EE8402 TRANSMISSION AND DISTRIBUTION

UNIT V

Structure of electric power system: generation, transmission and distribution; Types of AC and DC distributors-distributors and concentrated loads-interconnection-EHVAC and HVDC transmission-Introduction of FACTS.

INTRODUCTION

In early days, there was a little demand for electrical energy so that small power stations were built to supply lighting and heating loads. However, the widespread use of electrical energy by modern civilisation has necessitated producing bulk electrical energy economically and efficiently. The increased demand of electrical energy can be met by building big power stations at favourable places where fuel (coal or gas) or water energy is available in abundance. This has shifted the site of power stations to places quite away from the consumers. The electrical energy produced at the power stations has to be supplied to the consumers. There is a large network of conductors between the power station and the consumers. This network can be broadly divided into two parts *viz.*, transmission and distribution. The purpose of this chapter is to focus attention on the various aspects of transmission of electric power.

ELECTRIC SUPPLY SYSTEM

Draw and explain the structure of electric power (i) system in detail. (ii) State the advantages of HVDC transmission.[16][May/June'13][May/June'16]

Draw and explain the structure of electric power system indicating the voltage level in each transmission levels. [10][Nov/Dec'13]

Draw and explain the structure of typical electric power system with various voltage levels.[16][April/May'11][Nov/Dec'15]

The conveyance of electric power from a power station to consumers' premises is known as electric supply system. An electric supply system consists of three principal components viz., the power station, the transmission lines and the distribution system. Electric power is produced at the power stations which are located at favourable places, generally quite away from the consumers. It is then transmitted over large distances to load centres with the help of conductors known as transmission lines.

Finally, it is distributed to a large number of small and big consumers through a distribution network. The electric supply system can be broadly classified into

(i) d.c. or a.c. system

(ii) overhead or underground system.

Now-a-days, 3-phase, 3-wire a.c. system is universally adopted for generation and transmission of electric power as an economical proposition. However, distribution of electric power is done by 3-phase, 4-wire a.c. system. The underground system is more expensive than the overhead system. Therefore, in our country, overhead system is mostly adopted for transmission and distribution of electric power.

TYPICAL A.C. POWER SUPPLY SCHEME

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

(i) **Generating station:** In Fig 1.1, G.S. represents the generating station where electric power is produced by 3-phase alternators operating in parallel. The usual generation voltage is 11 kV. For economy in the transmission of electric power, the generation voltage (i.e., 11 kV) is stepped up to 132 kV (or more) at the generating station with the help of 3-phase transformers. The transmission of electric power at high voltages has several advantages including the saving of conductor material and high transmission efficiency. It may appear advisable to use the highest possible voltage for transmission of electric power to save conductor material and have other advantages. But there is a limit to which this voltage can be increased. It is because increase in transmission voltage introduces insulation problems as well as the cost of switchgear and transformer equipment is increased. Therefore, the choice of proper transmission voltage is essentially a question of economics. Generally the primary transmission is carried at 66 kV, 132 kV, 220 kV or 400 kV.

(ii) Primary transmission. The electric power at 132 kV is transmitted by 3-phase, 3-wire overhead system to the outskirts of the city. This forms the primary transmission.

(iii) Secondary transmission. The primary transmission line terminates at the receiving station (RS) which usually lies at the outskirts of the city. At the receiving station, the voltage is reduced to 33kV by step-down transformers. From this station, electric power is transmitted at 33kV by 3-phase, 3-wire overhead system to various sub-stations (SS) located at the strategic points in the city. This forms the secondary transmission.

(iv) Primary distribution. The secondary transmission line terminates at the sub-station (SS) where voltage is reduced from 33 kV to 11kV, 3-phase, and 3-wire. The 11 kV lines run along the important road sides of the city. This forms the primary distribution. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub-stations.

(v) Secondary distribution. The electric power from primary distribution line (11 kV) is delivered to distribution sub-stations (DS). These sub-stations are located near the consumers' localities and step down the voltage to 400 V, 3-phase, 4-wire for secondary distribution. The voltage between any two phases is 400 V and between any phase and neutral is 230 V. The single-phase residential lighting load is connected between any one phase and neutral, whereas 3-phase, 400 V motor loads is connected across 3-phase lines directly. It may be worthwhile to mention here that secondary distribution system consists of feeders, distributors and service mains.

Fig. 1.2 shows the elements of low voltage distribution system. Feeders (SC or SA) Radiating from the distribution sub-station (DS) supply power to the distributors (AB, BC, CD and AD). No consumer is given direct connection from the feeders. Instead, the consumers are connected to the distributors through their service mains.

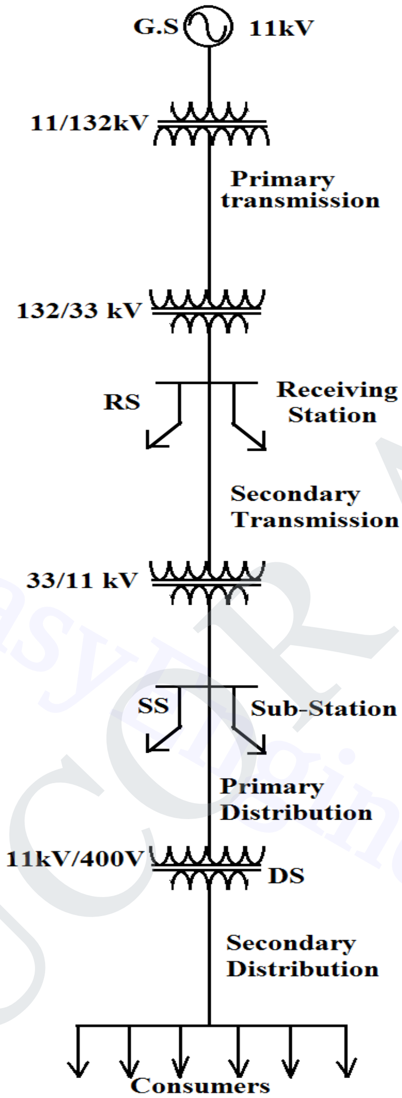


Fig 1.1 Electric Supply System

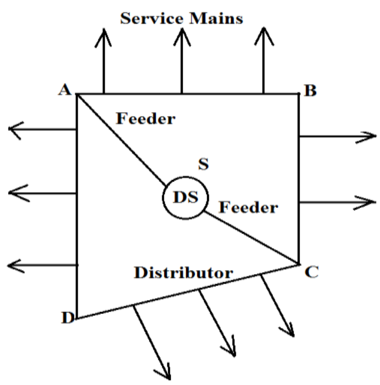


Fig 1.2

Note. A practical power system has a large number of auxiliary equipments (e.g., fuses, circuit breakers, voltage control devices etc.). However, such equipments are not shown in Fig. 1.1. It is because the amount of information included in the diagram depends on the purpose for which the diagram is intended. Here our purpose is to display general lay out of the power system. Therefore, the location of circuit breakers, relays etc., is unimportant. Further, the structure of power system is shown by a single line diagram. The complete 3-phase circuit is seldom necessary to convey even the most detailed information about the system. In fact, the complete diagram is more likely to hide than to clarify the information we are seeking from the system viewpoint.

COMPARISON OF D.C. AND A.C. TRANSMISSION

The electric power can be transmitted either by means of d.c. or a.c. Each system has its own merits and demerits. It is, therefore, desirable to discuss the technical advantages and disadvantages of the two systems for transmission of electric power.
1. D.C. transmission. For some years past, the transmission of electric power by d.c. has been receiving the active consideration of engineers due to its numerous advantages.
Advantages. The high voltage D.C. transmission has the following advantages over high voltage a.c. transmission:
(i) It requires only two conductors as compared to three for a.c. transmission.
(ii) There is no inductance, capacitance, phase displacement and surge problems in d.c. transmission.
(iii) Due to the absence of inductance, the voltage drop in a d.c. transmission line is less than the a.c. line for the same load and sending end voltage. For this reason, a d.c. transmission line has better voltage regulation.
(iv) There is no skin effect in a d.c. system. Therefore, entire cross-section of the line conductor is utilised.
(v) For the same working voltage, the potential stress on the insulation is less in case of d.c. system than that in a.c. system. Therefore, a d.c. line requires less insulation.
(vi) A d.c. line has less corona loss and reduced interference with communication circuits.
(vii) The high voltage d.c. transmission is free from the dielectric losses, particularly in the case of cables.
(viii) In d.c. transmission, there are no stability problems and synchronising difficulties.
Disadvantages
(i) Electric power cannot be generated at high d.c. voltage due to commutation problems.
(ii) The d.c. voltage cannot be stepped up for transmission of power at high voltages.
(iii) The d.c. switches and circuit breakers have their own limitations.
2. A.C. transmission. Now-a-days, electrical energy is almost exclusively generated, transmitted and distributed in the form of a.c.
Advantages
(i) The power can be generated at high voltages.
(ii) The maintenance of a.c. sub-stations is easy and cheaper.
(iii) The a.c. voltage can be stepped up or stepped down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.
Disadvantages
(i) An a.c. line requires more copper than a d.c. line.
(ii) The construction of a.c. transmission line is more complicated than a d.c. transmission line.
(iii) Due to skin effect in the a.c. system, the effective resistance of the line is increased.

(iv) An a.c. line has capacitance. Therefore, there is a continuous loss of power due to charging current even when the line is open.

Conclusion. From the above comparison, it is clear that high voltage d.c. transmission is superior to high voltage a.c. transmission. Although at present, transmission of electric power is carried by a.c., there is an increasing interest in d.c. transmission. The introduction of mercury arc rectifiers and thyratrons has made it possible to convert a.c. into d.c. and vice-versa easily and efficiently. Such devices can operate up to 30 MW at 400 kV in single units. The present day trend is towards a.c. for generation and distribution and high voltage d.c. for transmission. Fig. 1.3 shows the single line diagram of high voltage d.c. transmission. The electric power is generated as a.c. and is stepped up to high voltage by the sending end transformer T_S.

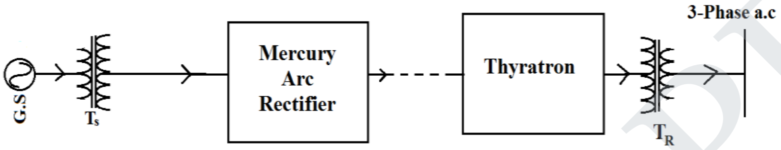


Fig 1.3

The a.c. power at high voltage is fed to the mercury arc rectifiers which convert a.c. into d.c. The transmission of electric power is carried at high d.c. voltage. At the receiving end, d.c. is converted into a.c. with the help of thyratrons. The a.c. supply is stepped down to low voltage by receiving end transformer T_R for distribution.

TYPES OF AC AND DC DISTRIBUTORS

Explain the basic types of DC distributors.

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

(i) Distributor fed at one end

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

Fig 1.4 shows the single line diagram of a d.c distributor AB fed at the end a (also known as singly fed distributor) and loads I_1, I_2 and I_3 tapped off at points C, D and E respectively.

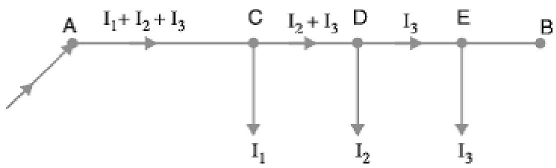


Fig 1.4

Note:

1. The current in the various section of the distributor away from feeding point goes on decreasing. Thus current in section AC is more than the current in section CD and current in section CD is more than the current in section DE.
2. The voltage across the loads away from the feeding point goes on decreasing. Thus Fig 1.4, the minimum voltage across at the load point E.
3. In case a fault occurs on any section of the distributor, the whole distributor will have to be disconnected from the supply mains; therefore continuity of supply is interrupted.

DC Distributor Fed at one end – Concentrated loading.

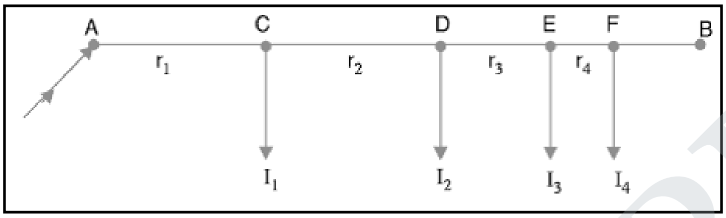


Fig 1.5

Fig 1.5 shows the single line diagram of a 2 wire dc distributor AB fed at one end A and having concentrated loads I_1, I_2, I_3 and I_4 tapped off at points C,D,E and F respectively. Let r_1, r_2, r_3 and r_4 be the resistances of both wires (go and return) of the sections AC, CD, DE and EF of the distributor respectively.

Current fed from point *A* $= I_1 + I_2 + I_3 + I_4$
Current in section *AC* $= I_1 + I_2 + I_3 + I_4$
Current in section *CD* $= I_2 + I_3 + I_4$
Current in section *DE* $= I_3 + I_4$
Current in section *EF* $= I_4$
Voltage drop in section *AC* $= r_1\,(I_1 + I_2 + I_3 + I_4)$
Voltage drop in section *CD* $= r_2\,(I_2 + I_3 + I_4)$
Voltage drop in section *DE* $= r_3\,(I_3 + I_4)$
Voltage drop in section *EF* $= r_4\, I_4$

$\therefore$ Total voltage drop in the distributor $= r_1\,(I_1 + I_2 + I_3 + I_4) + r_2\,(I_2 + I_3 + I_4) + r_3\,(I_3 + I_4) + r_4\, I_4$

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

Uniformly Loaded Distributor Fed at One End

Fig 1.6 shows the single line diagram of a 2-wire d.c. distributor *AB* fed at one end *A* and loaded uniformly with *i* amperes per metre length. It means that at every 1 m length of the distributor, the load tapped is *i* amperes. Let *l* metres be the length of the distributor and *r* ohm be the resistance per metre run.

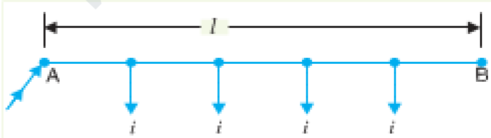


Fig 1.6

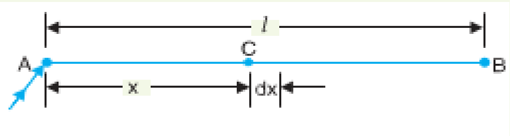


Fig 1.7

Consider a point *C* on the distributor at a distance *x* metres from the feeding point *A* as shown in Fig.1.7 Then current at point *C* is

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

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

$$dv = i(l - x)r.dx = ir(l - x)dx$$

Total voltage drop in the distributor up to point C is

$$v = \int_0^x ir(l - x)dx = ir(lx - \frac{x^2}{2})$$

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

∴ Voltage drop over the distributor AB

$$= ir(l \times l - \frac{l^2}{2})$$

$$= \frac{1}{2} irl^2 = \frac{1}{2}(il)(rl)$$

$$= \frac{1}{2} IR$$

Where $il = I$, the total current entering at point A

$rl = R$, the total resistance of the distributor

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

(ii) Distributor Fed at both ends

In this type of feeding, the distributor is connected to the supply mains at both ends and loads are tapped off at different points along the length of the distributor. The voltage at the feeding points may or may not be equal. Fig. 1.8 shows a distributor *AB* fed at the ends *A* and *B* and loads of I_1, I_2 and I_3 tapped off at points *C*, *D* and *E* respectively. Here, the load voltage goes on decreasing as we move away from one feeding point *say A*, reaches minimum value and then again starts rising and reaches maximum value when we reach the other feeding point *B*. The minimum voltage occurs at some load point and is never fixed. It is shifted with the variation of load on different sections of the distributor.

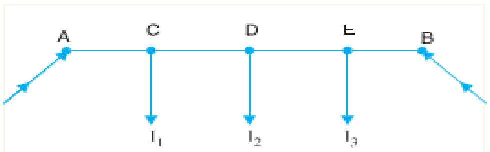


Fig 1.8

Advantages:

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

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

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

Distributor Fed at both ends – Concentrated Loading

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

(*i*) Two ends fed with equal voltages. Consider a distributor *AB* fed at both ends with equal voltages *V* volts and having concentrated loads I_1, I_2, I_3, I_4 and I_5 at points *C*, *D*, *E*, *F* and *G* respectively as shown in Fig.1.9 As we move away from one of the feeding points, *say A*, p.d. goes on decreasing till it reaches the minimum value at some load point, *say E*, and then again starts rising and becomes *V* volts as we reach the other feeding point *B*.

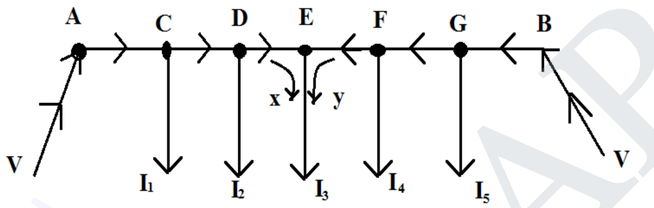


Fig 1.9

All the currents tapped off between points *A* and *E* (minimum p.d. point) will be supplied from the feeding point *A* while those tapped off between *B* and *E* will be supplied from the feeding point *B*. The current tapped off at point *E* itself will be partly supplied from *A* and partly from *B*. If these currents are *x* and *y* respectively, then,

$$I_3 = x + y$$

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

Point of minimum potential. It is generally desired to locate the point of minimum potential. There is a simple method for it. Consider a distributor *AB* having three concentrated loads I_1, I_2 and I_3 at points *C*, *D* and *E* respectively. Suppose that current supplied by feeding end *A* is I_A. Then current distribution in the various sections of the distributor can be worked out as shown in Fig. 1.10(*i*). Thus

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

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

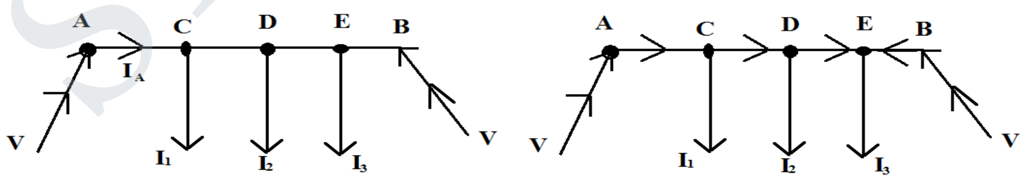


Fig 1.10

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

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

From this equation, the unknown I_A can be calculated as the values of other quantities are generally given. Suppose *actual* directions of currents in the various sections of the distributor are indicated as shown in Fig. 1.10 (*ii*). The load point where the currents are coming from both sides of the distributor is the point of minimum potential *i.e.* point *E* in this case.

***(ii)* Two ends fed with unequal voltages.** Fig. 1.11 shows the distributor *AB* fed with unequal voltages; end *A* being fed at V_1 volts and end *B* at V_2 volts. The point of minimum potential can be found by following the same procedure as discussed above. Thus in this case,
Voltage drop between *A* and *B* = Voltage drop over *AB*
Or $V_1 - V_2$ = Voltage drop over *AB*

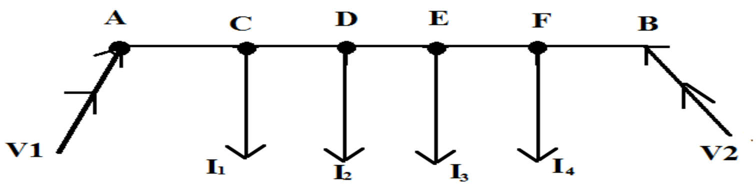


Fig 1.11

Uniformly Loaded Distributor Fed at both ends

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

***(i)* Distributor fed at both ends with equal voltages.** Consider a distributor *AB* of length *l* metres, having resistance *r* ohms per metre run and with uniform loading of *i* amperes per metre run as shown in Fig. 1.12 Let the distributor be fed at the feeding points *A* and *B* at equal voltages, say *V* volts. The total current supplied to the distributor is *i l*. As the two end voltages are equal, therefore, current supplied from each feeding point is *i l*/2 *i.e.*
Current supplied from each feeding point = *il/2*

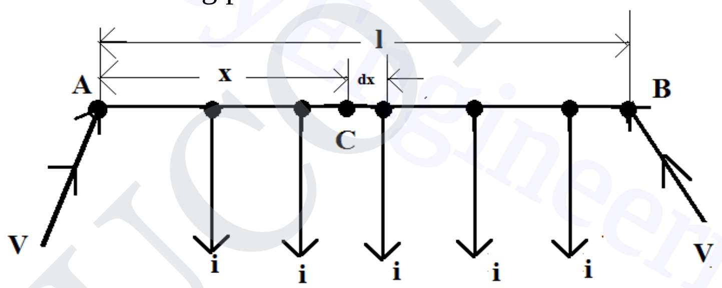


Fig 1.12

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

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

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

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

$\therefore$ Voltage drop upto point C $= \int_0^x ir\left(\frac{l}{2} - x\right)dx = ir\left(\frac{lx}{2} - \frac{x^2}{2}\right) = \frac{ir}{2}(lx - x^2)$

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

$\therefore$ Max. Voltage drop $= \frac{ir}{2}(lx - x^2) = \frac{ir}{2}\left(l \times \frac{l}{2} - \frac{l^2}{4}\right) = \frac{1}{8} irl^2 = \frac{1}{8}(il)(rl) = \frac{1}{8} IR$

where il = I, the total current fed to the distributor from both ends
r.l=R, the total resistance of the distributor

Minimum voltage = $V - \frac{IR}{8} volts$

(*ii*) Distributor fed at both ends with unequal voltages. Consider a distributor *AB* of length *l* metres having resistance *r* ohms per metre run and with a uniform loading of *i* amperes per metre run as shown in Fig. 1.13 Let the distributor be fed from feeding points *A* and *B* at voltages V_A and V_B respectively. Suppose that the point of minimum potential *C* is situated at a distance *x* metres from the feeding point *A*. Then current supplied by the feeding point *A* will be *i x*.

