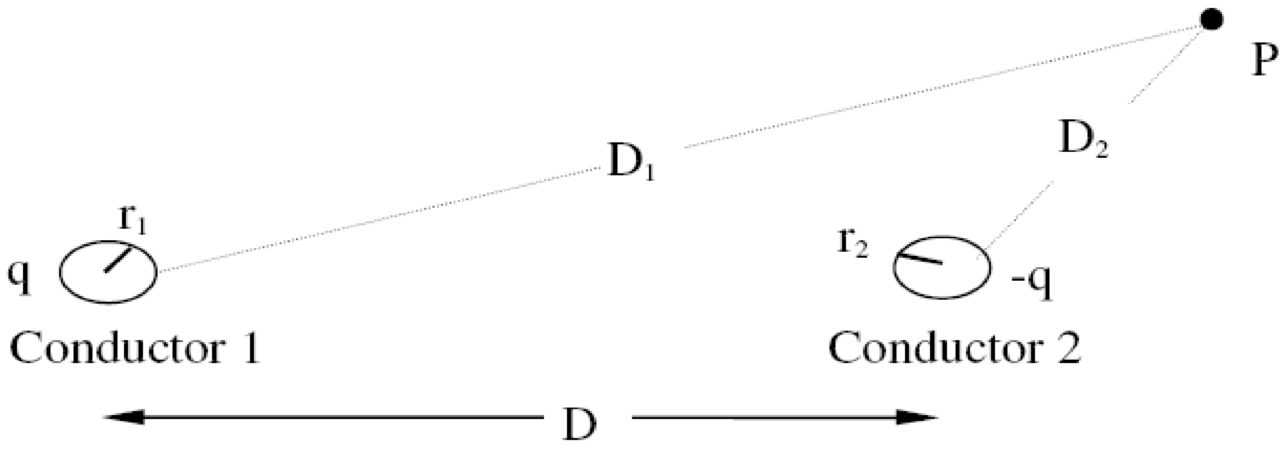
$$V_{12} = \int_{D_1}^{D_2} E dx = \int_{D_1}^{D_2} \frac{q}{2\pi x \varepsilon_o} dx = \frac{q}{2\pi \varepsilon_o} \ln \frac{D_2}{D_1} V$$

Capacitance For Single Phase Line

For a single phase line, both live and return conductors carry charge with the same magnitudes but different polarities.

This is shown in Figure in which conductor 1 with a radius of r_1 has charge of q and conductor 2 with a radius of r_2 has charge of -q.





The potential between conductors 1 and 2 given as

$$V_{12} = V_1 - V_2 = \frac{q}{2\pi\varepsilon}\left[\ln\frac{D}{r_1} - \ln\frac{r_2}{D}\right]$$

$$= \frac{q}{\pi\varepsilon}\left[\ln\frac{D}{\sqrt{r_1 r_2}}\right] \text{ V}$$

The capacitance for the line is

$$C_{12} = \frac{q}{V_{12}} = \frac{\pi \varepsilon}{\ln \frac{D}{\sqrt{r_1 r_2}}} \quad \text{F/m}$$

If the sizes of both conductors are the same ($r_1 = r_2 = r$), then

$$C_{12} = \frac{\pi \varepsilon}{\ln \frac{D}{r}} \quad \text{F/m}$$

Typically, capacitance of the conductor to a neutral or earth point, C_{1n} or C_{2n}, is used in the line modelling and analysis.

The value of capacitance to neutral is twice of that obtained from Equation.

$$C_{1n} = C_{2n} = \frac{2\pi\varepsilon}{\ln\left(\frac{D}{r}\right)}$$

The capacitive reactance of the conductor to neutral (in Ωm)

$$X_C = \frac{1}{2\pi f C_{1n}} = \frac{2.862}{f} \text{ x } 10^9 \ln\left(\frac{D}{r}\right)$$

Example:

A single phase 50 Hz transmission line has conductors with diameter of 2.4 cm and distance between centres of conductors of 305 cm. Calculate

(i) Line-to-neutral susceptance for the line in mho per km, (ii) capacitive reactance of the line in Ω,

considering the line length of 80.5 km.

Solution:

Radius of conductor, $r = \dfrac{2.4}{2x100} = 0.012$ m

(i) $X_C = \dfrac{2.862}{50} \text{ x } 10^9 \ln\left(\dfrac{3.05}{0.012}\right) = 3.16 \text{ x } 10^8\ \Omega\text{m}$ to neutral.

$= (3.16 \text{ x } 10^8) / 1000 = 3.16 \text{ x } 10^5\ \Omega\text{km}$ to neutral.

$B_C = \dfrac{1}{X_C} = \dfrac{1}{3.16 \text{ x } 10^5} = 3.16 \text{ x } 10^{-6}$ mho/km to neutral.