∴ Voltage drop in section $AC = \frac{irx^2}{2} volts$

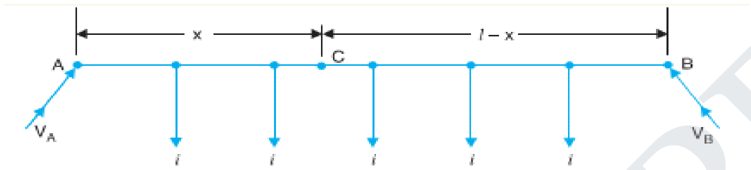


Fig 1.13

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

∴ Voltage drop in section $BC = \frac{ir(1-x)^2}{2} volts$

Voltage at point C, $V_C = V_A$ – Drop over AC

$$= V_A - \frac{irx^2}{2} \quad .....(i)$$

Also, voltage at point C, = V_B- Drop Over BC

$$= V_B - \frac{ir(1-x)^2}{2} \quad .....(ii)$$

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

$$V_A - \frac{irx^2}{2} = V_B - \frac{ir(1-x)^2}{2}$$

Solving the equation for x, we get,

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

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

(iii) Distributor fed at the centre.

In this type of feeding, the centre of the distributor is connected to the supply mains as shown in Fig. 1.14 It is equivalent to two singly fed distributors, each distributor having a common feeding point and length equal to half of the total length.

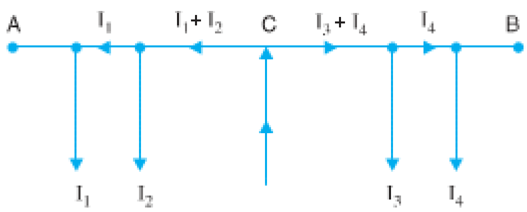


Fig 1.14

(iv) Ring mains.

In this type, the distributor is in the form of a closed ring as shown in Fig.1.15 It is equivalent to a straight distributor fed at both ends with equal voltages, the two ends being brought together to form a closed ring. The distributor ring may be fed at one or more than one point.

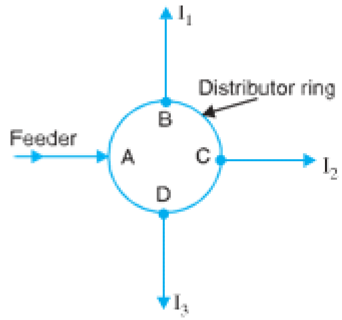


Fig 1.15

A distributor arranged to form a closed loop and fed at one or more points is called a *ring distributor*. Such a distributor starts from one point, makes a loop through the area to be served, and returns to the original point. For the purpose of calculating voltage distribution, the distributor can be considered as consisting of a series of open distributors fed at both ends. The principal advantage of ring distributor is that by proper choice in the number of feeding points, great economy in copper can be affected.

Ring Main Distributor with Interconnector

Sometimes a ring distributor has to serve a large area. In such a case, voltage drops in the various sections of the distributor may become excessive. In order to reduce voltage drops in various sections, distant points of the distributor are joined through a conductor called *interconnector*.

Fig. 1.16 shows the ring distributor *ABCDEA*. The points *B* and *D* of the ring distributor are joined through an interconnector *BD*. There are several methods for solving such a network. However, the solution of such a network can be readily obtained by applying Thevenin's theorem. The steps of procedure are:

(*i*) Consider the interconnector *BD* to be disconnected [See Fig. 1.17 (*i*)] and find the potential difference between *B* and *D*. This gives Thevenin's equivalent circuit voltage E_0.
(*ii*) Next, calculate the resistance viewed from points *B* and *D* of the network composed of distribution lines only. This gives Thevenin's equivalent circuit series resistance R_0.
(*iii*) If R_{BD} is the resistance of the interconnector *BD*, then Thevenin's equivalent circuit will be as shown in Fig. 1.17 (*ii*).

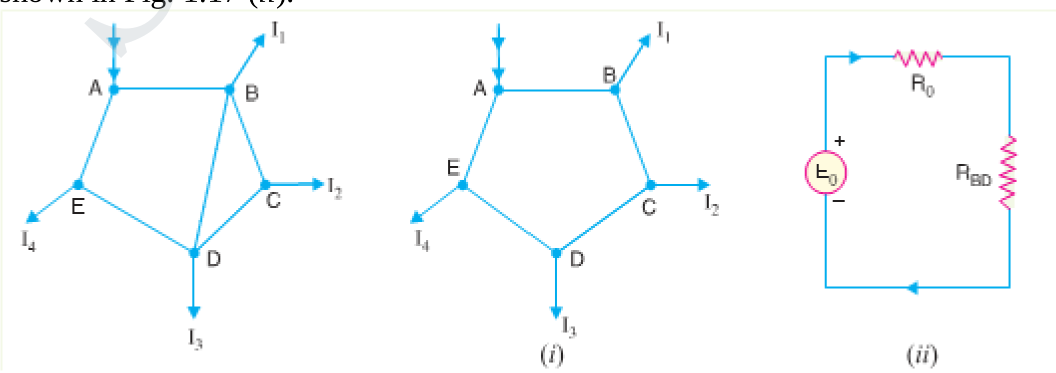


Fig 1.16 Fig 1.17

$\therefore$ Current in interconnector $BD = \dfrac{E_o}{R_o + R_{BD}}$

Therefore current distribution in each section and the voltage of load points can be calculated.

Explain the basic principle and current of 3-Wire D.C system.

The great disadvantage of direct current for general power purposes lies in the fact that its voltage cannot readily be changed, except by the use of rotating machinery, which in most cases is too expensive.

The problem can be solved to a limited extent by the use of 3-wire d.c. system which makes available two voltages *viz*. V volts between any outer and neutral and 2V volts between the outers.

Motor loads requiring high voltage are connected between the outers whereas lighting and heating loads requiring less voltage are connected between any one outer and the neutral. Due to the availability of two voltages, 3-wire system is preferred over 2-wire system for d.c. distribution.

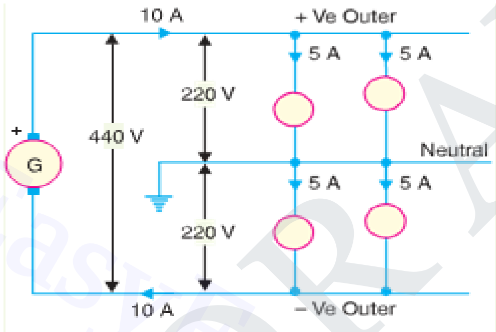


Fig 1.18

Fig. 1.18 shows the general principles of a 3-wire d.c. system. It consists of two outers and a middle or neutral wire which is earthed at the generator end. The potential of the neutral wire is half-way between the potentials of the outers. Thus, if p.d. between the outers is 440 V, then positive outer is at 220 V *above* the neutral and negative outer is 220 V *below* the neutral. The current in the neutral wire will depend upon the loads applied to the two sides.

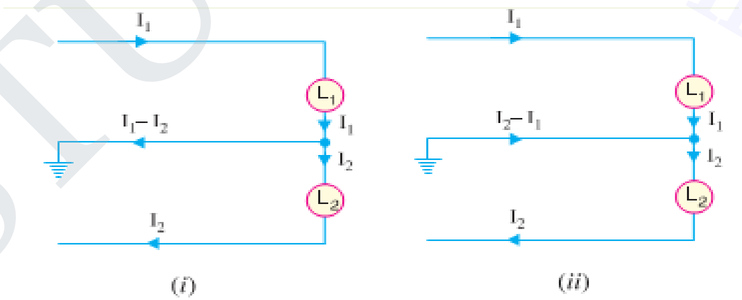


Fig 1.19

(i) If the loads applied on both sides of the neutral are equal (*i.e.* balanced) as shown in Fig 1.18, the current in the neutral wire will be zero. Under these conditions, the potential of the neutral will be exactly half-way between the potential difference of the outers.

(ii) If the load on the positive outer (I_1) is greater than on the negative outer (I_2), then out of balance current $I_1 - I_2$ will flow in the neutral wire from load end to supply end as shown in Fig. 1.19 (*i*). Under this condition, the potential of neutral wire will no longer be midway between the potentials of the outers.

(iii) If the load on the negative outer (I_2) is greater than on the positive outer (I_1), then out of balance current $I_2 - I_1$ will flow in the neutral from supply end to load end as shown in Fig. 1.19 (*ii*). Again, the neutral potential will not remain half-way between that of the outers.

(iv) As the neutral carries only the out of balance current which is generally small, therefore, area of X-section of neutral is taken half as compared to either of the outers. It may be noted that it is desirable that voltage between any outer and the neutral should have the same value. This is achieved by distributing the loads equally on both sides of the neutral.

Current distribution in 3-Wire D.C system

Fig. 1.20 shows a 3-wire 500/250 V d.c. distributor. Typical values of loads have been assumed to make the treatment more illustrative. The motor requiring 500 V is connected across the outers and takes a current of 75 A. Other loads requiring lower voltage of 250 V are connected on both sides of the neutral.

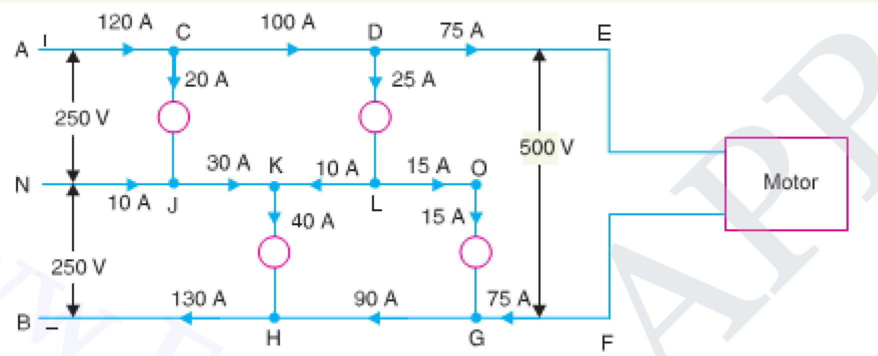


Fig 1.20

Applying Kirchhoff's current law, it is clear that a current of 120 A enters the positive outer while 130 A comes out of the negative outer. Therefore, 130 − 120 = 10 A must flow *in* the neutral at point *N*. Once the magnitude and direction of current in the section *NJ* is known, the directions and magnitudes of currents in the other sections of the neutral can be easily determined. For instance, the currents meeting at point *K* must add up to 40 A to supply the load *KH*. As seen in Fig. 13.50, 20A of *CJ* and 10A of *NJ* flow towards *K*, the remaining 10A coming from point *L*. The current of 25A of load *DL* is divided into two parts; 10A flowing along section *LK* and the remaining 15 A along the section *LO* to supply the load *OG*.

Load-point voltages. Knowing the currents in the various sections of the outers and neutral, the voltage at any load point can be determined provided resistances are known. As an illustration, let us calculate the voltage across load *CJ* of Fig.13.50. Applying Kirchhoff's voltage law to the loop *ACJNA*, we have,

[Algebraic sum of voltage drops] + [Algebraic sum of e.m.f.s.] = 0

or [− drop in AC − voltage across CJ + drop in NJ] + [250] = 0

or Voltage across CJ = 250 − drop in AC + drop in NJ

Describe A.C Distributors.

Introduction

Now-a-days, electrical energy is generated, transmitted and distributed in the form of alternating current as an economical proposition. The electrical energy produced at the power station is transmitted at very high voltages by 3-phase, 3- wire system to step-down sub-stations for distribution. The distribution system consists of two parts *viz.* primary distribution and secondary distribution. The primary distribution circuit is 3- phase, 3-wire and operates at voltages (3·3 or 6·6 or 11kV) somewhat higher than general utilisation levels. It delivers power to the secondary distribution circuit through distribution transformers situated near consumers' localities. Each distribution transformer steps down the voltage to 400 V and power is distributed to ultimate consumers' by 400/230 V, 3-phase, 4-wire system. In this chap- ter, we shall focus our attention on the various aspects of a.c. distribution.

A.C Distribution Calculations

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

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

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

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

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

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

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

Methods of solving A.C Distribution Problems

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

(i) Power factors referred to receiving end voltage.

Consider an a.c distributor AB with concentrated loads of I1 and I2 tapped off at points C and B as shown in Fig 1.21. Taking the receiving end voltage V_B as the reference vector, let lagging power factors at C and B be cos Φ_1 and cos Φ_2 w.r.t V_B. Let R_1, X_1 and R_2, X_2 be the resistance and reactance of sections AC and CB of the distributor.

Impedance of section AC, $\vec{Z}_{AC} = R_1 + jX_1$

Impedance of section CB, $\vec{Z}_{CB} = R_2 + jX_2$

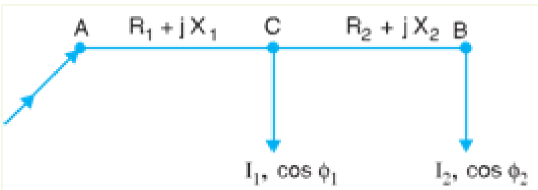


Fig 1.21

Load current at point C, $\vec{I_1} = I_1(\cos\Phi_1 - j\sin\Phi_1)$

Load current at point B, $\vec{I_2} = I_2(\cos\Phi_2 - j\sin\Phi_2)$

Current in section CB, $\overrightarrow{I_{CB}} = \vec{I}_2 = I_2(\cos\Phi_2 - j\sin\Phi_2)$

Current in section AC, $\overrightarrow{I_{AC}} = \vec{I_1} + \vec{I_2} = I_1(\cos\Phi_1 - j\sin\Phi_1) + I_2(\cos\Phi_2 - j\sin\Phi_2)$

Voltage drop in section CB, $\overrightarrow{V_{CB}} = \overrightarrow{I_{CB}}\,\overrightarrow{Z_{CB}} = I_2(\cos\Phi_2 - j\sin\Phi_2)(R_2 + jX_2)$

Voltage drop in section AC, $\vec{V}_{AC} = \vec{I}_{AC}\vec{Z}_{AC} = (\vec{I}_1 + \vec{I}_2)Z_{AC}$

$$= [I_1(\cos\Phi_1 - j\sin\Phi_1) + I_2(\cos\Phi_2 - j\sin\Phi_2)][R_1 + jX_1]$$

Sending end voltage, $\vec{V}_A = \vec{V}_B + \vec{V}_{CB} + \vec{V}_{AC}$

Sending end current, $\vec{I}_A = \vec{I}_1 + \vec{I}_2$

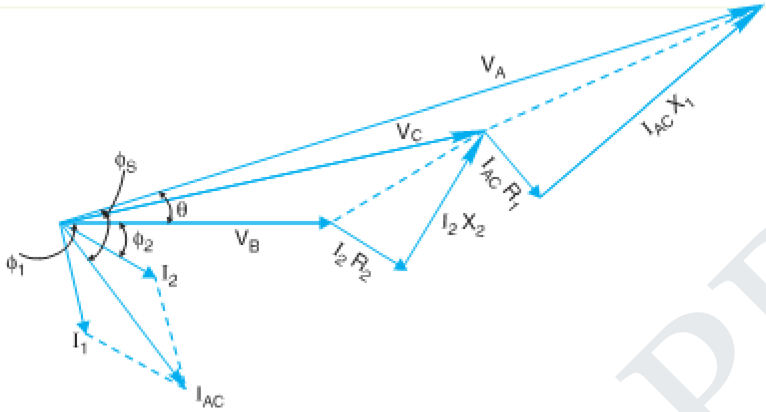


Fig 1.22

The vector diagram of the a.c. distributor under these conditions is shown in Fig.1.22 Here, the receiving end voltage V_B is taken as the reference vector. As power factors of loads are given *w.r.t.* V_B, therefore, I_1 and I_2 lag behind V_B by Φ_1 and Φ_2 respectively.

(ii) Power factors referred to respective load voltages

Suppose the power factors of loads in the previous Fig 1.21 are referred to their respective load voltages. Then Φ_1 is the phase angle between V_c and I_1 and Φ_2 is the phase angle between V_B and I_2. The vector diagram under these conditions is shown in Fig 1.23

Voltage drop in section $CB = \vec{I}_2\vec{Z}_{CB} = I_2(\cos\Phi_2 - j\sin\Phi_2)(R_2 + jX_2)$

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

Now $\vec{I}_1 = I_1\underline{|-\Phi_1}$ w.r.t voltage V_C

∴ $\vec{I}_1 = I_1\underline{|-(\Phi_1 - \alpha)}$ w.r.t voltage V_B

i.e $\vec{I}_1 = I_1[\cos(\Phi_1 - \alpha) - j\sin(\Phi_1 - \alpha)]$

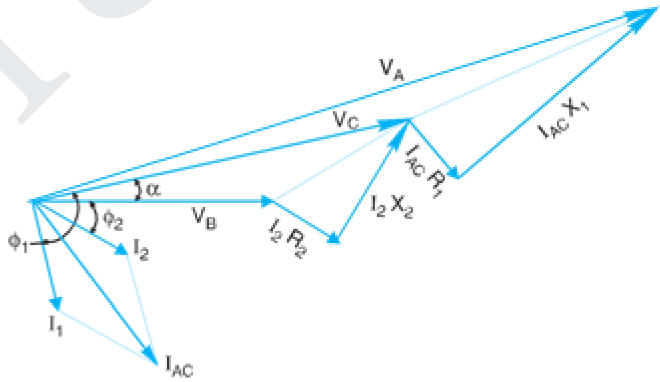


Fig 1.23

Now

$\vec{I}_{AC} = \vec{I}_1 + \vec{I}_2 = I_1[\cos(\Phi_1 - \alpha) - j\sin(\Phi_1 - \alpha)] + I_2(\cos\Phi_2 - j\sin\Phi_2)$

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

∴ Voltage at point A= V_B+Drop in CB+Drop in AC

3-Phase unbalanced Loads

The 3-phase loads that have the same impedance and power factor in each phase are called balanced loads. The problems on balanced loads can be solved by considering one phase only ; the conditions in the other two phases being similar. However, we may come across a situation when loads are unbalanced *i.e.* each load phase has different impedance and/or power factor. In that case, current and power in each phase will be different. In practice, we may come across the following unbalanced loads:

(i) Four-wire star-connected unbalanced load
(ii) Unbalanced Δ-connected load
(iii) Unbalanced 3-wire, *Y*-connected load

The 3-phase, 4-wire system is widely used for distribution of electric power in commercial and industrial buildings. The single phase load is connected between any line and neutral wire while a 3-phase load is connected across the three lines. The 3-phase, 4-wire system invariably carries unbalanced loads. In this chapter, we shall only discuss this type of unbalanced load.

Four-Wire Star-Connected Unbalanced Loads

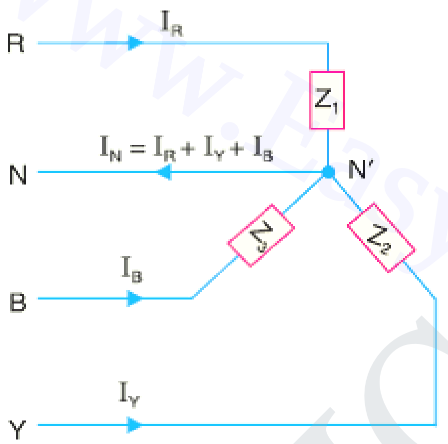


Fig 1.24

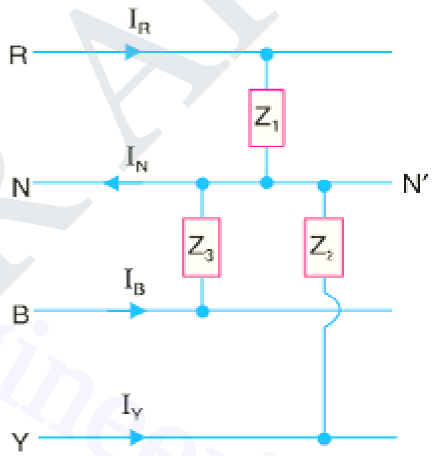


Fig 1.25

We can obtain this type of load in two ways. First, we may connect a 3-phase, 4-wire unbalanced load to a 3-phase, 4-wire supply as shown in Fig. 1.24. Note that star point *N* of the supply is connected to the load star point *N'*. Secondly, we may connect single phase loads between any line and the neutral wire as shown in Fig.1.25 This will also result in a 3-phase, 4-wire unbalanced load because it is rarely possible that single phase loads on all the three phases have the same magnitude and power factor. Since the load is unbalanced, the line currents will be different in magnitude and displaced from one another by unequal angles. The current in the neutral wire will be the phasor sum of the three line currents *i.e.*

The following points may be noted carefully :

(i) Since the neutral wire has negligible resistance, supply neutral *N* and load neutral *N'* will be at the same potential. It means that voltage across each impedance is equal to the phase voltage of the supply. However, current in each phase (or line) will be different due to unequal impedances.

(ii) The amount of current flowing in the neutral wire will depend upon the magnitudes of line currents and their phasor relations. In most circuits encountered in practice, the neutral current is equal to or smaller than one of the line currents. The exceptions are those circuits having severe unbalance.

EHVAC transmission

In recent years the electrical energy is generated and consumed at a very high rate throughout the world. There are many new trends and developments which have occurred in the field of transmission of electric power which leads to use high voltages extensively. Currently large amount of power is transmitted over medium and long transmission lines at the voltage of 300kV and above.

As per current terminology, voltages which are less than 300kV are termed as High voltages. The voltages which are in the range of 300 kV and 765kV are celled Extra High Voltage (EHV) whereas the voltages above 765kV are termed as Ultra High voltages (UHV). In India, transmission voltages range from 66kV to 400kV rms (line to line) in three phase bulk power transmission.

Necessity of EHV AC transmission

1. With the increase in transmission voltage, for same amount of power to be transmitted current in the line decreases which reduces I^2R losses (or copper losses). This will lead to increase in transmission efficiency.
2. With decrease in transmission current, size of conductor required reduces which decreases the volume of conductor.
3. The transmission capacity is proportional to square of operating voltages. Thus the transmission capacity of line increases with increase in voltage. The costs associated with tower, insulation, and different equipments are proportional to voltages rather than square of voltages. Thus the overall capital cost of transmission decreases as voltage increases. Hence large power can be economically transmitted with EHV or UHV.
4. With increase in level of transmission voltage, the installation cost of the transmission line per km decreases.
5. It is economical with EHV transmission to interconnect the power systems on a large scale.
6. The number of circuits and the land requirement for transmission decreases with the use of high transmission voltages.
7. Large amounts of power over long distances are technically and economically feasible only at voltages in EHV and UHV range. Thus economics can be achieved in power generation.

Configuration of EHV A. C transmission

The typical configuration of a very long EHV/UHV three phase AC transmission system is shown in the Fig 1.26.