(ii) Capacitive reactance for 80.5 km line is

$$X = \frac{X_C}{80.5} = \frac{3.16 \text{ x } 10^5}{80.5} = 3925.5\ \Omega.$$

Self-assessment Question:

A single phase 50 Hz transmission line consists of two conductors that are separated by 5 m from each other. The radius of each conductor is 2 cm. Obtain susceptance of the line to neutral in mho if the length of the line is 40 km.

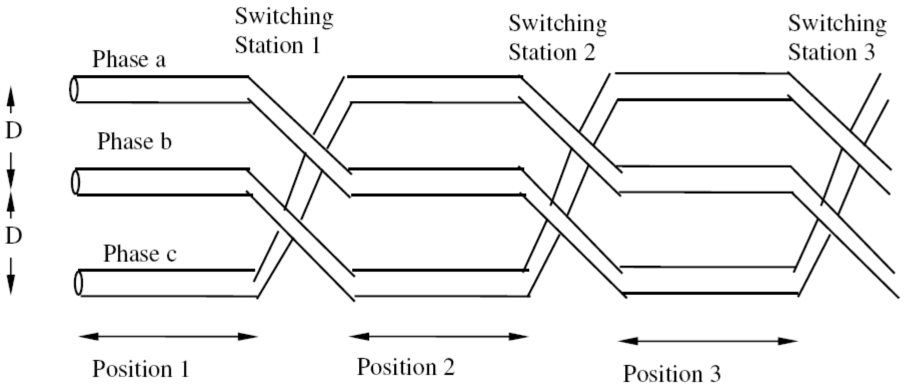
[0.13 x 10^{-3} mho]

Capacitance For Three Phase Line

We refer again to three phase line arrangement given in Figure, with the conductors have the same radius and are properly transposed.

In balanced condition, the total line charges is zero,

$$q_a + q_b + q_c = 0.$$



In general, the potential at a point P in the three phase line system is

$$V_P = \frac{1}{2\pi\varepsilon}\left[q_a \ln\frac{1}{D_{ap}} + q_b \ln\frac{1}{D_{bp}} + q_c \ln\frac{1}{D_{cp}}\right]$$

The potential at phase a conductor is

$$V_{aj} = \frac{3q_a}{2\pi\varepsilon}\left[\ln\frac{D_{eq}}{r}\right]$$

$$\text{where } D_{eq} = \sqrt[3]{D_{ab}D_{bc}D_{ca}}$$

D_{eq} is the same as GMD (or D_m) in inductance calculation for the line.

For line with symmetrical arrangement in which the distances between phase conductors are the same,

$D_{ab}=D_{bc}=D_{ca} = D$, then $D_{eq} = D$.

The average potential between phase a to neutral is obtained as

$$V_{an} = = \frac{V_{aj} - V_n}{3}$$

$$= \frac{q_a}{2\pi\varepsilon}\left[\ln\frac{D_{eq}}{r}\right]$$

Thus, capacitance of phase a conductor to the neutral in F/m is

$$C_{an} = = \frac{q_a}{V_{an}} = \frac{2\pi \varepsilon}{\ln \frac{D_{eq}}{r}}$$

In transposed condition, the value of phase-to-neutral capacitances are the same for all three phases,

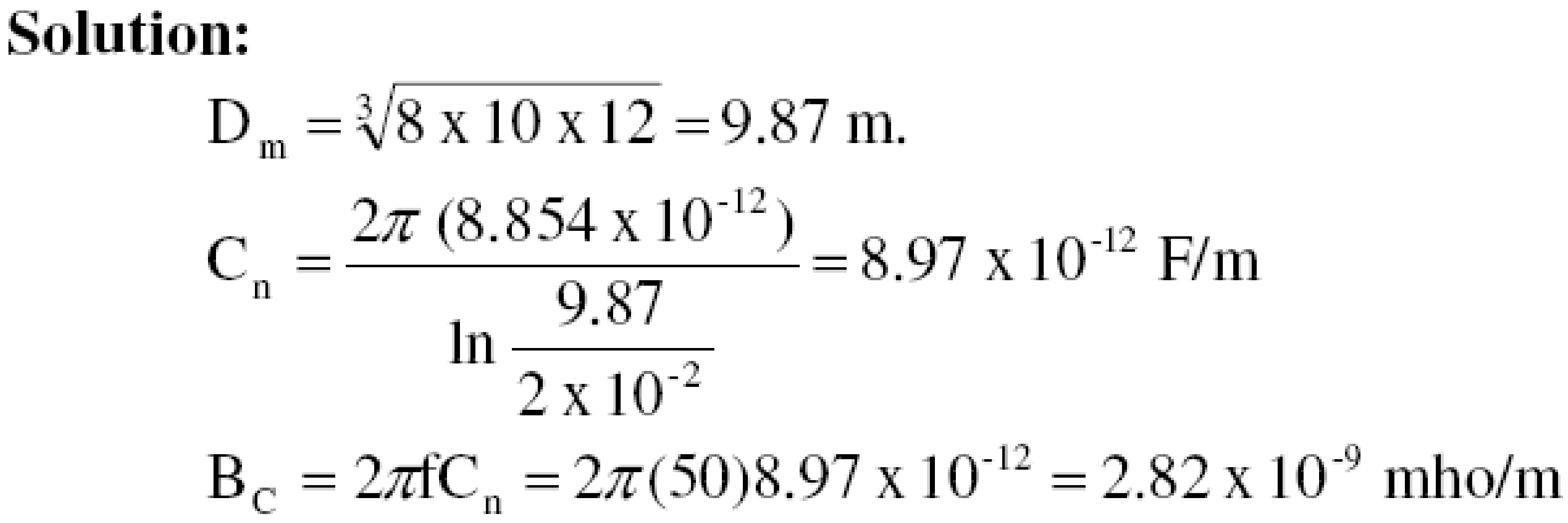
$C_{an} = C_{bn} = C_{cn}$.