EHV AC transmission line requires minimum two parallel three phase transmission circuits to ensure reliability and stability during a fault on any one phase of the three phase lines.

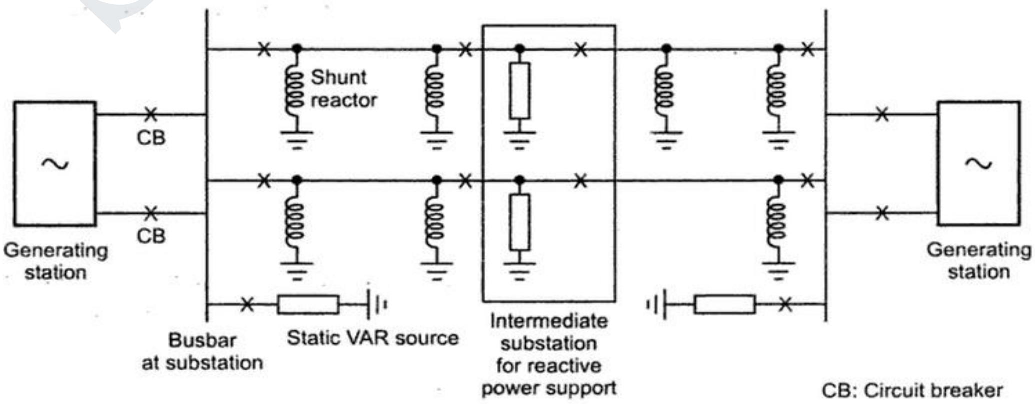


Fig 1.26

Similarly EHV lines also require one or more intermediate substations for installing series capacitors, shunt reactors, switching and protection equipment. Generally an intermediate substation is required at an interval of 250 to 300 km.

Advantages of EHV transmission system

Electrical energy is generated at a voltage about 11kV using alternators. This voltage is then stepped up to 132, 220 or 400 kV for transmission purpose. For transmission of electric power high voltage is preferred because of following advantages,

1. **Reduction in the current**

Power transmitted is given by

$$P = \sqrt{3} V_L I_L \cos\Phi$$

Where V_L = Line voltage, I_L = Load Line current
Cos Φ = Load power factor

Hence load current is given by, $I_L = \dfrac{P}{\sqrt{3} V_L \cos\Phi}$

From the above expression it can be seen that for the constant power and power factor, the load current is inversely proportional to the transmission voltage. With increase in transmission voltage, load current gets reduced. As current gets reduced, size of conductor required also reduces for transmitting same amount of power, which reduces the cost.

2. **Reduction in the losses**

Power loss in a line is given by, $W = 3I_L^2 R$

$$\therefore \quad W = 3\left[\frac{P}{\sqrt{3} V_L \cos\Phi}\right]^2 R = \frac{P^2 R}{V_L^2 \cos^2\Phi}$$

From the above expression it can be seen that power loss in a line is inversely proportional to square of transmission voltage i.e. greater the transmission voltage lesser in the loss in the line.

3. **Reduction in volume of conductor material required**

We have seen that,

$$W = \frac{P^2 R}{V_L^2 \cos^2\Phi} \text{ and } R = \rho\frac{l}{a} \qquad \text{a= area of cross-section}$$

$$\therefore W = \frac{P^2}{V_L^2 \cos^2\Phi} . \rho\frac{l}{a} \quad \text{i.e } a = \frac{P^2 \rho l}{W V^2 \cos^2\Phi}$$

Volume of conductor material required = 3x area of conductor x length of line

$$= 3 \times a \times l = 3 . \frac{P^2 \rho l}{W V_L^2 \cos^2\Phi} \times l$$

$$\therefore \quad volume = \frac{3P^2 \rho l^2}{W V_L^2 \cos^2\Phi}$$

It can be seen that with increase in the transmission voltage, volume of conductor material reduces.

4. **Decrease in voltage drop and improvement of voltage regulation**

The voltage drop in the transmission line is given by,
Voltage drop = 3 I R
With reduction in current due to increase in voltage, voltage drop in the line reduces.

Voltage regulation = Voltage drop/Sending voltage X 100

As voltage drop decreases, regulation of the line is improved.

5. **Increase in transmission efficiency**

Transmission efficiency is given by,

$$Transmission\ Efficiency = \frac{Output\ Power}{Input\ Power} \times 100$$

$$= \frac{Input\ power - Power\ loss}{Input\ Power} \times 100 = \left(1 - \frac{Power\ loss}{Input\ power}\right) \times 100$$

We have seen that with increase in transmission line voltage power loss gets reduced. Hence the transmission efficiency increases as losses in the line are reduced.

6. **Increased power handling capacity**

Power transmitted over a transmission line is given by,

$$P = \frac{V_S.V_R}{X} \sin\delta$$

Thus if we assume that $V_S = V_R$ then power transmitted is proportional to square of voltage which increases power handling capacity of the line.

7. The number of circuits and the land requirement reduces as transmission voltage increases.
8. The total line cost per MW per km decreases considerably with the increase in line voltage.
9. The operation with EHV AC voltage is simple and can be adapted easily and naturally to the synchronously operating a.c. systems.
10. The equipments used in EHV AC system are simple and reliable without need of high technology.
11. The lines can be easily tapped and extended with simple control of power flow in the network.

Disadvantages of problems involved in EHV AV Transmission system

The major problems that can be occurred with EHV transmission system are as follows

1. Corona loss and radio interference

   The corona loss is greatly influenced by choice of transmission voltage. If weather conditions are not proper then this loss further increases. There is also interference in radio and TV which causes disturbance.
2. Line supports

   In order to protect the transmission line during storms and cyclones and to make of wind resistant, extra amount of metal is required in the tower which may increase the cost.
3. Erection difficulties

   There are lots of problems that arise during the erection of EHV lines. It requires high standard of workmanship. The supporting structures are to be efficiently transported.
4. Insulation needs

   With increase in transmission voltage, insulation required for line conductors also increases which increases its cost.
5. The cost of transformers, switchgear equipments and protective equipments increases with increase in transmission line voltage.
6. The EHV lines generate electrostatic effects which are harmful to human beings and animals.

Environmental considerations for EHV AC Transmission

The various environmental considerations for EHV AC transmission system are,

1. Corona effect and ozone gas discharge at the time of corona. It affects the sun and hence affects the environment. So corona effect must be reduced.

2. Radio and television interference is generated due to corona which causes disturbance in wireless signals and communication lines. In bad weather conditions the corona is more and radio interference is more. The radio interference plays an important role in designing of EHV AC lines.
3. For a large voltage, a hissing sound is generated due to corona which can be easily heard and affects the environment. The humming noise from transformers and other electrical equipments also create audible noise. The care must be taken to keep such audible noise as low as possible.
4. Practically EHV AC lines run through forests, farm lands and hilly areas. Thus clearing a path for these lines is an important aspect without affecting environmental balance. The possibility of fire due to the branches of dead trees near such lines is another issue. Such trees and branches must be cur and removed.
5. EHV AC lines are responsible to produce electromagnetic and electrostatic fields which are harmful to human and animals. These fields produce adverse effects of human health such as changes in immune system, changes to the functions of the cells and tissues, including currents on the surface of the human body, changes in the fields so as to restrict their biological effects.
6. Proper protective equipments must be provided to reduce the effects of lightning, storms and other adverse atmospheric conditions on the environment.

Standard rated voltages of EHVAC lines

The standard rated voltages for AC transmission are given in the Table 1.1. The choice for the transmission line voltage is made by referring this table. For a new line, the choice of voltage is made in such a way that the nearest existing system voltage is preferred.

Description	HV		EHVAC			UHVAC		
Rated voltage (Nominal) in kV (rms ph to ph)	132	220	345	400	500	750	1000	1150
Highest voltage in kV(rms ph to ph)	145	245	362	420	525	765	1050	1200

Table 1.1 Standard voltages for 3 ph AC overhead lines

In EHVAC lines additional parallel three phase line is always provided to maintain continuous flow of power and stability of transmission line.

High Voltage Direct Current Transmission (HVDC)

In early days the transmission, distribution and utilization of electrical energy was dominated by a.c. After the introductions of large, high powered mercury are rectifiers, d.c is also considered for transmission of electrical energy economically.

Principle of HVDC Transmission System Operation

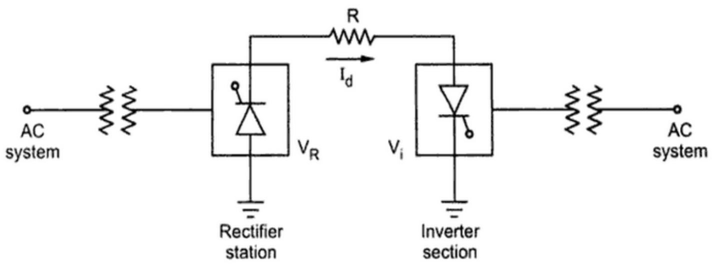


Fig 1.27 simplified HVDC system

A typical HVDC transmission system is shown in the Fig 1.27. At sending end there is one rectifier unit whereas one inverter unit at the receiving end. The two ends are interconnected by a d.c transmission line. The ac produced by generating stations after stepping up is converted to dc by rectifier whereas the inverter converts dc to ac.

The converter makes use of thyristor for controlled operation. Thus by varying the firing angle of the thyristor, the d.c output voltage magnitude is controlled. The firing angle is between 0° and 90° in rectifier while is inverter the firing angle is between 90° and 180°. The converter and inverter station in HVDC uses three phase controlled bridge converters.

From the Fig 1.27 current I_d is given by,

$$I_d = \frac{V_R - V_i}{R}$$

Where V_R = D.C output voltage at rectifier side.

Vi = D.C input voltage at inverter side.

The power transfer is given by,

$$P_d = I_d . V_i = (\frac{V_R - V_i}{R}) V_i$$

Advantages of HVDC Transmission

1. These systems are economical for bulk transmission of power for long distances as the cost of conductor reduces since d.c system requires only two conductors or even one if ground is used as return. Similarly the cost of supporting towers and insulation is also reduced. Also the transmission losses are reduced.
2. There are no stability problems with d.c system. Hence asynchronous operation of transmission link is possible.
3. The line length is not limitation as there is no charging current in d.c systems. Cables in d.c system do not suffer from high dielectric loss. The skin effect is also low in d.c system.
4. Greater power transmission per conductor is possible with d.c system.
5. There are no serious problems of voltage regulation as there is no reactance drop that exists in d.c at steady state.
6. The corona loss a low in d.c systems. The radio interference with HVDC is less.
7. The losses are less in transmission with d.c
8. The fault level increases with interconnections of ac grids through ac lines whereas interconnection of a.c grids through d.c links does not increase fault level to that extent.
9. With HVDC link there is easy reversibility and controllability of power flow.
10. Shunt compensated is not required in d.c lines.
11. Intermediate substations are not required with HVDC transmission.
12. During fault with HVDC system, the grid control of the converter reduces the fault current significantly.
13. The transient stability of the power system can be improved by making parallel connection of HVAC and HVDC lines.

Disadvantages of HVDC Transmission

1. The power transmission with HVDC is not economical if length of transmission is less than 500 km as HVDC system additionally requires converters, inverters and filters.
2. With multiterminal d.c the circuit breaking is difficult and expensive.
3. Considerable reactive power is required by converter stations.
4. Harmonics are generated with d.c system hence filtration is necessary.
5. Overload capacity of HVDC converters is low.
6. There should be local supply of reactive power if required as HVDC will not transmit reactive power.
7. The maintenance of insulators in HVDC system is more.
8. There are additional losses in converter transformers and valves. These losses are continuous. Hence cooling system must be effective to dissipative the heat.

Types of HVDC systems (HVDC Links)

Depending on the arrangement of pole and earth return, HVDC systems are classified in different types. The pole is nothing but the path of direct current which has same polarity with respect to earth.

Following are the different types of HVDC systems.

1. Monopolar HVDC transmission system

Monopolar HVDC transmission system is represented in Fig 1.28. This system has only one pole and the return path is provided by permanent earth or sea. The pole generally has negative polarity with respect to earth.

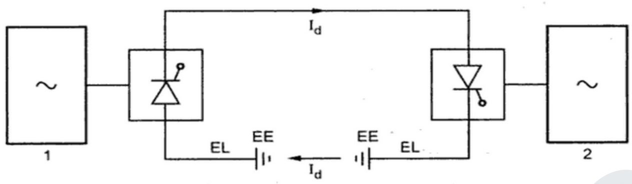


Fig 1.28

Full power and current is transmitted through a line conductor with earth or sea as a return conductor. The earth electrodes are designed for continuous full current operation. The sea or ground return is permanent and of continuous rating.

2. Bipolar HVDC transmission system

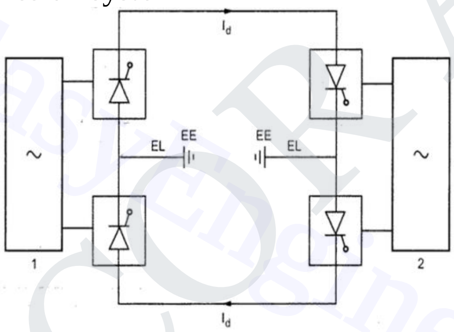


Fig 1.29

This system has two poles, one positive and one negative pole with respect to earth. During fault on one pole the bipolar system is changed to monopolar mode. The system is represented in the Fig 1.29.

This system is more commonly used for transmission of power over long distance. The mid points of converters at each terminal are earthed through electrode line and earth electrode. Power rating of one pole is about half of bipolar power rating. The earth carries only small our of balance current during normal operation.

The normal bipolar HVDC system consists of two separate monopolar systems with a common earth. The two poles can operate independently. Normally they are operated with equal currents and hence ground carries no current.

3. Homopolar HVDC system

This system consists of two poles of same polarity and the return is through permanent earth. It is shown in the Fig 1.30.

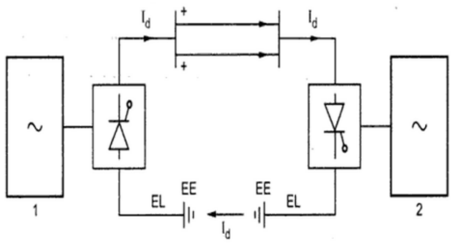


Fig 1.30

4. Back to back HVDC coupling system.

In this system there is no dc transmission line but the rectification and inversion is done in the same substation. It is shown in the Fig 1.31

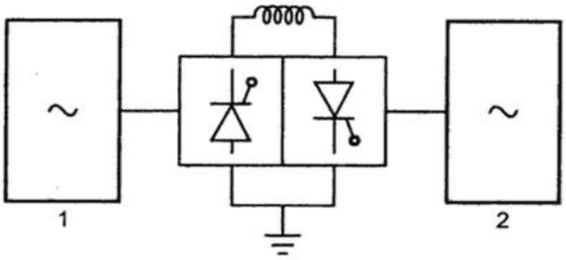


Fig 1.31

5. Multiterminal HVDC system

It has three or more terminal substations. It is shown in Fig 1.32

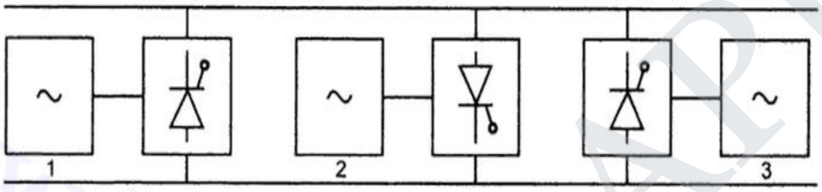


Fig 1.32

Standard Rated voltages for HVDC system

The bipolar HVDC line has two conductors, one of positive polarity with respect to earth and other has negative polarity. The voltage between the poles is twice that of the pole to earth voltage. Hence bipolar HVDC system is given as ± 500kV. The standard rated voltages are given in the Table 1.2

Description	Rated voltage, kV DC					
Bipolar voltage pole to ground	± 100	± 250	± 300	± 400	± 500	± 600
Voltage between poles	200	500	600	800	1000	1200

Table 1.2

The following HVDC systems are present and are operating in India.

1. Vindyachal 500 MW
2. Chandrapur 2×500 MW
3. Visakhapatnam 500 MW
4. Sasaram 500 MW

HVDC Substation

Draw the schematic layout of HVDC substation and explain. (May '04, Dec'10 8 Marks)

Or

Discuss the main components of HVDC system. (May'08)

The central equipment of a d.c substation is a thyristor converter. There are two such thyristor converter units. As a separate pole is used for positive and negative (return path) of d.c., there are two poles and the configuration is called bipole d.c substation.

The converter transformers are used to transform a.c system voltage to which d.c system is connected. This ensures derivation of correct d.c voltage by converter bridges. The converter transformers are generally located in switchyard while the converter bridges are located busbars or with wall bushing.

When wall bushings are used at HVDC level of 400kV or greater than wall bushings must be designed perfectly and with the care to avoid external or internal insulation breakdown. The harmonics filters consisting L and C are required on a.c and d.c side.

The d.c reactors are included in each pole of a converter station. They assist d.c filters in filtering harmonic currents and smooth the d.c side current so that a discontinuous current mode is not reached at low load current operation. This makes the commutation process of d.c converter, more robust.

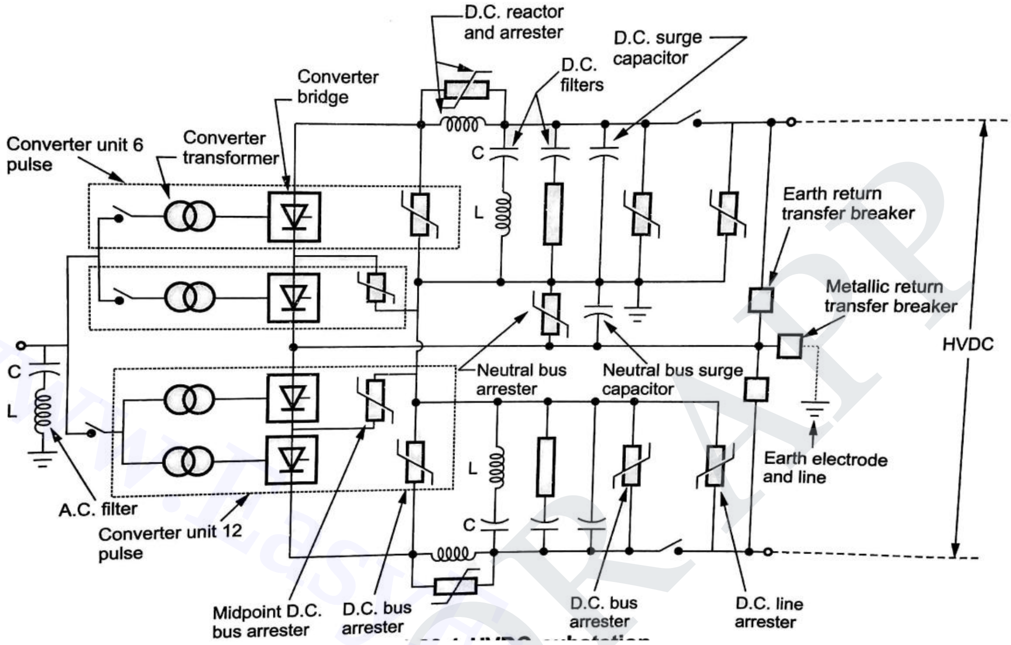


Fig 1.33

Surge arresters across each valve in the converter bridge, across each converter bridge and in the d.c and a.c switchyard are necessary to protect the equipment from all overvoltages regardless of their source. Modern HVDC substations use metal-oxide arresters. The Fig 1.33 shows the layout of a typical HVDC substation.

Terminal Equipments of a DC Transmission Line

For proper operation of dc transmission system, various additional auxiliary equipments are required.

These equipments include

1. DC line inductors
2. Harmonic filters on DC side
3. Converter transformers
4. Reactive power source
5. Harmonics filters on AC side
6. Ground electrodes
7. Microwave communication link between the converter stations.

The dc transmission line with these auxiliary equipments is shown in the Fig 1.34

1. Inductors and Harmonic Filters on DC side.

On dc and ac side of the dc transmission system harmonics are produced. Normally 6th and 12th harmonic currents are produced. If these currents are allowed to flow through line, it may produce undesirable noise in neighbouring telephone lines. Thus to eliminate these harmonic currents, harmonic filters are used. This filter consists of two inductors and a shunt filter which short circuits the harmonic currents to ground by providing low impedance path.

With the use of these inductors the dc line current is prevented from increasing rapidly under faculty condition. The inductors connected in series with the line are used to smoothen the dc current output of a converter. An air cored magnetically shielded reactor is used for this purpose.

2. Converter Transformers

The converter transformer is used to provide ac voltage as required by the converter. Three phase transformers of the type star-star or star-delta may be used. A third winding called tertiary winding may sometimes be added for direct connection to source of the reactive power.

It is required to keep dc line voltage constant from no load to full load. Also for reducing the reactive power absorbed by converter the firing angle α should be kept small. It indicates that the ratio between input AC voltage and output DC voltage of the converter is fixed. But as dc line voltage is fixed, the input ac line voltage must also be fixed.

But it may happen that the line voltage on input ac side may go on varying. Thus the converter transformers on rectifier side are provided with tapping's which will maintain the ac input voltage nearly constant.

The taps are automatically switched by a motorised tap changer. The taps are also needed on converter transformer on inverter side.

3. Reactive power source

The variable static capacitors or synchronous capacitors are required for absorbing reactive power by the converters. The amount of reactive power required increases with the firing angle α of a rectifier and the extinction angle γ of the inverter. This power requirement is about 50% to 60% of real power transfer. The reactive power consumption is provided by capacitors, filters or synchronous compensators. As the active power transmitted goes on varying, the reactive power must also be varied.

4. Harmonic filters on AC side

The three phase, 6-pulse converters produce 5^{th}, 6^{th}, 11^{th} and 13^{th} order harmonics on AC side. These currents are undesirable from the point of view of telephone interference. These currents are bypassed through low impedance filters connected between three phase lines and ground. The filters for each frequency are connected in star and the neutral point is grounded.

5. Ground Electrode

Proper attention must be given towards the ground electrode at each end of dc line DC currents in the ground have a corrosive effect on pipes, cables and metallic structures. In order that the dc ground current does not produce any local problem around the station, the actual ground electrode is located away from converter station. At the grounding site, special means are used to minimize electrode resistance. When bipolar system is temporarily used as monopole system, the ground current may exceed which may produce excessive heat then this electrode resistance factor is important.

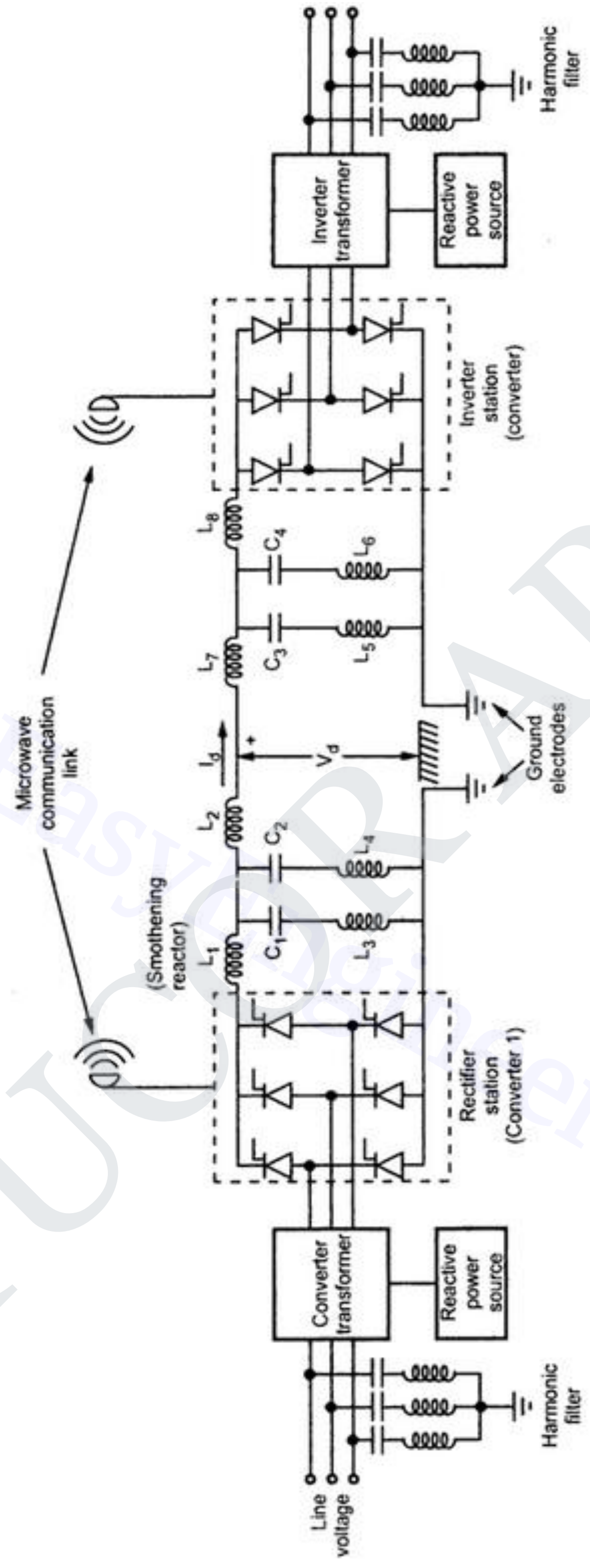


Fig 1.34

6. Communication link

For controlling purpose of the converters at both the ends of the line, a communication link between them is necessary. E.g. to maintain the current margin ΔI, the inverter side must know what is rectifier current setting is. This information is continually relayed by a high speed communication link between the two converters.

Comparison between HVDC and HVAC Transmission (May'05, 09, 12 marks)

Sino	HVDC	HVAC
1	Economical over long distances as it requires only two conductors	Cost is more as it requires three conductors
2	Ground can be used as return conductor where only one conductor is required. This is because ground impedance is negligible.	The ground impedance is high which causes telephonic interference when high ground current flow. Thus high ground current is objectionable in steady state and hence avoided.
3	The line length is not the limitation due to the absence of charging current. Hence power carrying capacity does not depend on distance of transmission.	The power transfer depends on the angle between sending end and receiving end voltages denoted as δ. This δ depends on distance of line. Thus power carrying capacity depends on distance of transmission.
4	No reactance drop hence voltage regulation is better.	Due to reactance voltage drop, voltage regulation is poor than d.c transmission.
5	Corona loss and the radio interference are less.	Corona loss and the radio interference are more and depend on choice of voltage level.
6	The voltage level cannot be changed using transformers.	The voltage level can be raised or lowered using transformers.
7	The cost of the terminal equipments converters, inverters and filters is much more.	The .converters inverters and filters are not required.
8	The fault level of short circuit current is less if d.c links are used to interconnect a.c. lines	The seriousness of short circuit current fault level increases with interconnections of a.c. grids using a.c links
9	If does not require compensation	To overcome line charging and stability problems, shunt and series compensation is required.
10	The maintenance of insulators and other equipments is more.	The maintenance is low compared to dc.
11	Considerable reactive power is required by converter stations but line itself does not require reactive power control.	The line itself requires reactive power control to keep constant voltage at the two ends. The reactive power control increases with the length of the line.
12	Intermediate substations are not required	Intermediate substations are required.
13	For a given power level cost of conductors is less and requires cheaper towers.	Cost of towers and conductors is high for a given power level.
14	Insulation required is less	Insulation required is more and increases with increased voltage level.
15	Skin effect is absent hence power loss is less.	Higher power loss due to presence of skin effect.

Introduction to FACTS

Flexible AC Transmission Systems (FACTS)

In the modern power systems, the power flow in the transmission lines can be controlled with the use of power electronics. The Flexible AC Transmission System (FACTS) give solutions to the problems and limitations which were introduced in the power system with the introduction of power electronics based control for reactive power.

The FACTS technology making use of power electronics promotes the control of transmission line. It also increases load on the line up to the thermal limits without having compromise with the reliability. The line capacity is thus increases which improve reliability of the system. Due to this, there is maximum utilisation of available equipments and additional bulk power transfers are possible. This also avoids the construction of new transmission lines which is time consuming process.

The FACTS based controller's gives instantaneous control of transmission voltage and increase capacity providing larger flexibility in bulk power transmission. It also helps in damping out major grid oscillations. Tennessee Valley Authority (TVA) has installed the first static synchronous compensator (STATCOM) in the year 1995. This has strengthened between Sullivan substation and the rest of the network.

Advantages of FACTS based controllers

1. It controls line impedance angle and voltage which helps in controlling the power flow in transmission lines.
2. The power flow in the transmission lines can be made optimum.
3. It helps in damping out the oscillations and avoids damage of various equipments.
4. It supports the power system security by increasing the transient stability limit. It also limits overloads and short circuit currents.
5. The reserve requirements for generators are considerably reduced as these controllers provide secure and controllable tie line connections to neighboring electric utilities.
6. The loading capacity of the line is greatly increased up to their thermal capabilities. Thus upgrading of lines is possible.
7. It limits the impacts of faults and equipment failures.
8. The reactive power flow in the lines can be decreased and the lines are made to carry more active power.
9. There is increase in utilization of low cost generation due to cost effective enhancement of transmission line capacity.

Objectives of FACTS

The concept of FACTS was established in order to solve the problem which was emerging in power systems in the l ate 1980s as there are restrictions on the construction of transmission line and to promote power growth of import and export.

The main objectives behind the FACTS based controllers are

1. The power transfer capability of transmission systems is to be increased.
2. The power flow is to be kept over the designated routes.

The first objective indicates that the power flow in a given transmission line can be increased up to its thermal limit. This can be achieved by passing the required current through the stress line impedance and maintaining the stability of the system through the proper real time control of power during and after system faults.

The second objective indicates that the flow of power in the line can be restricted to select proper transmission corridors by controlling current in the line.

If these two objectives are fulfilled then there will be significant increase in the utilisation of new and existing transmission lines. It will promote the deregulation of power system and there will minimum requirements for new transmission lines. In order to implement these objectives, high power compensators and controllers are required.

The concept of Flexible AC Transmission Systems (FACTS) was first defined in 1988 by N.G. Hingorani. These controllers control all the interrelated parameters which are involved in power system operations such as series and shunt impedance, current, voltage and phase angle. Also it damps the oscillations at various frequencies below the rated frequency. Thus these controllers are advantageous to power systems in terms of its operations, control, planning of lines and finance.

Types of FACTS Controllers

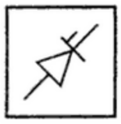


Fig 1.35 Basic symbol of FACTS controller

There are large numbers of types of FACTS controllers with the recent advancement power system. Some of this controller are already installed and put in operation while some of them are still under construction. However more work is to be carried out in this area so that new characteristics of these controllers can be fully used.

Presently FACTS highlight highlight on power flow control and modulation, operating devices, damping of oscillations and stability enhancement. The basic symbol of FACTS controller is shown in the Fig 1.35.

1. Series controllers

These types of controllers inject voltage in series with the line. The current flowing through the line multiplied by variable impedance represents injected series voltage in the line. Till the time the voltage is in the phase quadrature with the line current, these controllers only supply variable reactive power. If there phase relationship between voltage and current is different than real power is also handled in addition to reactive power. A typical series FACTS controller is shown in Fig 1.36.

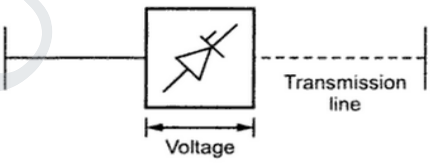


Fig 1.36 Series controller

The series controller is normally a variable impedance type such as capacitor, reactor or power electronics based variable source of main, subsynchronous and harmonic frequencies to satisfy the requirement.

2. Shunt Controllers

The shunt controllers inject current in the system at the point of connection. The shunt controllers are of variable impedance type, variable source type or a combination. The shunt type of FACTS controller is shown in Fig 1.37

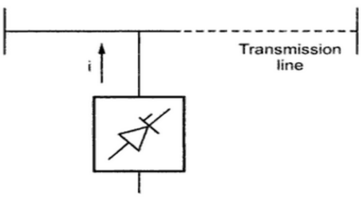


Fig 1.37

If a variable shunt impedance is connected to line voltage, variable current flows and current is injected in the line. So long as there is quadrature relationship between voltage and current, these controllers either supply or deal with reactive power. For other phase relationship, active power is also handled.

3. Combined Series Series Controllers

In these type of controllers, series controllers are controlled in co-ordinated manner in case of multiline transmission system. It is alternatively unified controller in which series controllers individually supply reactive power compensation independently for every line and also transfer real power among the lines through power link. The meaning of the term unified indicates that the dc terminals of all the controller converters are all connected together for transferring real power.

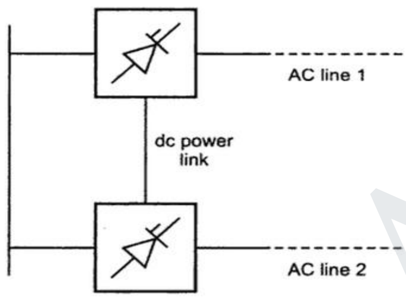


Fig 1.38 Unified series-series controller

4. Combined series-shunt controllers

It may be a combination of separate series and shunt controllers which are controlled in a co-ordinated manner as shown in the Fig 1.39 (a) or a unified power flow controller with series and shunt elements as shown in Fig 1.39 (b)

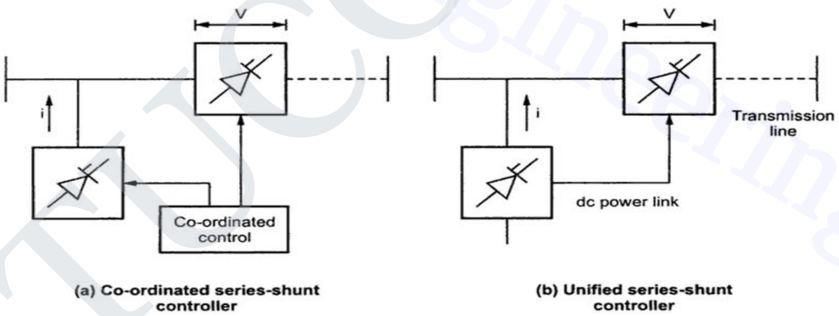


Fig 1.39

In these types of controllers, current is injected in the system through shunt part of the controller while voltage is injected in the line through series part of the controller. In unified series-shunt controller, it is possible to exchange real power between series and shunt controllers through dc power link.

FACTS devices

In this section, various FACTS based devices are listed. The various FACTS devices are as given below.

1. Static synchronous compensator (STATCOM)
2. Static Synchronous Generator (SSG)
3. Static VAR Compensator (SVC)
4. Thyristorized switched or controlled reactor (TSR/TCR)
5. Thyristor switched capacitor
6. Static VAR Generator or absorber (SVG)
7. Static VAR system (SVS)

8. Thyristor Controlled Braking Resistor (TCBR)
9. Static Synchronous Series Compensator (SSSC)
10. Interline Power Flow Controller (IPFC)
11. Thyristor controlled or switched series capacitor or series reactor (TCSC/TSSC/TCSR/TSSR)
12. Unified Power Flow Controller (UPFC)
13. Thyristor Contolled Phase Shifting Transformer (TCPST)
14. Interphase Power Controller (IPC)
15. Thyristor Controlled Voltage Limiter (TCVL)
16. Thyristor Controlled Voltage Regulator(TCVR)

1. Static Synchronous Compensator (STATCOM)

It is shunt connected static VAR compensator whose capacitive or inductive output current can be controlled independently of the ac system voltage. It is shown in the Fig 1.40

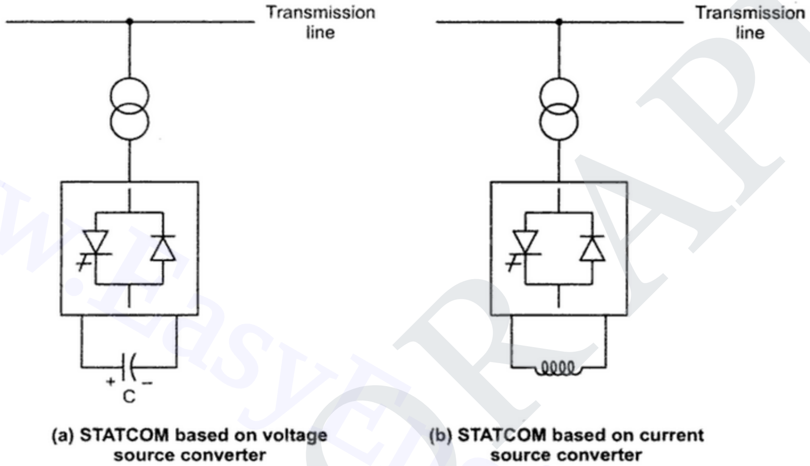


Fig 1.40 STATCOM

In case of voltage source converter, the ac output voltage is controlled in such a way as the proper reactive current will flow for any bus voltage. The dc capacitor voltage is automatically adjusted as per the requirement so that it acts as voltage source for the converter. The harmonics in the system can be absorbed by designing STATCOM as an active filter.

It is a three phase inverter driven by voltage across capacitor and the three phase output voltages are in phase with ac system voltages. The difference in the amplitudes of the voltages gives how many current flows. The reactive power and its polarity can be changed by controlling the voltage. The performance of STATCOM is better than SVC.

With depression in voltage, STATCOM will still supply high reactive power by using it's over current capability. The large capacitor present acts as storage device and can continue to deliver some energy for short duration just like synchronous condenser.

The use of STATCOM needs Gate Turn off (GTO) thyristors which are costly as compared to normal thyristors.

2. Static VAR Compensator (SVC)

In STATCOM, converters are used while in SVC thyristors without gate turn off capability are used. It is shunt connected static VAR generator or absorber. The output of SVC is adjusted to control capacitive or inductive current in order to control or maintain certain parameters, normally magnitude of bus voltage of the power systems. A basic model of SVC is shown in the Fig 1.41

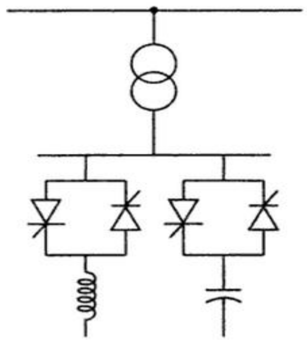


Fig 1.41 SVC

The separate equipments are present in SVC for lagging and leading VARs. It is a low cost substitute for STATCOM. In STATCOM, the most reactive power that is delivered is product of voltage and current whereas in case of SVC, it is the square of voltage divided by the impedance. The reactive power-capability steeply falls off as a function of square of voltage in this case.

Comparison of STATCOM and SVC

The comparison between SVC and STATCOM is given in this section.

S.No	SVC	STATCOM
1	Generating of more harmonics	Generation of less harmonics
2	During the transients, the performance is slow.	Better performance during transients and faster response.
3	Acting as a variable susceptance	Acting as a voltage source behind a reactance.
4	Operates mainly in capacitive region	Operation in both inductive and capacitive regions is possible.
5	Sensitive to transmission system harmonic resonance.	Insensitive to transmission system harmonic resonance.
6	Operation in difficult for a week ac system	With a very weak system, it can maintain a stable voltage.

3. Thyristor Controlled Series Capacitor (TSCS)

It is a capacitive reactance type of compensator consisting of a series capacitor bank connected in parallel with a thyristor controlled reactor so as to provide smooth variable capacitive reactance.

It is important type of FACTS controller based on thyristors without the gate turn off capability. It is shown in the Fig 1.42

The thyristor controlled Reactor (TCR) is connected across a series capacitor. When the firing angle of TCR is 180°, the reactor in non conducting and the series capacitor has its normal impedance. If the firing angle is decreased from 180°, the capacitive impedance increases. The reactor is fully conducting when the firing angle is 90°. In this case, the total impedance is inductive as the designed value of reactor impedance is less than the impedance of series capacitor. The TCSC helps in limiting fault current for a firing angle of 90°.

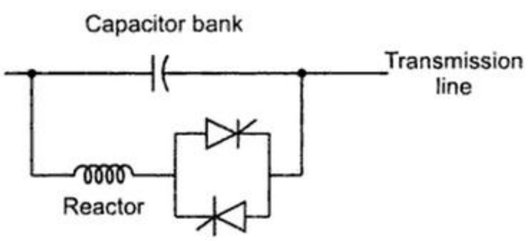


Fig 1.42 TSCS

For getting best performance from TCSC, it has different sized smaller capacitors or several equal capacitors instead of a single large unit.

4. Unified Power Flow Controller (UPFC)

It is a combination of Static Synchronous Compensator (STATCOM) and Static Synchronous Series Compensator (SSSC). These two are coupled through a dc link and allows bidirectional flow of real power between series output terminals of SSSC and shunt output terminals of the STATCOM. These can be controlled to provide real and reactive series line compensation without an external electrical energy source. It is shown in the Fig 1.43.

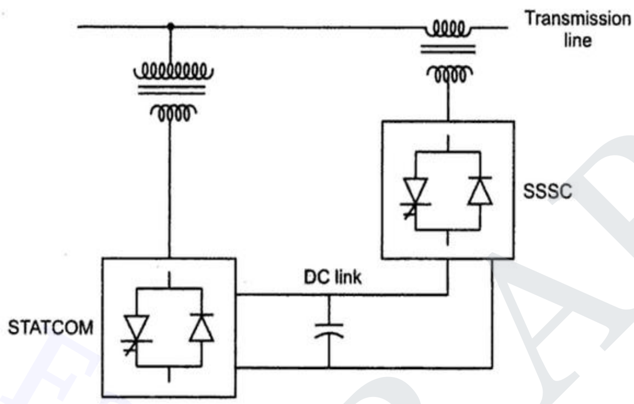


Fig 1.43 UPFC

The meaning of UPFC is angular, unconstrained injection of series voltage to control selectively the line voltage, impedance and angle. Alternatively, real and reactive power flow in the line is controlled. The independent controllable shunt compensation is also provided by UPFC.

UPFC can be made more effective by connecting additional storage shunt as a super conducting magnet connected to the dc link through the electronic interface. The controlled exchange of real power is possible in case of UPFC.

TWO MARKS

PART-A

1. Distinguish between a feeder and a distributor.[April/May '15]

Feeder	Distributor
A feeder is a conductor which connects the substation or localized generating station to the area where power is to be distributed. Generally no tapping are taken from the feeders so current in it remains the same throughout. The main consideration in the design of a feeder is the current carrying capacity.	A distributor is a conductor from which tapping are taken for supply to the consumers. The current through the distributors are not constant as tappings are taken at various places along its length. While designing a distributor, voltage drop along the length is main consideration-limit of voltage variations is ± 6volts at the consumer terminal.

2. **Why is electrical power preferably to be transmitted at a high voltage? [April/May '15][Nov/Dec'15]**

Electric power is preferably transmitted at a high voltage because it improves transmission efficiency, reduces percentage line drop and reduces the cost of conductor material.

3. **What is a feeder? [Nov/Dec '12][Nov/Dec'15]**

A feeder is a conductor which connects the substation or localized generating station to the area where power is to be distributed.

4. **List the types of HVDC links. [May/June'13]**

Monopolar HVDC system
Bipolar HVDC system
Homopolar HVDC system
Back to back HVDC coupling system.

5. **Give reason why the transmission lines are three phase 3 wire circuits while distribution lines are three phase 4 wire circuits.[Nov/Dec '13]**

The transmission is at very high voltage level and such a balanced three phase system does not require neutral conductor. Hence the transmission line circuits are 3 phase 3 wire circuits. While distribution, it is necessary to supply single phase loads along with the three phase loads. For single phase distribution a neutral conductor is must. Hence distribution lines are 3 phase 4 wire circuits.

6. **List out the basic types of FACTS controller.[April/May'11]**
   (a) Series controller
   (b) Shunt controller
   (c) Combined series-series controller
   (d) Combined series-shunt controller

7. **List out the advantages of high voltage A.C transmission.[Nov/Dec'11][May/June'16]**
   (i) Reduction of current and losses
   (ii) Reduction of volume of conductor material
   (iii) Improvement in voltage regulation
   (iv) Increase in transmission efficiency
   (v) Reduction in %line drop.

8. **State the disadvantages of HVDC transmission.[Nov/Dec'10]**
   (i) Converters at both ends though reliable they are much expensive than the ordinary AC equipments and they have little overload capacity and needs supply of reactive power locally.
   (ii) Using HVDC becomes economically only for long distances
   (iii) It is impossible to either step up or step down DC voltages directly so conversion is required every time-transformation is required.
   (iv) The converters produce a lot of harmonics which may cause interference with communication lines requiring filters which increase the cost.
   (v) Circuit breaking for multi terminal line is difficult.