Thus, in general the line-to-neutral capacitance in Farad per metre for the line can be represented by

$$C_n = \frac{2\pi \varepsilon}{\ln \frac{D_m}{r}}$$

Example:

A three phase 50 Hz transmission line has phase conductors with radius of 2 cm. Distances between phases a –b, b-c and c-a are 8 m, 10 m, and 12 m, respectively. Compute capacitive susceptance per phase in mho per metre for the line.



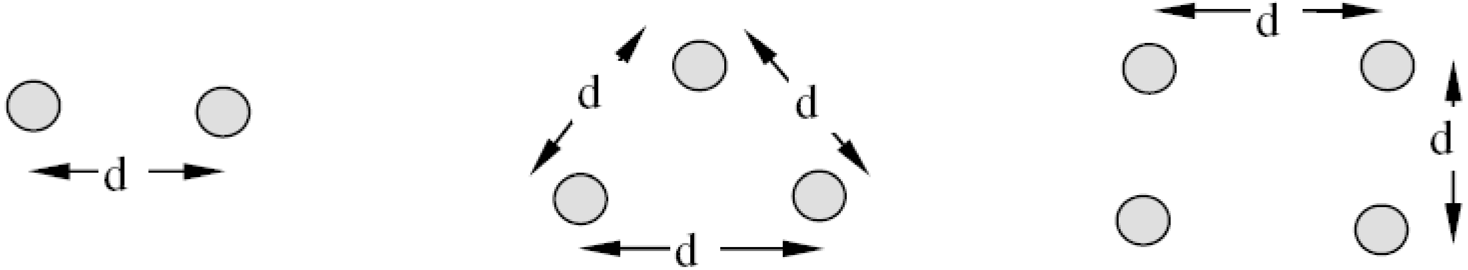
Solution:

$$D_m = \sqrt[3]{8 \text{ x } 10 \text{ x } 12} = 9.87 \text{ m.}$$

$$C_n = \frac{2\pi\,(8.854 \text{ x } 10^{-12})}{\ln \dfrac{9.87}{2 \text{ x } 10^{-2}}} = 8.97 \text{ x } 10^{-12} \text{ F/m}$$

$$B_C = 2\pi f C_n = 2\pi(50)8.97 \text{ x } 10^{-12} = 2.82 \text{ x } 10^{-9} \text{ mho/m}$$

Capacitance For Bundled Conductors



(a) (b) (c)

Referring to Figure for line with bundled conductors, the GMR to be used for computing capacitance for bundled conductors is as follows:

Two conductors: $D_{bs} = \sqrt{r\,d}$

Three conductors: $D_{bs} = \sqrt[3]{r\,d^2}$

Four conductors: $D_{bs} = 1.09\sqrt[4]{rd^3}$

where D_{bs} : the GMR for the group of bundled conductors,

r : the radius of a conductor in the group,

d : the distance between two conductors in the group.