9. What are the objectives of FACTS?[May/June'16]

(i) Regulation of power flow is prescribed transmission routes
(ii) Loading of transmission lines nearer to their thermal limits
(iii) Contributing to emergency control without disconnecting more equipments from source
(iv) Improves system stability by damping oscillations.

10. List out the limitations of high transmission voltage.[Nov/Dec'15]

(i) More insulation is required for the conductors and towers
(ii) More clearance is required between the conductors and ground. So height of the supporting tower increases.
(iii) More distance is required between the conductors. So length of the cross arms used increases.
(iv) The transformers, switchgears and other terminal equipments should be designed to handle such high voltages.

11. State the meaning of an electrical grid.[April/May'09]

An electrical grid is a network in which the various generating, transmission and distribution systems are interconnected with each other to supply electricity to the consumers.

12. List the various elements of power system.[April/May'14]

The various elements of power system are generators, transformers, transmission lines, bus bars, circuit breakers, isolating switches, feeders, distributors, service mains etc.

13. State the practical transmission and distribution voltage levels commonly used.[April/May'05]

Generating station	:	6.6kV, 11kV or 22kV
Primary transmission	:	11kV/132kV/220kV/400kV
Secondary transmission	:	11kV/22kV/33kV
Primary distribution	:	6.6kV/3.3kV/11kV
Secondary distribution	:	400V/230V

14. State the advantages of FACTS.[April/May'10]

It controls line impedance angle and voltage which helps in controlling the power flow in transmission lines.

The power flow in transmission lines can be made optimum.

It helps in damping out the oscillations and prevent the damage of equipments

It supports the power system security by increasing the transient stability.

It limits the overloads and short circuit currents

The reserve requirements for generators are considerable reduced.

The loading capacity of the line is greatly increased up to their thermal capabilities.

15. List out the various FACTS devices.[April/May'08]

a. Static synchronous compensator(STATCOM)
b. Static synchronous generator(SSG)
c. Static VAR compensator (SVC)
d. Thyristor switched or controlled reactor.(TSR/TCR)
e. Static VAR generator(SVG)
f. Static VAR systems(SVS)
g. Thyristor controlled braking resistor.(TCBR)

h. Static synchronous series compensator(SSSC)
i. Interline power flow controller(IPFC)
j. Unified power flow controller (UPFC)
k. Interphase power controller(IPC)
l. Thyristor controlled voltage limiter(TCVL)

16. What is the highest a.c transmission voltage we have in India?[April/May'10]

The highest a.c transmission voltage we have in India is now 1200kV in Madhya Pradesh.

17. Give any two HVDC lines in india.[April/May'08]

The HVDC lines in india are,

(i) Rihand and Dadri (ii) Talcher-Kolar (iii) Kanpur

18. What is service mains?[April/may'11]

The small cables used to connect the distributors and the actual consumer premises are called service mains.

19. Explain the term regional grid. [Nov/Dec'07]

In order to achieve economy, reliability and continuity in the supply, individual power systems generating electrical power are arranged in the form of electricity connected areas called regional grid.

20. Compare STATCOM and SVC. [May/June'04]

S.No	SVC	STATCOM
1	Generating of more harmonics	Generation of less harmonics
2	During the transients, the performance is slow.	Better performance during transients and faster response.
3	Acting as a variable susceptance	Acting as a voltage source behind a reactance.
4	Operates mainly in capacitive region	Operation in both inductive and capacitive regions is possible.
5	Sensitive to transmission system harmonic resonance.	Insensitive to transmission system harmonic resonance.
6	Operation in difficult for a week ac system	With a very weak system, it can maintain a stable voltage.

UNIT - I

Parameters of single and three phase transmission lines with single and double circuits - Resistance, inductance and capacitance of solid, stranded and bundled conductors, symmetrical and unsymmetrical spacing and transposition - application of self and mutual GMD; skin and proximity effects - interference with neighboring communication circuits - Typical configurations, conductor types and electrical parameters of EHV lines, Corona discharges.

1. **Describe Constants of a Transmission Line.**

A transmission line has resistance, inductance and capacitance uniformly distributed along the whole length of the line.

(i) Resistance

(ii) Inductance

(iii) Capacitance.

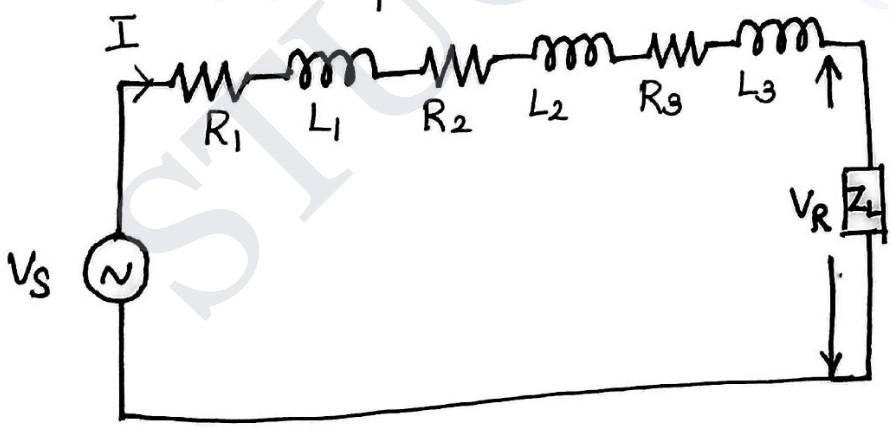


Fig. (i)

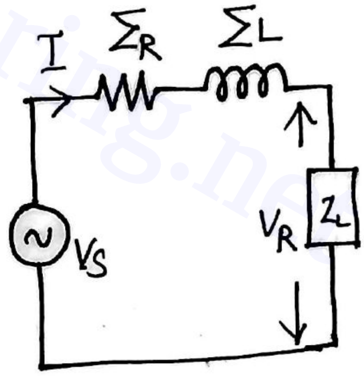


Fig. (ii).

(i) **Resistance**

It is the opposition of line conductors to current flow. The resistance is distributed uniformly along the whole length of the line as shown in Fig.(i).

However, the performance of a transmission line can be analysed conveniently if distributed resistance is considered as lumped as shown in Fig.(ii).

(ii) Inductance.

When an alternating current flows thr'h a conductor, a changing flux is set up which links the conductor.

Due to these flux linkages, the conductor possesses inductance. Mathematically, inductance is defined as the flux linkages per ampere, i.e,

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

ψ = flux linkages in weber-turns

I = current in amperes.

The inductance is also uniformly distributed along the length of the line as shown in Fig (i). Again for the convenient of analysis it can be taken to be lumped as shown in Fig (ii).

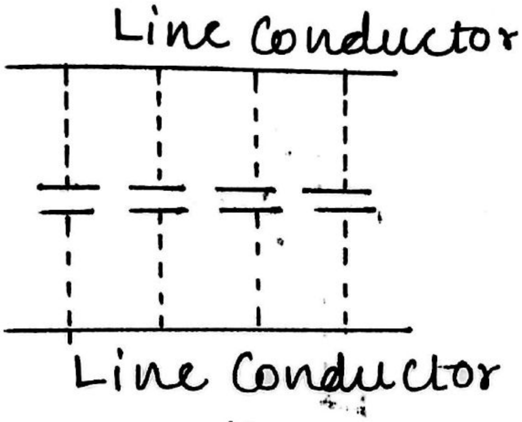
(iii) Capacitance.

We know that any two conductors separated by an insulating material constitute a capacitor. As any two conductors of an overhead transmission line are separated by air which acts as an insulation, therefore capacitance exists between any two overhead line conductors.

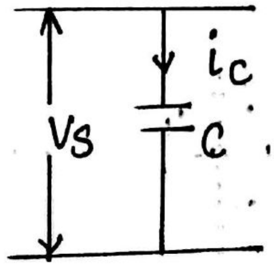
The capacitance between the conductors is the charge per unit potential difference, i.e,

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

Where, q = Charge on the line in coulomb
V = p.d between the conductors in volts.



(iii)



(ii)

The Capacitance is uniformly distributed along the whole length of the line and may be regarded as a uniform series of capacitors connected between the conductors as shown in Fig (iii).

When an alternating voltage is impressed on a transmission line, the charge on the conductors at any point increases and decreases with the increase and decrease of the instantaneous value of the voltage between conductors at that point. The result is that a current (known as charging current) flows between the conductors (Fig (iv)).

This charging current flows in the line even when it is open-circuited i.e., supplying no load. It affects the voltage drop along the line as well as efficiency and power factor of the line.

2. Derive an expression for loop inductance of a single phase transmission line. [4]
[Nov/Dec '15] 16 marks.

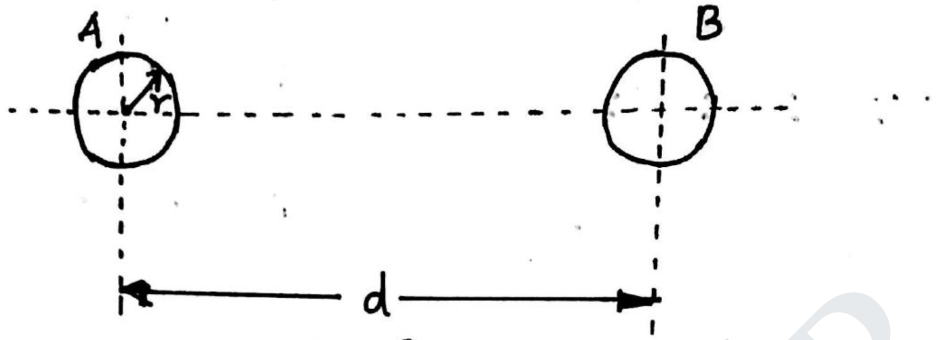


Fig (i).

A single phase line consists of two parallel conductors which form a rectangular loop of one turn. When an alternating current flows through such a loop, a changing magnetic flux is set up.

The changing flux links the loop and hence the loop (or single phase line) possesses inductance.

It may appear that inductance of a single phase line is negligible because it consists of a loop of one turn and the flux path is through air of high reluctance.

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

Consider a single phase overhead line consisting of two parallel conductors A and B spaced d metres apart as shown in Fig (i).

Conductors A and B carry the same amount of current (i.e, $I_A = I_B$), but in the opposite direction because one forms the return circuit of the other.

$$\therefore I_A + I_B = 0$$

In order to find the inductance of conductor A (or Conductor B), we shall have to consider the flux linkages with it.

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

Flux linkages with conductor A due to its own current.

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

Flux linkages with conductor A due to current I_B.

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

Total flux linkages with conductor A is

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

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

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

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

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

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

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

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

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

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

Inductance of conductor A,

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

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

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

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

Loop inductance $= 2 L_A$ H/m

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

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

~~∴ Loop induct~~

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

[7].

3. Derive an expression for the inductance per phase for a 3-phase overhead transmission line when
(i) Conductors are symmetrically spaced.
(ii) Conductors are unsymmetrically place but the line is completely transposed. [16] Nov/Dec'15

(Or)

Derive an expression for the inductance of a 3ϕ over head transmission lines with unsymmetrical spacing. Also spacing the concept of transposition of conductors. [16] [May/June'13] [Nov/Dec'10].

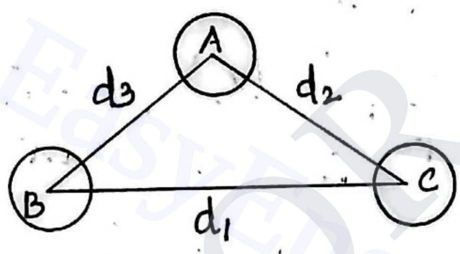


Fig. 1.

Figure 1 shows the three conductors A, B and C of a 3-phase line carrying currents I_A, I_B and I_C respectively.

Let d_1, d_2 and d_3 be the spacings between the conductors as shown. Let us further assume that the loads are balanced,

$$\text{ie}\quad I_A + I_B + I_C = 0.$$

Consider the flux linkages with conductor A. There will be flux linkages with conductor A due to its own current and also due to the mutual inductance effects of I_B and I_C.

Flux linkages with conductor A due to its own current

$$= \frac{\mu_0 I_A}{2\pi}\left(\frac{1}{4} + \int_0^{\infty}\frac{dx}{x}\right) \quad \ldots\ldots (i)$$

Flux linkages with conductor A due ~~its~~ to current I_B

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

Flux linkages with conductor A due to current I_C.

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

Total flux linkages with conductor A is,

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

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

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

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

As $I_A + I_B + I_C = 0$.

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

(i) Symmetrical spacing.

If the three conductors A, B and C are placed symmetrically at the corners of an equilateral triangle of side d, then

$$d_1 = d_2 = d_3 = d.$$

Under such conditions, the flux linkages with conductor A become:

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

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

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

$$\because I_B + I_C = -I_A$$

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

Inductance of conductor A,

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

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

$$\therefore L_A = 10^{-7}\left[0.5 + 2\log_e \frac{d}{r}\right] \text{ H/m.}$$

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

(ii) Unsymmetrical spacing.

When 3-phase line conductors are not equidistant from each other, the conductor spacing is said to be unsymmetrical. Under such conditions, the flux linkages and inductance of each phase are not the same.

A different inductance in each phase results in unequal voltage drops in the three phases even if the currents in the conductors are balanced. Therefore, the voltage at the receiving end will not be the same for all phases.

In order that voltage drop are equal in all conductors, we generally interchange the positions of the conductors at regular intervals along the line so that each conductor occupies the original position of every other conductor over an equal distance.

Such an exchange of positions is known as transposition.

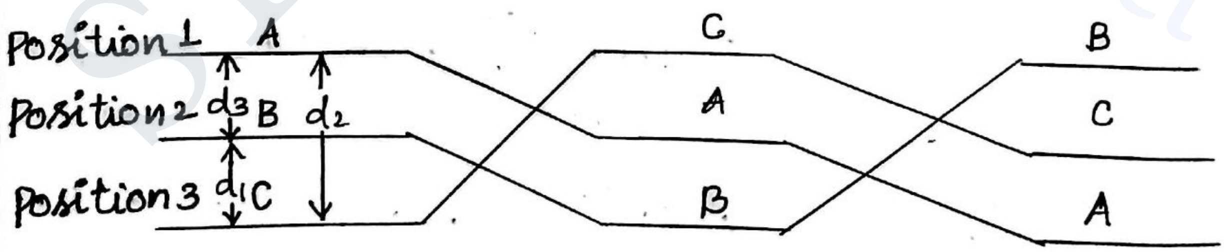


Fig (2)

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

Fig (2) shows a 3-phase transposed line having unsymmetrical spacing. Let us assume that each of the three sections is 1m in length. Let us further assume balanced conditions ie

$$I_A + I_B + I_C = 0.$$

Let the line currents be:

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

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

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

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

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

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

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

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I - I \log_e r + 0.5 I \log_e d_3 + j0.866 \log_e d_3 + 0.5 I \log_e d_2 - j0.866 I \log_e d_2\right]$$

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

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I - I \log_e r + I \log_e \sqrt{d_2 d_3} + j0.866 I \log_e \frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0}{2\pi}\left[\frac{1}{4} I + I \log_e \frac{\sqrt{d_2 d_3}}{r} + j0.866 I \log_e \frac{d_3}{d_2}\right]$$

$$= \frac{\mu_0 I}{2\pi}\left[\frac{1}{4} + \log_e \frac{\sqrt{d_2 d_3}}{r} + j0.866 \log_e \frac{d_3}{d_2}\right]$$

∴ Inductance of Conductor A is

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

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

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

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

Similarly inductance of conductors B and C will be:

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

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

Inductance of each line conductor.

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

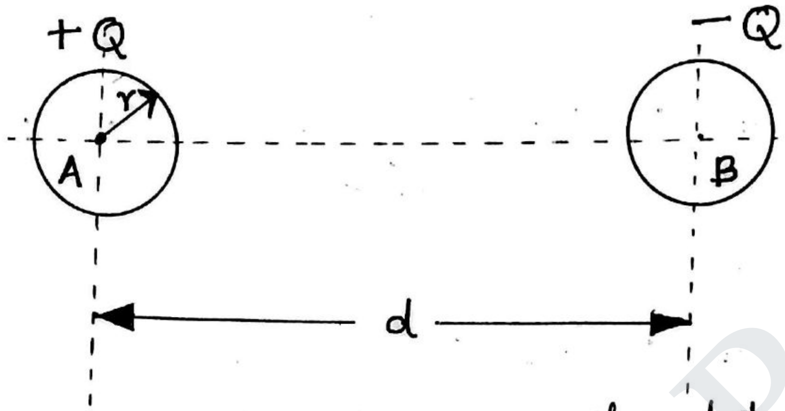
$$= \left[\frac{1}{2} + 2\log_e \frac{\sqrt[3]{d_1 d_2 d_3}}{r}\right] \times 10^{-7} \text{ H/m}$$

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

If we compare the formula of inductance of an unsymmetrically spaced transposed line with that of symmetrically spaced line we find that inductance of each line conductor in the two cases will be equal if $d = \sqrt[3]{d_1 d_2 d_3}$.

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

4. Derive an expression for the capacitance of a 1φ overhead transmission line. [8] (May/June'13)



Fig(1)

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

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

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

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

$$V_A = \frac{Q}{2\pi\epsilon_0} \log_e \frac{d}{r} \text{ Volts}.$$

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

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

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

$$V_B = \frac{-Q}{2\pi\epsilon_0} \log_e \frac{d}{r} \text{ Volts}.$$

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

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

∴ Capacitance,

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

$$\therefore C_{AB} = \frac{\pi\epsilon_0}{\log_e \frac{d}{r}} \text{ F/m} \quad \ldots\ldots (1)$$

Capacitance to neutral.

Equation (1) gives the capacitance between the conductors of a two wire line [Fig 2]. Often it is desired to know the capacitance between one of the conductors and a neutral point between them.

Since potential of the mid-point between the conductors is zero, the potential difference between each conductor and the ground or neutral is half the potential difference between the conductors.

Thus the capacitance to ground or capacitance to neutral for the two wire line is twice the line to line capacitance (capacitance between conductors as shown in Fig 3).

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

$$C_N = \frac{2\pi\epsilon_0}{\log_e \frac{d}{r}} \text{ F/m} \quad \ldots\ldots (ii).$$

The radius in the equation for Capacitance is the actual outside radius of the conductor and not the GMR of the conductor as in the inductance formula.

Eqn (2) applies only to a solid round conductor.

15

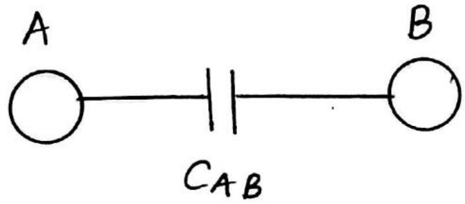


Fig 2

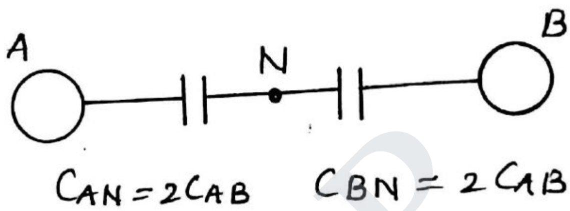


Fig 3.

5. Derive an expression for capacitance of 3ϕ unsymmetrically spaced transmission line. [16] [Nov/Dec'12] [May/June'16].

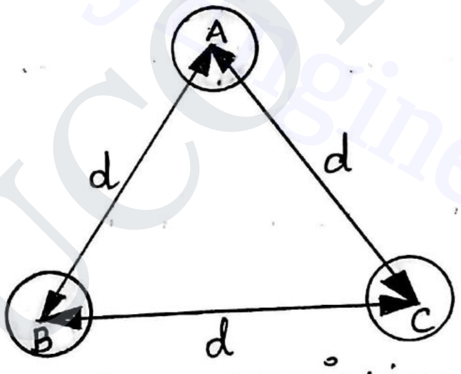


Fig (1)

In a 3-phase transmission line, the Capacitance of each conductor is considered instead of capacitance from conductor to conductor.

(i) Symmetrical spacing
(ii) Unsymmetrical (or) asymmetrical spacing

(i) Symmetrical Spacing

Fig 1 shows the three conductors A, B and C of the 3-phase overhead transmission line having charges Q_A, Q_B and Q_C per metre length respectively.

Let the conductors be equidistant (d metre) from each other. We shall find the capacitance from line conductor to neutral in this symmetrically spaced line.

Referring to Fig 1, overall potential difference between conductor A and infinite plane is given by,

$$V_A = \int_r^\infty \frac{Q_A}{2\pi x \epsilon_0} dx + \int_d^\infty \frac{Q_B}{2\pi x \epsilon_0} dx + \int_d^\infty \frac{Q_C}{2\pi x \epsilon_0} dx .$$

$$= \frac{1}{2\pi\epsilon_0}\left[Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d} + Q_C \log_e \frac{1}{d}\right]$$

$$= \frac{1}{2\pi\epsilon_0}\left[Q_A \log_e \frac{1}{r} + (Q_B + Q_C) \log_e \frac{1}{d}\right]$$

Assuming balanced supply, we have,

$$Q_A + Q_B + Q_C = 0.$$

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

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

$$= \frac{Q_A}{2\pi\epsilon_0} \log_e \frac{d}{r} \text{ Volts.}$$

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

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

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

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

(ii) Unsymmetrical spacing.

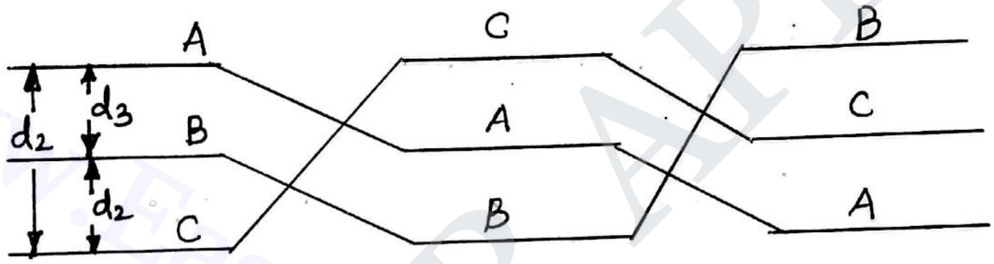


Fig 2.

Fig 2 shows a 3-phase transposed line having unsymmetrical spacing. Let us assume balanced conditions.

$$\text{ie, } Q_A + Q_B + Q_C = 0$$

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

potential of 1st position,

$$V_1 = \frac{1}{2\pi\epsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_3} + Q_C \log_e \frac{1}{d_2}\right).$$

potential of 2nd position,

$$V_2 = \frac{1}{2\pi\epsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_1} + Q_C \log_e \frac{1}{d_3}\right).$$

Potential of 3rd position,

$$V_3 = \frac{1}{2\pi\epsilon_0}\left(Q_A \log_e \frac{1}{r} + Q_B \log_e \frac{1}{d_2} + Q_C \log_e \frac{1}{d_1}\right)$$

Average Voltage on Conductor A is,

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

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

As $Q_A + Q_B + Q_C = 0$,

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

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

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

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

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

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

$\therefore$ Capacitance from Conductor to neutral is,

$$C_A = \frac{Q_A}{V_A}$$

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

6. Explain the concept of self-GMD and Mutual-GMD.

The use of self geometrical mean distance (GMD) and mutual geometrical mean distance (mutual-GMD) simplifies the inductance calculations, particularly relating to multiconductor arrangements.

The symbols used for these are respectively D_s and D_m.

(i) Self-GMD (D_s).

In order to have concept of self-GMD consider the expression for inductance per conductor per metre,

$$\text{Inductance/Conductor/m} = 2\times10^{-7}\left(\frac{1}{4}+\log_e\frac{d}{r}\right)$$

$$= 2\times10^{-7}\times\frac{1}{4}+2\times10^{-7}\log_e\frac{d}{r} \quad \ldots\ldots (i)$$

In this expression, the term $2\times10^{-7}\times(1/4)$ is the inductance due to flux within the solid conductor.

For many purposes, it is desirable to eliminate this term by the introduction of a concept called self-GMD or GMR.

If we replace the original solid conductor by an equivalent hollow cylinder with extremely thin walls, the current is confined to the conductor surface and internal conductor flux linkage would be almost zero.

Consequently, inductance due to internal flux would be zero and the term $2\times10^{-7}\times(1/4)$ shall be eliminated.

The radius of this equivalent hollow cylinder must be sufficiently smaller than the physical radius of the conductor to allow room for enough additional flux to compensate for the absence of internal flux linkage.

It can be proved mathematically that for a solid round conductor of radius r, the self-GMD or GMR = 0.7788r. Using self-GMD, the eqn (i) becomes:

$$\text{Inductance/conductor/m} = 2\times10^{-7}\log_e \frac{d}{D_s}$$

Where,

D_s = GMR or self-GMD = 0.7788r.

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

(ii) Mutual-GMD.

The mutual-GMD is the geometrical mean of the distance from one conductor to the other and, therefore, must be between the largest and smallest such distance.

In fact, mutual-GMD simply represents the equivalent geometrical spacing.

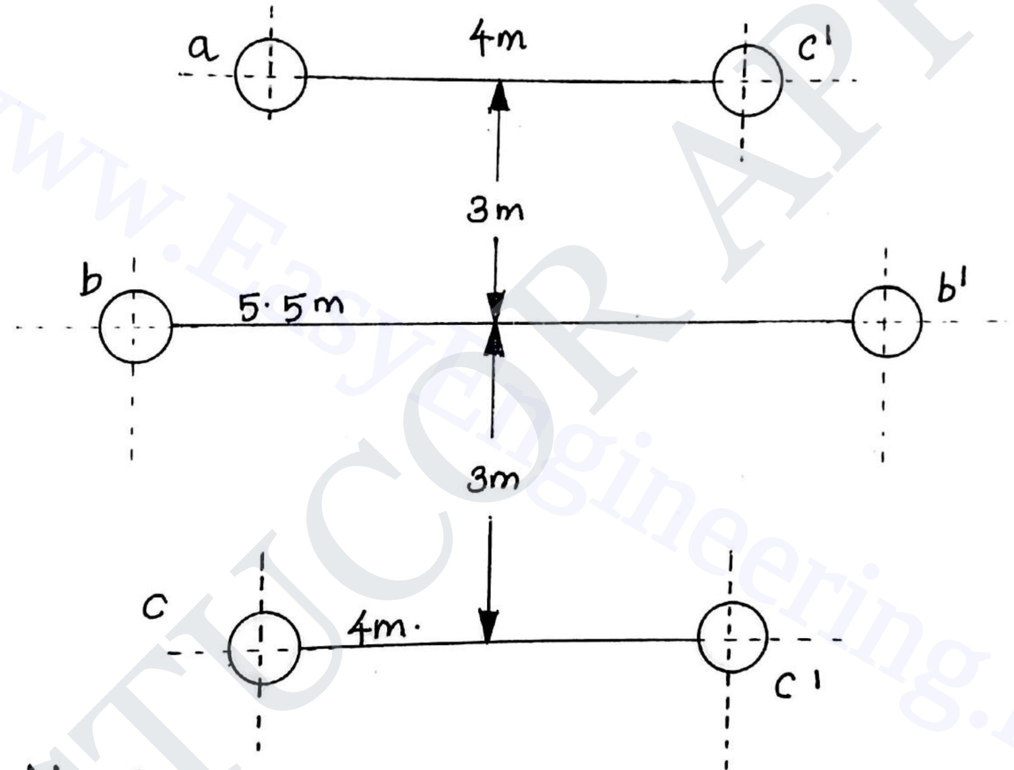
(a) The mutual-GMD between two conductors (assuming that spacing between conductors is large compared to the diameter of each conductor) is equal to the distance between their centres i.e,

D_m = Spacing between conductors = d.

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

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

6. Find the inductance per phase per km of double circuit 3-phase line shown in Fig. The conductors are transposed and are of radius 0.75 cm each. The phase sequence is ABC.



Solution:

G.M.R of conductor $= 0.75 \times 0.7788 = 0.584$ cm

Distance a to b $= \sqrt{3^2 + (0.75)^2} = 3.1$ m

Distance a to b' $= \sqrt{3^2 + (4.75)^2} = 5.62$ m

Distance a to a' $= \sqrt{6^2 + 4^2} = 7.21$ m.

Equivalent self G.M.D of one phase is

$$D_s = \sqrt[3]{D_{s1} \times D_{s2} \times D_{s3}}$$

where $D_{s1} = \sqrt[4]{D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a}}$

$$= \sqrt[4]{(0.584\times10^{-2})\times(7.21)\times(0.584\times10^{-2})\times(7.21)}$$

$$= 0.205m = D_{S3}$$

$$D_{S2} = \sqrt[4]{(D_{bb}\times D_{bb'}\times D_{b'b'}\times D_{b'b}}$$

$$= \sqrt[4]{(0.584\times10^{-2})\times(5.5)\times(0.584\times10^{-2})\times5.5}$$

$$D_{S2} = 0.18\,m$$

$$D_S = \sqrt[3]{0.205\times0.18\times0.205} = 0.195\,m$$

Equivalent mutual G.M.D is

$$D_m = \sqrt[3]{D_{AB}\times D_{BC}\times D_{CA}}$$

$$D_{AB} = \sqrt[4]{D_{ab}\times D_{ab'}\times D_{a'b}\times D_{a'b'}}$$

$$= \sqrt[4]{3.1\times5.62\times5.62\times3.1}$$

$$= 4.17m = D_{BC}.$$

$$D_{CA} = \sqrt[4]{D_{ca}\times D_{ca'}\times D_{c'a}\times D_{c'a'}}$$

$$= \sqrt[4]{6\times4\times4\times6}$$

$$= 4.9\,m$$

$$\therefore D_m = \sqrt[3]{4.17\times4.17\times4.9} = 4.4m$$

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

$$= 10^{-7}\times 2\log_e \frac{4.4}{0.195}\,H.$$

$$= 6.23\times10^{-7}\,H$$

$$= 0.623\times10^{-3}\,mH$$

Inductance/phase/Km $= 0.623\times10^{-3}\times1000$

$$= 0.623\,mH$$

7. Explain the Types of Conductors.

Conductors used for electrical system are those having less resistance, low weight, high-tensile strength, low cost and low coefficient of expansion.

Normally, we use aluminium and copper as conductors for the same. The main advantages of aluminimum conductors over copper conductors are:

* low weight
* high conductivity (less resistance) and less corona loss
* low cost.

The main problems with aluminium conductors are:

* low tensile strength
* high coefficient of expansion
* large area (thus to high wind pressure)

Normally, conductors for ac transmission system are used in the form of stranded except for smaller cross-section.

Stranded conductors are electrically parallel and spiralled together. The main reason for stranding the conductors is to reduce the skin effect.

The size of conductor is decided based on the voltage and the current carrying capacity. A general formula for the total number of strands (N) for n layers (including the centre strand) of strands in a conductor, if each strand is uniform, is

$$N = 3n^2 - 3n + 1 \rightarrow (1)$$

The overall outer diameter of the conductor, if the diameter of one strand is d, will be

$$D = (2n-1)d \rightarrow (2)$$

To increase the tensile strength of the conductor, one or more central conductors (of different materials) are used. which have a high tensile strength.

In modern overhead transmission systems bare aluminium conductors are used which are classified as

AAC : all-aluminium conductor
AAAC : all-aluminium alloy conductor
ACSR : aluminium conductor steel reinforced
ACAR : aluminium conductor alloy reinforced.

In most applications, ACSR conductors are used for both distribution lines and transmission lines.

Reasons for these are given as follows:

(a) Steel core aluminium conductors are normally cheaper than copper conductor of equal resistance which is obtained without sacrificing efficiency, durability or length of useful life.

(b) By high mechanical strength, the length of span can be increased and cost of erection and maintenance can be reduced.

Names of ACSR Conductors

Name	size (mm)
Mole	6/1/1·50
Squirrel	6/1/2·11
Weasel	6/1/2·59
Rabbit	6/1/3·55
Raccoon	6/1/4·09
Dog	6/4·72(Al) + 7/1·57(steel)
Wolf	30/7/2·59
Panther	30/7/3·00
Zebra	54/7/3·00
Moose	54/7/3·53
Bersimis	42/4·57(Al) + 7/2·54(steel).

$$\frac{\text{number of strands}}{\dfrac{\text{no. of steel strands}}{\text{diameter of strands}}}$$

conductors is not zero.

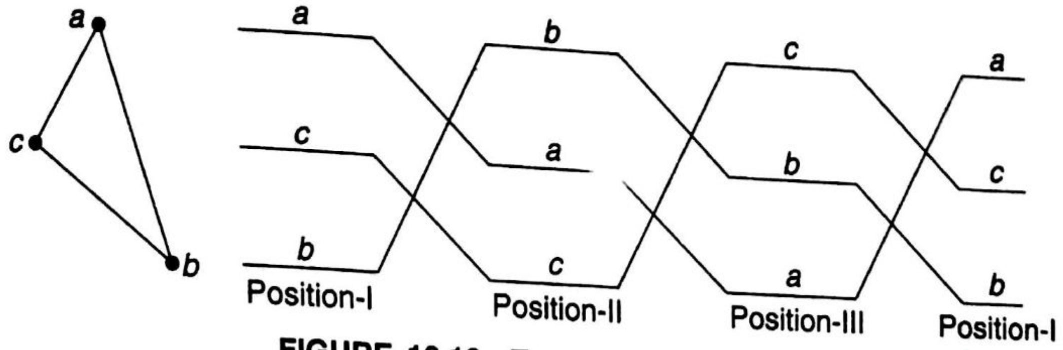


FIGURE 10.10 Transposition of lines.

Normally, modern power lines are not transposed, however, it is done at the stations. The effects of difference in inductance are very small in the case of asymmetrical spacing. The inductance of untransposed line is taken as average value of inductances.

If a line is transposed, each line will take all the three positions for the one-third length of the line. The average value of inductance will be

$$L = \frac{L_a + L_b + L_c}{3} = \frac{2}{3} \times 10^{-7}\left(3 \ln \frac{1}{R'} - \ln \frac{1}{\sqrt{D_{ab}D_{cb}D_{ab}D_{ac}D_{ca}D_{cb}}}\right)$$

$$= 2 \times 10^{-7}\left(\ln \frac{1}{R'} - \frac{1}{3} \ln \frac{1}{D_{ab}D_{bc}D_{ca}}\right)$$

$$= 2 \times 10^{-7} \ln \frac{\sqrt[3]{D_{ab}D_{bc}D_{ca}}}{R'} \text{ H/m}$$

Thus GMD will be

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

For the equilateral spacing $D_m = D$.

10.11 Inductance of a Three-Phase Double-Circuit Line

To increase power transfer from one point to another point, transmission lines run in parallel, normally on the same tower, are called *double circuit*. There are different configurations possible: symmetrically spaced and asymmetrically spaced. If these circuits are on the same tower, the effect of self and mutual inductance are more than if they are on the different towers. The main aim to run more than one circuit is to reduce the inductance of the equivalent circuit. It can be seen from Equation (10.22) that for low inductance, the D_m should be low and D_s should be as high as possible. Therefore, the rule is to separate the individual conductors of a phase as widely as possible and keep the distance between the phases small. So, in the case of double circuit line, arrangement of Figures 10.11(a) and 10.11(b) are preferred to the arrangements as shown in Figures 10.11(c) and 10.11(d). Conductors *a* and *a'* are connected in parallel and form one phase of supply.

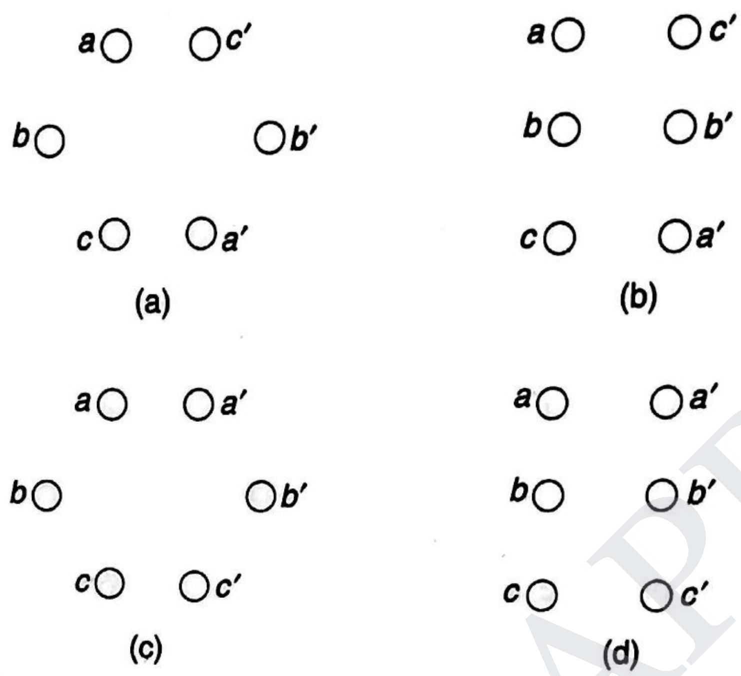


FIGURE 10.11 Three-phase, double-circuit arrangements.

Inductance with symmetrical spacing

Inductance can be calculated from the basic theory of flux linkages or with GMD and GMR concepts. For symmetrical spacing, the conductors must be placed at the vertices of a regular hexagonal, as shown in Figure 10.12. Conductors a, b and c belongs to one circuit and a', b' and c' are of second circuit. The words a, b, c denoted the respective phases of the system. From Figure 10.12,

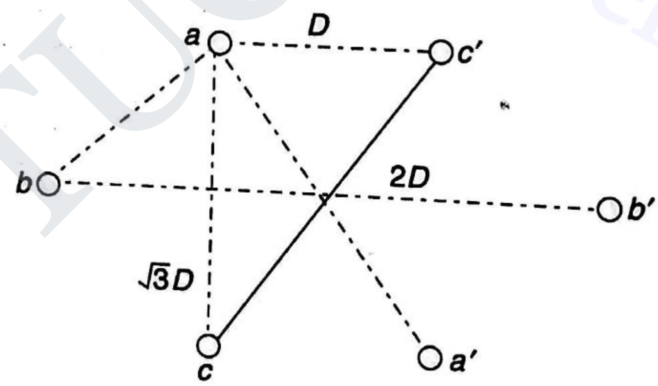


FIGURE 10.12 Three-phase, double-circuit with symmetrical spacing.

$$D_{ab} = D_{bc} = D_{ac'} = D_{c'b'} = D_{ca'} = D_{b'a'} = D$$

$$D_{ac} = D_{b'c} = D_{c'a'} = D_{bc'} = D_{ba'} = D_{ab'} = \sqrt{3}D$$

$$D_{aa'} = D_{bb'} = D_{cc'} = 2D.$$

Let us assume a balance case, i.e. $I_a + I_b + I_c = 0$ and radius of each conductor is R.

Method 1: Flux linkages approach. Flux linkage of conductor *a*

$$\lambda_a = 2\times10^{-7}\left[I_a\left(\ln\frac{1}{R'}+\ln\frac{1}{2D}\right)+I_b\left(\ln\frac{1}{D}+\ln\frac{1}{\sqrt{3}D}\right)+I_c\left(\ln\frac{1}{\sqrt{3}D}+\ln\frac{1}{D}\right)\right]$$

$$= 2\times10^{-7}\left[I_a\left(\ln\frac{1}{2DR'}\right)+I_b\left(\ln\frac{1}{\sqrt{3}D^2}\right)+I_c\left(\ln\frac{1}{\sqrt{3}D^2}\right)\right]$$

$$= 2\times10^{-7}\left[I_a\left(\ln\frac{1}{2DR'}\right)+(I_b+I_c)\left(\ln\frac{1}{\sqrt{3}D^2}\right)\right]$$

Substituting the value of $I_b + I_c = -I_a$, we get

$$\lambda_a = 2\times10^{-7}\left[I_a\left(\ln\frac{1}{2DR'}\right)-I_a\left(\ln\frac{1}{\sqrt{3}D^2}\right)\right]$$

$$= 2\times10^{-7}\left[I_a\left(\ln\frac{\sqrt{3}D^2}{2DR'}\right)\right]$$

$$= 2\times10^{-7}\,I_a\left(\ln\frac{\sqrt{3}D}{2R'}\right)\text{ Wb-T/m}$$

Hence the inductance of conductor *a* will be

$$L_a = \frac{\lambda_a}{I_a} = 2\times10^{-7}\left(\ln\frac{\sqrt{3}D}{2R'}\right)\text{ H/m} \tag{10.26}$$

Since the conductors of a phase are in parallel, the inductance of phase *a* will be $L_a/2$.

Method 2: GMR and GMD approach. Mutual GMD of phase *a* is

$$\sqrt[8]{D_{ab}D_{ac}D_{ab'}D_{ac'}D_{a'b}D_{a'c}D_{a'b'}D_{a'c'}} = \sqrt[8]{D\sqrt{3}D\sqrt{3}D\,D\sqrt{3}DD\,D\sqrt{3}D} = \sqrt[4]{3}D$$

and

$$\text{Self-GMD (or GMR) of phase } a = \sqrt[4]{R'D_{aa'}D_{aa'}R'} = \sqrt[4]{R'2D2DR'} = \sqrt{2DR'}$$

Inductance of phase *a* using Equation (10.22) will be

$$L_A = 2\times10^{-7}\left(\ln\frac{D_m}{D_{sA}}\right) = 2\times10^{-7}\left(\ln\frac{\sqrt[4]{3}D}{\sqrt{2DR'}}\right)$$

$$= 2\times10^{-7}\left(\frac{1}{2}\ln\frac{\sqrt{3}D}{2R'}\right) = 1\times10^{-7}\left(\ln\frac{\sqrt{3}D}{2R'}\right)\text{ H/m}$$

Inductance of each conductor will be $2 \times L_A$ which will be

$$2 \times 10^{-7}\left(\ln \frac{\sqrt{3}D}{2R'}\right) \text{ H/m}$$

It is same as in Equation (10.26). It must be noted that using GMD and GMR concept, inductance of phase (not conductor) is calculated.

Inductance with unsymmetrical spacing (transposed lines)

Since the conductors are not symmetrically placed, to calculate the inductance of the line, the line should be assumed to be transposed. If transposition is not there, there will be imaginary terms in inductance. Figure 10.13 shows the possible arrangement of transposed lines. To remember the sequence of the transposition, the position of phases of first circuit will move downward in cycle and the phases of second circuit will move upward cyclically.

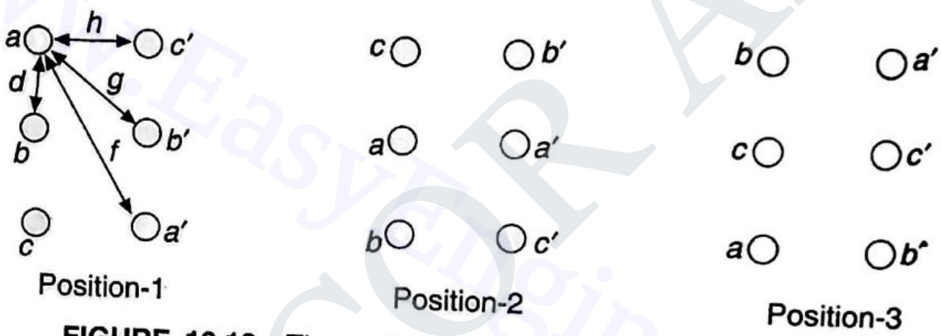


FIGURE 10.13 Three-phase double-circuit arrangements.