The line-to-neutral capacitance in F/m is

$$C_n = \frac{2\pi \varepsilon}{\ln \frac{D_m}{D_{bs}}}$$

Self-assessment Question:

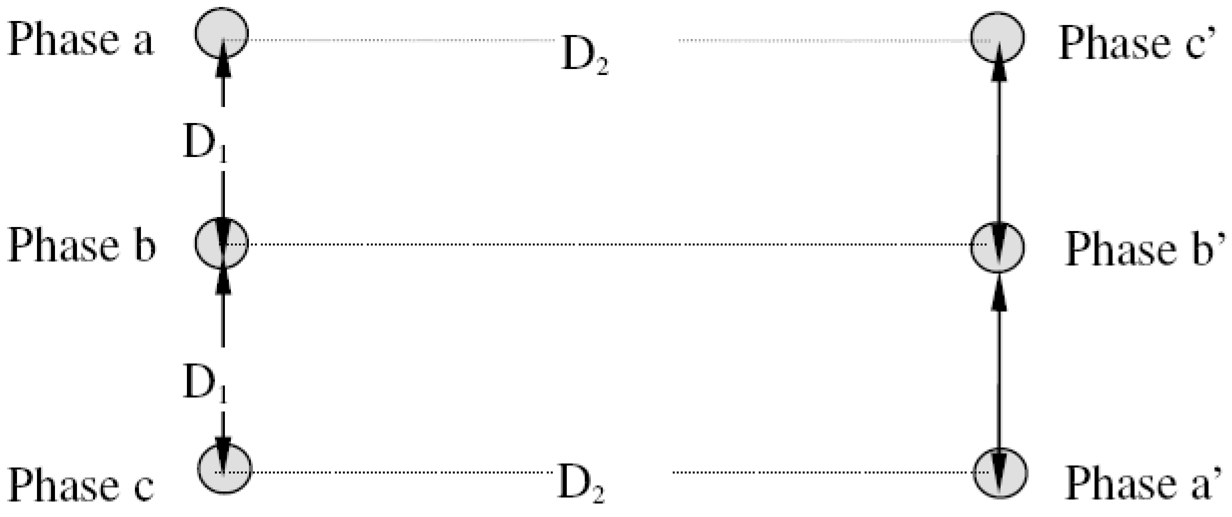
Calculate the line-to-neutral capacitance in F/m for a transposed three phase line arranged in vertical manner. The average distance between adjacent phase conductors is 1.8 m. Each phase conductor consists of two bundled conductors with the separation between conductors, d is 15.3 cm. Each conductor has a radius of 1.6 cm.

[15 x 10^{-12} F/m]

Capacitance For Parallel Three Phase Line

The concept for capacitance calculation will be applied to obtain capacitance value for parallel three phase line as given in Figure.

Note again that GMD for capacitance is the same as that for inductance, while GMR is different for capacitance compared to that for inductance.



An example of three phase line arranged in parallel

Example: A three phase line is arranged as in Figure. The radius of for each conductor is 8.5 mm. The distance D1 and D2 are 3.1 m and 4.6 m, respectively. If the line frequency is 50 Hz, calculate capacitive susceptance per phase to neutral of line in mho per km .

Solution:

$$D_{m\text{-}ab} = \sqrt[4]{D_{ab}D_{ab'}D_{a'b}D_{a'b'}}$$

$$D_{m\text{-}bc} = \sqrt[4]{D_{bc}D_{bc'}D_{b'c}D_{b'c'}}$$

$$D_{m\text{-}ca} = \sqrt[4]{D_{ca}D_{ca'}D_{c'a}D_{c'a'}}$$

$$D_{m} = \sqrt[3]{D_{m\text{-}ab}D_{m\text{-}bc}D_{m\text{-}ca}}$$

GMD is obtained as follows:

$$D_{m\text{-}ab} = \sqrt[4]{(3.1 \mathrm{x}\, 5.6)^2} = 4.2 \text{ m}$$

$$D_{m\text{-}bc} = \sqrt[4]{(3.1 \mathrm{x}\, 5.6)^2} = 4.2 \text{ m}$$

$$D_{m\text{-}ca} = \sqrt[4]{(6.2 \mathrm{x}\, 4.6)^2} = 5.3 \text{ m}$$

$$D_{m} = \sqrt[3]{4.2 \mathrm{x}\, 4.2 \mathrm{x}\, 5.3} = 4.5 \text{ m}$$

Distance aa' = $\sqrt{6.2^2 + 4.6^2}$ =7.7 m

GMR is obtained as follows:

$$D_{sa} = \sqrt{8.5x10^{-3} \text{ x } 7.7} = 0.26 \text{ m}$$

$$D_{sb} = \sqrt{8.5x10^{-3} \text{ x } 4.6} = 0.20 \text{ m}$$

$$D_{sc} = \sqrt{8.5x10^{-3} \text{x } 7.7} = 0.26 \text{ m}$$

$$D_S = \sqrt[3]{0.26 \text{ x } 0.20 \text{ x } 0.26} = 0.24 \text{ m}$$

$$C_n = \frac{2\pi\,\varepsilon}{\ln\left(\frac{4.5}{0.24}\right)} = 19.0 \text{ x } 10^{-12} \text{ F/m.}$$

B_C=2π(50)(19.0x10^{-12})x1000= 6.0x10^{-6} mho/km per phase to neutral.

THE END