Method 1: Flux linkages approach. Flux linkages of conductor a in position-1

$$\lambda_{a1} = 2 \times 10^{-7}\left[I_a\left(\ln\frac{1}{R'} + \ln\frac{1}{f}\right) + I_b\left(\ln\frac{1}{d} + \ln\frac{1}{g}\right) + I_c\left(\frac{1}{2d} + \ln\frac{1}{h}\right)\right]$$

$$= 2 \times 10^{-7}\left[I_a\left(\ln\frac{1}{R'f}\right) + I_b\left(\ln\frac{1}{dg}\right) + I_c\left(\ln\frac{1}{2dh}\right)\right]$$

Similarly, flux linkages of conductor a in position-2 and position-3 will be

$$\lambda_{a2} = 2 \times 10^{-7}\left[I_a\left(\ln\frac{1}{R'} + \ln\frac{1}{h}\right) + I_b\left(\ln\frac{1}{d} + \ln\frac{1}{g}\right) + I_c\left(\ln\frac{1}{d} + \ln\frac{1}{g}\right)\right]$$

The average flux linkages of conductor $a(\lambda_a)$ will be $(\lambda_{a1} + \lambda_{a2} + \lambda_{a3})/3$. Hence

$$\lambda_a = \frac{2 \times 10^{-7}}{3}\left[I_a\left(\ln\frac{1}{R' fR'hR' f}\right) + I_b\left(\ln\frac{1}{dgdg2dh}\right) + I_c\left(\ln\frac{1}{2dhdgdg}\right)\right]$$

$$= \frac{2 \times 10^{-7}}{3}\left[I_a\left(\ln\frac{1}{R' fR'hR' f}\right) + (I_b + I_c)\left(\ln\frac{1}{2dhdgdg}\right)\right]$$

Substituting the value of $I_b + I_c = -I_a$, we get

$$\lambda_a = \frac{2 \times 10^{-7}}{3}\left[I_a\left(\ln\frac{1}{R' fR'hR' f}\right) - I_a\left(\ln\frac{1}{2dhdgdg}\right)\right]$$

$$= \frac{2 \times 10^{-7}}{3}\left[I_a\left(\ln\frac{2dhdgdg}{R' fR'hR' f}\right)\right]$$

$$= 2 \times 10^{-7} I_a\left(\ln\frac{2^{1/3}dg^{2/3}}{R'f^{2/3}}\right)$$

Hence inductance of conductor a will be

$$L_a = \frac{\lambda_a}{I_a} = 2 \times 10^{-7} \ln\left[2^{1/3}\left(\frac{d}{R'}\right)\left(\frac{g}{f}\right)^{2/3}\right] \text{ H/m} \qquad (10.27)$$

Since the conductors of a phase are in parallel, the inductance of phase a will be $L_a/2$.

Method 2: GMR and GMD approach. Mutual GMD of phase a in position-1,

$$\text{GMD}_1 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{d(2d)gh}$$

Similarly, mutual GMD of phase a in position-2 and position-3 can be written as

$$\text{GMD}_2 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{ddgg}$$

and

$$\text{GMD}_3 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{2ddhg}$$

(Note that GMD_1 is of conductor a only and for a' it will be the same. Therefore, the effective GMD of phase a will be equal to the GMD of conductor a.)

Self-GMD (or GMR) of phase a in position-1,

$$\text{GMR}_1 = \sqrt[2]{R'D_{aa'}} = \sqrt{R'f}$$

Similarly self-GMR of phase a in position-2 and position-3 can be written as

$$\text{GMR}_2 = \sqrt{R'D_{aa'}} = \sqrt{R'h} \quad \text{and} \quad \text{GMR}_3 = \sqrt{R'D_{aa'}} = \sqrt{R'f}$$

The equivalent GMD (D_m) and GMR (D_s) of the system will be

$$D_m = \sqrt[3]{\text{GMD}_1 \times \text{GMD}_2 \times \text{GMD}_3}$$

$$= \sqrt[3]{(d \times 2d \times g \times h)^{1/4} (d \times d \times g \times g)^{1/4} (2d \times d \times h \times g)^{1/4}}$$

$$= 2^{1/6} d^{1/2} g^{1/3} h^{1/6}$$

and

$$D_s = \sqrt[3]{\text{GMR}_1 \times \text{GMR}_2 \times \text{GMR}_3}$$

$$= \sqrt[3]{(R'f)^{1/2} (R'h)^{1/2} (R'f)^{1/2}}$$

$$= R'^{1/2} f^{1/3} h^{1/6}$$

Inductance of phase a using Equation (10.22) will be

$$L_A = 2 \times 10^{-7} \left(\ln \frac{D_m}{D_{sA}} \right) = 2 \times 10^{-7} \left(\ln \frac{2^{1/6} d^{1/2} g^{1/3} h^{1/6}}{R'^{1/2} h^{1/6} f^{1/3}} \right) = 2 \times 10^{-7} \left(\ln \frac{2^{1/6} d^{1/2} g^{1/3}}{R'^{1/2} f^{1/3}} \right)$$

Inductance of each conductor will be $2L_A$. Therefore,

$$L_a = 2 \times 10^{-7} \left(\ln \frac{2^{1/3} d g^{2/3}}{R' f^{2/3}} \right)$$

It is same as in Equation (10.27).

It should be noted that GMD concept could not be applied to non-homogeneous conductors. If the current is not uniformly distributed over the section of conductor, GMD approach will not be suitable. It is defined as GMD of a point with respect to a number of points, which is the geometric mean distance between that point and other points. It can also be applied to the area.

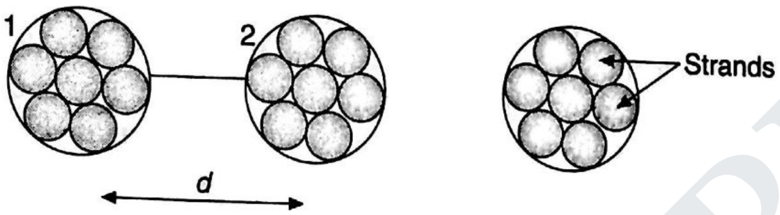
10.12 BUNDLED CONDUCTORS

Stranded or composite conductors touch each other, however, bundled conductors are separated from each other by 30 cm or more and conductors of each phase are connected by conducting wires at particular length. Figure 10.14 shows the stranded and bundled conductors. For the voltage rating more than 230 kV, it is not possible to use the round conductors due to excessive corona loss. It is preferred to have the hollow conductor, normally in substations, and bundled conductors in transmission lines. The main advantages of using bundled conductors are:

- Reduced corona loss
- Reduced voltage gradient at the surface of the conductor
- Low reactance due to increase in the self-GMD

- Reduced radio interference
- Increase in capacitance
- Larger loading capability and
- Increase surge impedance loading.

The reactance of bundled conductors can be calculated with the help of GMD and GMR approach.



(a) Bundled conductors (b) Stranded conductors

FIGURE 10.14 Bundled and stranded conductors.

10.13 SKIN EFFECT

The alternating current distribution in a wire is not uniform. The current density near the surface is more than near to the centre. It is affected by the frequency of the current. If the frequency of current is more, the current distribution is more non-uniform. This effect is known as *skin effect*. Due to this effect the effective resistance (or ac resistance of the conductors) becomes more than the direct current (dc), where the current distribution is uniform, resistance (called the dc resistance). This can be understood by an example.

Consider a solid current carrying conductor of circular cross-section, as shown in Figure 10.15. This can be replaced by a large number of conductors bunched together with small radii. These conductors occupy the same cross-sectional area. If the current is same, the loss can be calculated in both the cases and thus the effective resistance. In n strands, each of resistance nR ohm carries a uniformly distributed current (of I/n ampere). The loss will be same as a single conductor (I^2R). Let us assume half of the conductors ($n/2$) carry currents of $[(I/n) + \Delta I]$ ampere and the other half ($n/2$) carry $[(I/n) - \Delta I]$ ampere. The total loss is

$$\frac{n}{2}\left(\frac{I}{n} + \Delta I\right)^2 nR + \frac{n}{2}\left(\frac{I}{n} - \Delta I\right)^2 nR = \frac{n^2R}{2}\left[2\left(\frac{I}{n}\right)^2 + 2\Delta I^2\right] = I^2R + n^2R\Delta I^2$$

which is greater than I^2R. This indicates that the effective resistance will be more than the dc resistance if current distribution is not uniform.

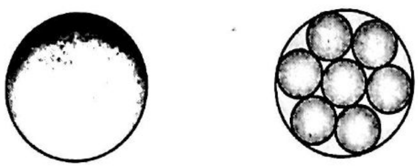


FIGURE 10.15 Skin effect.

Due to non-uniformity of current, skin effect, the flux linkages are reduced and thus skin effect reduces the effective internal reactance. The inner filaments carrying currents give rise to flux which links the inner filaments only whereas the flux due to the current carrying outer filaments enclose both inner and outer filaments.

10.14 Proximity Effect

Like skin effect, the *proximity effect* also increases the resistance of the conductor. The alternating flux in a conductor caused by the current flowing in neighbouring conductors gives rise to circulating currents, which cause the non-uniformity of the current and thus increases resistance. Let us consider two-wire system, as shown in Figure 10.16. When conductor A carries current, its flux links with the other conductor B. The flux linkages are nearer to the conductor, as shown by shaded portion, than the opposite side. If the current in conductor B is opposite to the current in A, the current density will be more in the adjacent portion of the conductor. If the current direction is same, the current density will be more in the remote part of the conductor. Due to this non-uniformity, the effective resistance is more than the dc resistance.

FIGURE 10.16 Proximity effect.

This effect is more pronounced in cable where the phase conductors are nearer to each other. The proximity effect is negligible in overhead transmission line. Both skin effect and proximity effect depend on the conductor size, frequency of the supply, resistivity and permeability of the conductor material. For the circular conductors, the increase in effective resistance is proportional to $d^2 f \mu_r / \rho$, where d is the diameter of the conductor.

10.15 Guy's Theorem

If the number of strands is more, it is very cumbersome to calculate the effective radius of the conductor. These can be calculated by Guy's Theorem. It is stated as:

1. GMD between n conductors symmetrically placed on the periphery of a circle of radius r will be $r \times (n)^{1/(r-1)}$.
2. GMD of any point inside the circle from a line or point placed on the periphery of a circle of radius r will be r.

Example 10.1 Find the equivalent radius of 7-strand conductor. The radius of each strand is r.

Solution From Figure 10.17,

$$D_{12} = D_{23} = D_{34} = D_{45} = D_{56} = D_{17} = D_{27} = D_{37} = D_{47} = D_{57} = D_{67} = 2r$$

10.21 CAPACITANCE OF SYMMETRICALLY SPACED THREE-PHASE LINES

If a line is symmetrically spaced, the distances D_{ab}, D_{bc} and D_{ca} in Figure 10.26 will be the same (say D). Using Equation (10.34), the potential difference between phases a and b (V_{ab}) due to charges on the conductors will be

$$V_{ab} = \frac{q_a}{2\pi\varepsilon_0} \ln \frac{D}{R} + \frac{q_b}{2\pi\varepsilon_0} \ln \frac{R}{D} + \frac{q_c}{2\pi\varepsilon_0} \ln \frac{D}{D}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R} + q_b \ln \frac{R}{D}\right) \qquad (10.41)$$

Similarly

$$V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R} + q_c \ln \frac{R}{D}\right) \qquad (10.42)$$

Solving Equations (10.41) and (10.42) similar to Equation (10.39), we get

$$V_{an} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R}\right)$$

and therefore

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon_0}{\ln (D/R)} \text{ F/m}$$

The value of $2\pi\varepsilon_0$ is equal to 0.0555 µF/km or $\varepsilon_0 = \dfrac{10^{-9}}{36\pi}$.

10.22 CAPACITANCE OF SYMMETRICALLY SPACED DOUBLE-CIRCUIT, THREE-PHASE LINES

For symmetrical spacing, the conductors must be placed at the vertices of a regular hexagonal as shown in Figure 10.12. Conductors a, b and c belong to one circuit and a', b' and c' to the second circuit. The letters a, b and c denote the respective phases of the system. From Figure 10.12,

$$D_{ab} = D_{bc} = D_{ac'} = D_{c'b'} = D_{ca'} = D_{b'a'} = D$$
$$D_{ac} = D_{b'c} = D_{c'a'} = D_{bc'} = D_{ba'} = D_{ab'} = \sqrt{3}D$$
$$D_{aa'} = D_{bb'} = D_{cc'} = 2D$$

Let us assume that there are no other charges in the vicinity, i.e. $q_a + q_b + q_c = 0$ and radius of each conductor is R. Using Equation (10.35), the potential difference between phases a and b

(V_{ab1}) due to charges on the conductors of the first circuit, i.e. a, b and c, will be

$$V_{ab1} = \frac{q_a}{2\pi\varepsilon_0} \ln \frac{D}{R} + \frac{q_b}{2\pi\varepsilon_0} \ln \frac{R}{D} + \frac{q_c}{2\pi\varepsilon_0} \ln \frac{D}{\sqrt{3}D}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R} + q_b \ln \frac{R}{D} + q_c \ln \frac{D}{\sqrt{3}D}\right) \tag{10.43}$$

The potential difference between phases a and b (V_{ab2}) due to charges on the conductors of the second circuit, i.e. a', b' and c' will be

$$V_{ab2} = \frac{q_a}{2\pi\varepsilon_0} \ln \frac{\sqrt{3}D}{2D} + \frac{q_b}{2\pi\varepsilon_0} \ln \frac{2D}{\sqrt{3}D} + \frac{q_c}{2\pi\varepsilon_0} \ln \frac{\sqrt{3}D}{D}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2D} + q_b \ln \frac{2D}{\sqrt{3}D} + q_c \ln \frac{\sqrt{3}D}{D}\right) \tag{10.44}$$

Using Equations (10.43) and (10.44), the total potential difference between phases a and b (V_{ab}) due to charges on the conductors of both circuits, will be

$$V_{ab} = V_{ab1} + V_{ab2}$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R} + q_b \ln \frac{R}{D} + q_c \ln \frac{D}{\sqrt{3}D}\right)$$

$$+ \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2D} + q_b \ln \frac{2D}{\sqrt{3}D} + q_c \ln \frac{\sqrt{3}D}{D}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R} + q_b \ln \frac{2R}{\sqrt{3}D} + q_c \ln 1\right)$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R} + q_b \ln \frac{2R}{\sqrt{3}D}\right)$$

Similarly

$$V_{ac} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{D}{R} + q_b \ln \frac{\sqrt{3}D}{D} + q_c \ln \frac{R}{2D} + q_a \ln \frac{\sqrt{3}D}{2D} + q_b \ln \frac{D}{\sqrt{3}D} + q_c \ln \frac{2D}{\sqrt{3}D}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R} + q_c \ln \frac{2R}{\sqrt{3}D}\right)$$

Since $V_{ab} + V_{ac} = 3V_{an}$, from above equations, we can have

$$V_{ab} + V_{ac} = 3V_{an} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R} + q_b \ln \frac{2R}{\sqrt{3}D}\right) + \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R} + q_c \ln \frac{2R}{\sqrt{3}D}\right)$$

$$= \frac{1}{2\pi\varepsilon_0}\left[2q_a \ln \frac{\sqrt{3}D}{2R} + (q_b + q_c) \ln \frac{2R}{\sqrt{3}D}\right] \qquad (10.45)$$

Thus

$$V_{an} = \frac{1}{2\pi\varepsilon_0}\left(q_a \ln \frac{\sqrt{3}D}{2R}\right)$$

The capacitance of conductor a with respect to neutral plane will be

$$C_{an} = \frac{q_a}{V_{an}} = \frac{2\pi\varepsilon_0}{\ln [\sqrt{3}D/(2R)]} \text{ F/m/conductor} \qquad (10.46)$$

The capacitance per phase (C_n) will be $2C_{an}$, because each phase has two conductors and they are in parallel.

$$C_n = \frac{4\pi\varepsilon_0}{\ln [\sqrt{3}D/(2R)]} \text{ F/m/phase} \qquad (10.47)$$

Using GMD and GMR concept

Calculation of capacitance can also be done based on the GMD and GMR, if lines are transposed. Since there is no electric field inside the conductors as they are assumed to be perfect conductors, in GMR calculation, radius R is taken instead of R' in the case of inductance calculations. Then

$$\text{Mutual GMD of phase } a = \sqrt[8]{D_{ab}D_{ac}D_{ab'}D_{ac'}D_{a'b}D_{a'c}D_{a'b'}D_{a'c'}}$$

$$= \sqrt[8]{D\left(\sqrt{3}D\right)D\left(\sqrt{3}D\right)\left(\sqrt{3}D\right)DD\left(\sqrt{3}D\right)}$$

$$= \sqrt[4]{3}D$$

and

$$\text{Self-GMD (or GMR) of phase } a = \sqrt[4]{(R)(D_{aa'})(D_{aa'})(R)} = \sqrt[4]{(R)(2D)(2D)(R)} = \sqrt{2DR}$$

The capacitance per phase (C_n) will be

$$C_n = \frac{2\pi\varepsilon_0}{\ln [(\text{GMD})/(\text{GMR})]} \text{ F/m/phase}$$

Thus

$$C_n = \frac{2\pi\varepsilon_0}{\ln \left(\sqrt[4]{3D^4}/\sqrt{2RD}\right)} = \frac{2\pi\varepsilon_0}{(1/2) \ln [(\sqrt{3}D)/(2R)]} = \frac{4\pi\varepsilon_0}{\ln [(\sqrt{3}D)/(2R)]} \text{ F/m/phase} \qquad (10.48)$$

Equation (10.48) is equal to Equation (10.47).

10.23 Capacitance of Unsymmetrically Spaced Double Circuit, Three-Phase Line (Transposed)

Figure 10.13 shows the arrangement of a three-phase double circuit line. The capacitance can be calculated using the potential difference concept or GMD/GMR concept. Here, GMD and GMR concept is used to calculate capacitances. GMD of conductor a will be the same as GMD of conductor a'. Then

Mutual GMD of phase a in position-1, $\text{GMD}_1 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{d(2d)gh}$

Similarly mutual-GMD of phase a in position-2 and position-3 can be written as

$$\text{GMD}_2 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{ddgg}$$

and

$$\text{GMD}_3 = \sqrt[4]{D_{ab}D_{ac}D_{ab'}D_{ac'}} = \sqrt[4]{2ddhg}$$

Self-GMD (or GMR) of phase a in position-1,

$$\text{GMR}_1 = \sqrt{RD_{aa'}} = \sqrt{Rf}$$

Similarly self-GMR of phase a in position-2 and position-3 can be written as

$$\text{GMR}_2 = \sqrt{RD_{aa'}} = \sqrt{Rh} \quad \text{and} \quad \text{GMR}_3 = \sqrt{RD_{aa'}} = \sqrt{Rf}$$

The equivalent GMD (D_m) and GMR (D_s) of the system will be

$$D_m = \sqrt[3]{(\text{GMD}_1)(\text{GMD}_2)(\text{GMD}_3)}$$
$$= \sqrt[3]{[d(2d)gh]^{1/4}(ddgg)^{1/4}(2ddhg)^{1/4}}$$
$$= 2^{1/6}d^{1/2}g^{1/3}h^{1/6}$$

$$D_s = \sqrt[3]{(\text{GMR}_1)(\text{GMR}_2)(\text{GMR}_3)}$$
$$= \sqrt[3]{(Rf)^{1/2}(Rh)^{1/2}(Rf)^{1/2}}$$
$$= R^{1/2}f^{1/3}h^{1/6}$$

Capacitance of phase a, using Equation (10.48) will be

$$C_n = \frac{2\pi\varepsilon_0}{\ln\dfrac{2^{1/6}d^{1/2}g^{1/3}h^{1/6}}{R^{1/2}f^{1/3}h^{1/6}}} = \frac{4\pi\varepsilon_0}{\ln\dfrac{2^{1/3}dg^{2/3}}{Rf^{2/3}}} \text{ F/m/phase} \qquad (10.49)$$

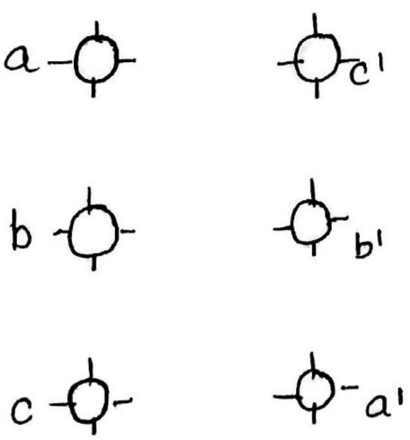
Names of ACSR Conductors

Name	size (mm)
Mole	6/1/1·50
Squirrel	6/1/2·11
Weasel	6/1/2·59
Rabbit	6/1/3·55
Raccoon	6/1/4·09
Dog	6/4·72(Al) + 7/1·57(steel)
Wolf	30/7/2·59
Panther	30/7/3·00
Zebra	54/7/3·00
Moose	54/7/3·53
Bersimis	42/4·57(Al) + 7/2·54(steel).

number of strands
no. of steel strands
diameter of strands.

(C) The principle of geometrical mean distances can be most profitably employed to 3-ϕ double circuit lines.

Consider the conductor arrangement of the double circuit show in Fig. Suppose the radius of each conductor is r.



Self - GMD of conductor = 0.7788 r

Self - GMD of Combination aa' is

$$D_{S1} = (D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a})^{1/4}$$

Self - GMD of combination ee' bb' is

$$D_{S2} = (D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b})^{1/4}.$$

Self - GMD of Combination cc' is

$$D_{S3} = (D_{cc} \times D_{cc'} \times D_{c'c'} \times D_{c'c})^{1/4}$$

Equivalent self - GMD of one phase

$$D_S = (D_{S1} \times D_{S2} \times D_{S3})^{1/3}.$$

The Value of D_S is the same for all the phases as each conductor has the same radius.

Mutual - GMD between phases A and B is

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

Mutual - GMD between phases B and C is

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

Mutual - GMD between phases C and A is

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

Equivalent mutual - GMD,

$$D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}.$$

Important Formulas in Terms of GMD.

(i) Single phase line

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

$D_s = 0.7788\, r$

D_m = spacing between conductors = d,

(ii) single circuit 3-φ line

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

$D_s = 0.7788\, r$

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

(iii) Double circuit 3-φ line

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

where,

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

$D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$.

Problem 1:

A single phase line has two parallel conductors 2 metres apart. The diameter of each conductor is 1.2 m. Calculate the loop inductance per Km of the line.

Solution:

Spacing of conductors, d = 2m = 200 cm.

Radius of conductor, $r = \frac{1.2}{2} = 0.6$ cm.

loop inductance per metre length of the line,

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

$= 10^{-7} (1 + 4 \log_e \frac{200}{0.6})$ H.

$= 24.23 \times 10^{-7}$ H.

Loop inductance per Km of the line,

$= 24.23 \times 10^{-7} \times 1000$

$= 2.423$ mH

Problem 2.

A single phase transmission line has two parallel conductors 3 m apart, the radius of each conductor being 1 cm. Calculate the loop inductance per Km length of the line if the material of the conductor is,

(i) copper

(ii) steel with relative permeability of 100.

Solution

Spacing of conductors, $d = 300$ cm

Radius of conductor, $r = 1$ cm

loop inductance, $= 10^{-7}\left(\mu_r + 4 \log_e \frac{d}{r}\right)$ H/m

(i) With copper conductors,

$\mu_r = 1$.

$\therefore$ loop inductance/m $= 10^{-7}\left(1 + 4 \log_e \frac{d}{r}\right)$ H

$= 10^{-7}\left(1 + 4 \log_e \frac{300}{1}\right)$ H

$= 23.8 \times 10^{-7}$ H.

loop inductance / Km $= 23.8 \times 10^{-7} \times 1000$

$= 2.38 \times 10^{-3}$ H

$= 2.38$ mH.

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

$\therefore$ loop inductance /m $= 10^{-7}\left(100 + 4 \log_e \frac{300}{1}\right)$ H

$= 122.8 \times 10^{-7}$ H

loop inductance/Km $= 122.8 \times 10^{-7} \times 1000$

$= 12.28 \times 10^{-3}$ H

$= 12.28$ mH.

problem 3:

Find the inductance per Km of a 3-phase transmission line using 1.24 cm diameter conductors when these are placed at the corners of an equilateral triangle of each side 2m.

Solution

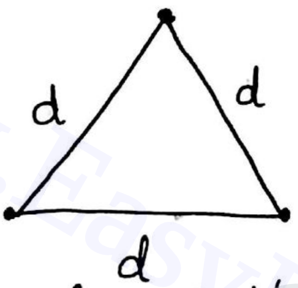


Figure shows the three conductors of the three phase line placed at the corners of an equilateral triangle of each side 2m. Here conductor spacing $d = 2$m and conductor radius

$$r = \frac{1.24}{2}$$

$= 0.62$ cm.

Inductance/phase/m $= 10^{-7}\left(0.5 + 2 \log_e \frac{d}{r}\right)$ H

$= 10^{-7}\left(0.5 + 2 \log_e \frac{200}{0.62}\right)$ H

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

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

$= 1.2$ mH.

Problem 4.

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

Solution

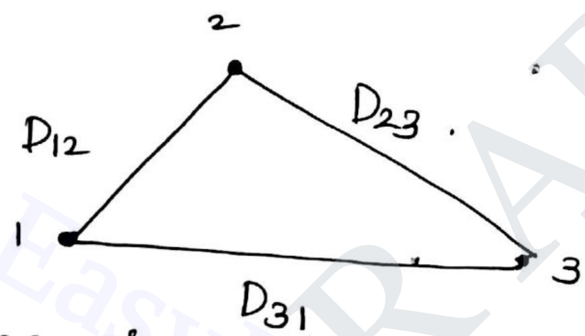


Figure shows three conductors of a 3-phase line placed at the corners of a triangle of sides $D_{12} = 2m$,

$D_{23} = 2.5m$,

$D_{31} = 4.5m$,

The conductor radius,

$$r = \frac{1.24}{2}$$

$$= 0.62 \text{ cm}$$

Equivalent equilateral spacing,

$$D_{eq} = \sqrt[3]{D_{12} \times D_{23} \times D_{31}}$$

$$= \sqrt[3]{2 \times 2.5 \times 4.5}$$

$$= 2.82m$$

$$D_{eq} = 282 \text{ cm}$$

Inductance/phase/m $= 10^{-7}\left(0.5 + 2\log_e \frac{D_{eq}}{r}\right) H$

$= 10^{-7}\left(0.5 + 2\log_e \frac{282}{0.62}\right) H$

$= 12.74 \times 10^{-7} H$.

Inductance/phase/km $= 12.74 \times 10^{-7} \times 1000$

$= 1.274 \times 10^{-3} H$

$= 1.274\ mH$.

Problem 5:

Calculate the inductance of each conductor in a 3-phase, 3-wire system when the conductors are arranged in a ~~hoz~~ horizontal plane with spacing such that $D_{31} = 4m$; $D_{12} = D_{23} =$ ~~3m~~ 2m. The conductors are transposed and have a diameter of 2.5 cm.

Solution:

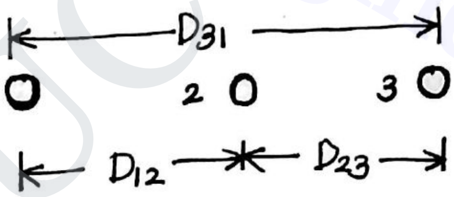


Figure shows the arrangement of the conductors of the 3-phase line. The conductor radius,

$$r = \frac{2.52}{2} = 1.25\ cm.$$

Equivalent ~~equilateral~~ spacing,

$$D_{eq} = \sqrt[3]{D_{12} \times D_{23} \times D_{31}}$$

$$= \sqrt[3]{2 \times 2 \times 4}$$

$$= 2.52\ m$$

$$D_{eq} = 252\ cm$$

$$\text{Inductance/phase/m} = 10^{-7}\left(0.5 + 2\log_e \frac{D_{eq}}{r}\right) H$$

$$= 10^{-7}\left(0.5 + 2\log_e \frac{252}{1.25}\right) H.$$

$$= 11.1 \times 10^{-7} H$$

$$\text{Inductance/phase/Km} = 11.1 \times 10^{-7} \times 1000$$

$$= 1.11 \times 10^{-3} H$$

$$= 1.11 mH$$

Problem 6:

Two conductors of a single phase line, each of 1cm diameter, are arranged in a vertical plane with one conductor mounted 1m above the other.

A second identical line is mounted at the same height as the first and spaced horizontally 0.25m apart from it. The two upper and the two lower conductors are connected in parallel. Determine the inductance per km of the resulting double circuit line.

Solution:

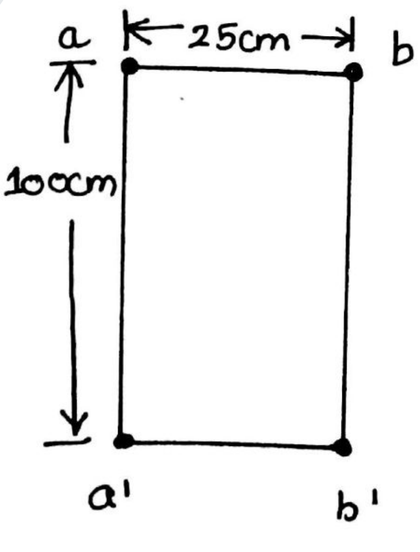


Figure shows the arrangement of double circuit single phase line, Conductors a, a' form one connection and Conductors b, b' form the return connection.

The Conductor radius,

$$r = 1/2 = 0.5\,cm$$

G.M.R of Conductor $= 0.7788r$

$$= 0.7788 \times 0.5 = 0.389\,cm.$$

Self G.M.D of aa' combination is,

$$D_s = \sqrt[4]{D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a}}.$$

$$= \sqrt[4]{(0.389 \times 100)^2} = 6.23\,cm$$

Mutual G.M.D. between a and b is

$$D_m = \sqrt{D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'}}$$

$$= \sqrt[4]{25 \times 103 \times 103 \times 25}$$

$$= 50.74\,cm$$

$$[\because D_{ab'} = D_{a'b} = \sqrt{25^2 + 100^2} = 103\,cm]$$

Inductance per Conductor per metre,

$$= 2 \times 10^{-7} \log_e \frac{D_m}{D_s}$$

$$= 2 \times 10^{-7} \log_e \frac{50.74}{6.23}\ H$$

$$= 0.42 \times 10^{-6}\ H$$

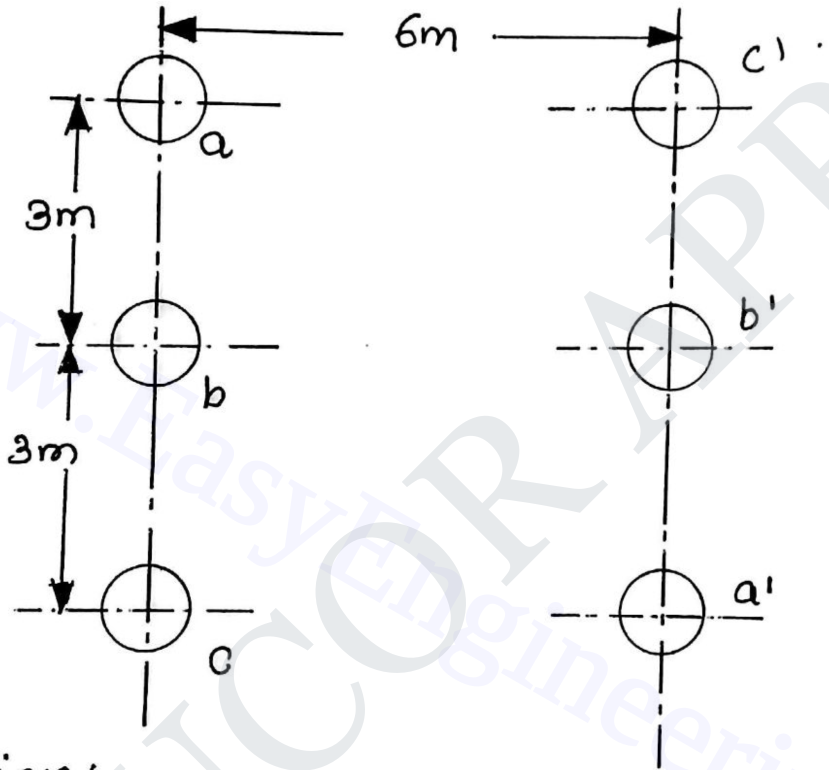
$\therefore$ loop inductance per Km of the line

$$= 2 \times 0.42 \times 10^{-6} \times 1000\ H$$

$$= \underline{0.84\,mH}$$

Problem 7:

Figure shows the spacings of a double circuit 3-phase overhead line. The phase sequence is ABC and the line is completely transposed. The conductor radius is 1.3 cm. Find the inductance per phase per kilometre.



Solution:

G.M.R of Conductor $= 1.3 \times 0.7788 = 1.01\,cm$

Distance a to b' $= \sqrt{6^2+3^2} = 6.7\,m$

Distance a to a' $= \sqrt{6^2+6^2} = 8.48\,m$.

Equivalent self G.M.D of one phase is

$$D_s = \sqrt[3]{D_{s1} \times D_{s2} \times D_{s3}}.$$

Where D_{s1}, D_{s2} and D_{s3} represent the self G.M.D in positions 1, 2 and 3 respectively. Also D_s is the same for all the phases.

Now $D_{s1} = \sqrt[4]{D_{aa} \times D_{aa'} \times D_{a'a'} \times D_{a'a}}$

$= \sqrt{(1.01\times10^{-2}) \times (8.48) \times (1.01\times10^{-2}) \times (8.48)}$

$= 0.292\,m = D_{s3}$.

$D_{s2} = \sqrt[4]{D_{bb} \times D_{bb'} \times D_{b'b'} \times D_{b'b}}$

$= \sqrt[4]{(1.01\times10^{-2}) \times (6) \times (1.01\times10^{-2}) \times (6)}$

$D_{s2} = 0.246\,m$

$D_s = \sqrt[3]{0.292 \times 0.246 \times 0.292}$

$= 0.275\,m$

Equivalent mutual G.M.D.,

$D_m = \sqrt[3]{D_{AB} \times D_{BC} \times D_{CA}}$.

Where D_{AB}, D_{BC} and D_{CA} represent the mutual G.M.D between phases A and B, B and C and C and A respectively.

Now,

$D_{AB} = \sqrt[4]{D_{ab} \times D_{ab'} \times D_{a'b} \times D_{a'b'}}$

$= \sqrt[4]{3 \times 6.7 \times 6.7 \times 3} = 4.48\,m = D_{BC}$.

$D_{CA} = \sqrt[4]{D_{ca} \times D_{ca'} \times D_{c'a} \times D_{c'a'}}$

$= \sqrt[4]{6 \times 6 \times 6 \times 6} = 6\,m$

$\therefore D_m = \sqrt[3]{4.48 \times 4.48 \times 6} = 4.94\,m$.

∴ Inductance per phase per metre length

$$= 10^{-7} \times 2 \log_e \frac{D_m}{D_s}$$

$$= 10^{-7} \times 2 \log_e \frac{4.94}{0.275}$$

$$= 5.7 \times 10^{-7} H$$

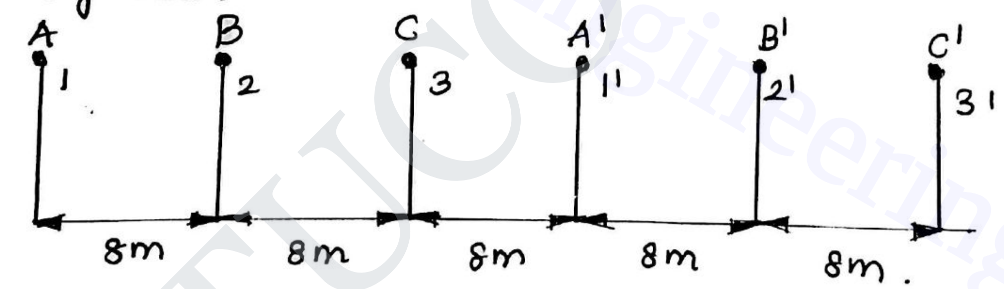
Inductance/phase/Km $= 5.7 \times 10^{-7} \times 1000$

$$= 0.57 \times 10^{-3} H$$

$$= 0.57 mH$$

Problem 8:

Calculate the inductance per phase per metre for a three-phase double-circuit line whose phase conductors have a radius of 5.3 Cm with the horizontal conductor arrangement as shown in Figure.



Solution:

G.M.R of Conductor $= 0.7788 r$

$$= 0.7788 \times 5.3 \times 10^{-2}$$

$$= 0.0413 m$$

Equivalent self G.M.D of one phase is

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

$$D_{s1} = (D_{AA} \times D_{AA'} \times D_{A'A'} \times D_{A'A})^{1/4}$$

$$= (0.0413 \times 24 \times 0.0413 \times 24)^{1/4}$$

$$= 0.995 m$$

$$D_{s2} = (D_{BB} \times D_{BB'} \times D_{B'B'} \times D_{B'B})^{1/4}$$

$$= (0.0413 \times 24 \times 0.0413 \times 24)^{1/4} = 0.995 m$$

Similarly, $D_{S3} = 0.995\,m$

$$D_s = \sqrt[3]{0.995 \times 0.995 \times 0.995}$$

$$\boxed{D_s = 0.995\,m}$$

Equivalent mutual G.M.D is

$$D_m = (D_{AB} \times D_{BC} \times D_{CA})^{1/3}$$

$$D_{AB} = (D_{AB} \times D_{AB'} \times D_{A'B} \times D_{A'B'})^{1/4}$$

$$= (8 \times 32 \times 16 \times 8)^{1/4}$$

$$D_{CA} = (D_{CA} \times D_{CA'} \times D_{C'A} \times D_{C'A'})^{1/4}$$

$$= (16 \times 8 \times 40 \times 16)^{1/4}$$

$$= 16.917\,m$$

$$\therefore D_m = (13.45 \times 13.45 \times 16.917)^{1/3}$$

$$= 14.518\,m$$

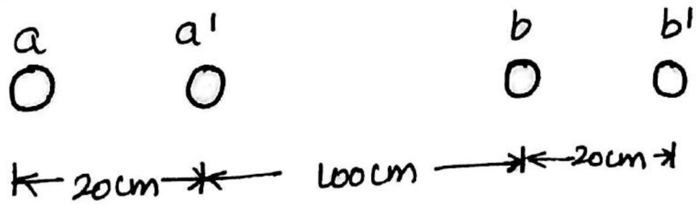
$$\text{Inductance / phase /m} = 10^{-7} \times 2 \log_e \frac{D_m}{D_s}\ H/m$$

$$= 10^{-7} \times 2 \log_e \frac{14.518}{0.995}\ H/m$$

$$= 5.36 \times 10^{-7}\ H/m.$$

Problem 9:

In a single phase line, conductors a and a' in parallel form one circuit while conductors b and b' in parallel form the return path. Calculate the total inductance of the line per km assuming that current is equally shared by the two parallel conductors. Conductor diameter is 2.0cm.



Solution

loop inductance /km,

$$L = 4\times10^{-4} \log_e \frac{D_m}{D_s} \ H/Km$$

Mutual G.M.D,

$$D_m = \sqrt[4]{D_{ab}\times D_{ab'}\times D_{a'b}\times D_{a'b'}}$$

$$= \sqrt[4]{120\times140\times100\times120}$$

$$= 119 \text{ cm}$$

Self G.M.D., $D_s = \sqrt[4]{D_{aa}\times D_{aa'}\times D_{a'a'}\times D_{a'a}}$

$D_{aa} = D_{a'a'} = 0.7788$ cm

$D_{aa'} = D_{a'a} = 20$ cm

$$\therefore D_s = \sqrt[4]{0.7788\times0.7788\times20\times20} = 3.94 \text{ cm}$$

$$\therefore L = 4\times10^{-4}\log_e \frac{119}{3.94}$$

$$= 1.36\times10^{-3} \ H/Km$$

$$\boxed{L = 1.36 \text{ mH/Km}}$$

8. Explain the following with respect to Corona.
   (i) Corona (2)
   (ii) Effects (2)
   (iii) Disruptive critical voltage (4)
   (iv) Visual critical voltage (4).
   (v) Corona power loss (4).

(i) Corona

The phenomenon of violet glow, hissing noise and production of ozone gas in an overhead transmission line is known as corona.

(ii) Effects

(i) Atmosphere
(ii) Conductor size
(iii) Spacing between conductors
(iv) line voltage.

(iii) Disruptive Critical Voltage (4).

It is the minimum phase-neutral voltage at which Corona occurs.

Consider two conductors of radii r cm and spaced d cm apart. If v is the phase-neutral potential, then potential gradient at the conductor surface is given by

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

In order that Corona is formed, the value of g must be made equal to the breakdown strength of air. The breakdown strength of air at 76cm pressure and temperature of 25°C is 30 kV/cm (max) on 21.2 kV/cm (r.m.s) and is denoted by g_0. If V_c is the phase-neutral potential required under these conditions, then,

$$g_0 = \frac{V_c}{r \log_e \frac{d}{r}}$$

g_0 = breakdown strength of air at 76cm of mercury and 25°C.

= 30 kV/cm (max) or 21.2 kV/cm (r.ms).

∴ Critical distriptive Voltage,

$$V_c = g_0 \, r \log_e \frac{d}{r}.$$

The above expression for distriptive Voltage is under standard Conditions ie at 76 cm of Hg and 25°C.

However, if these conditions vary, the air density also changes, thus altering the value of g_o.

The value of g_o is directly proportional to air density. Thus the breakdown strength of air at a barometric pressure of b cm of mercury and temperature of t°c becomes δg_o where,

$$\delta = \text{air density factor} = \frac{3.92 b}{273 + t}$$

Under strandard conditions, the values of $\delta = 1$,

∴ Critical disruptive voltage,

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

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

∴ Critical disruptive voltage,

$$V_c = m_o g_o \delta r \log_e \frac{d}{r} \text{ kV/phase}$$

where,

m_o = 1 for polished conductors
= 0.98 to 0.92 for dirty conductors
= 0.87 to 0.8 for stranded conductors.

(iv) Visual critical voltage.

It is the minimum phase-neutral voltage at which glow appears all along the line conductors.

It has been seen that in case of parallel conductors, the corona glow does not begin at the disruptive voltage V_c but at a higher voltage V_v, called visual critical voltage.

The phase-neutral effective value of visual critical voltage is given by the following empirical formula:

$$V_v = m_v g_0 \delta r \left(1 + \frac{0.3}{\sqrt{\delta r}}\right) \log_e \frac{d}{r} \text{ kV/phase.}$$

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

(v) Corona power loss.

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

$$P = 242.2\left(\frac{f+25}{\delta}\right)\sqrt{\frac{r}{d}}\,(V-V_c)^2 \times 10^{-5} \text{ kW/km/phase}$$

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

PART-A

1. **Write the expression for a capacitance of a 1ɸ transmission line. [Nov/Dec '12][R]**
Capacitance of the line per unit length is given by

$$C = \frac{q}{v} F/m$$

The capacitance of single phase line is obtained by substituting in above equation v in terms of q.

2. **What is skin effect and its consequence?[Nov/Dec '12][Nov/Dec'10][R]**
Skin effect is defined as the tendency for the alternating current (AC) to flow mostly near the outer surface of a conductor which causes non-uniform distribution of current. Thus the current density is largest near the surface of the conductor and decreases with greater depths inside the conductor. The effect becomes more and more apparent as the frequency increases. Due to reduction in effective area of cross section offered to the flow of current through the conductor, the resistance of conductor increases.

3. **What is proximity effect?[May/June'13][April/May'11][April/May '15][Nov/Dec'15][R]**
Due to non uniform distribution of current, the current density is non uniform which increases the effective resistance of the conductor. As the distance between the conductor goes on reducing, the distribution of current becomes more and more non uniform. This is known as proximity effect.

4. **Define: Visual critical voltage. [May/June'13][R]**
Experimental investigations have revealed that visual corona does not occur when the electric intensity becomes equal to critical value E_o but starts at a higher value of intensity E_v. This is because the dielectric breakdown of air requires a finite volume of over stressed air. In other words, a finite amount of dielectric energy is necessary to cause visual corona. The empirical relation for calculating E_v is

$$E_v = 3 \times \frac{10^6}{\sqrt{2}} \delta m_v (1 + \frac{0.03}{\sqrt{\delta r}}) V/m$$

Where r is the conductor radius in meter and m_v is the surface factor is calculating visual critical voltage. m_v is generally called irregularity factor.

5. **A three phase transmission line has its conductor at the corners of an equilateral triangle with side 3m. The diameter of each conductor is 1.63cm. Find the inductance per phase per km of the line.[Nov/Dec '13] [April/May '15][A]**
The expression for the inductance of a conductor. A in a three phase line with spacing D between the conductors and r' as the effective radius (GMR) is given by

$$L_A = 2\times10^{-4} \ln\frac{D}{r'} H/km$$

$$\therefore L_A = 2\times10^{-4} \ln\frac{3}{0.7788\times\frac{1.63\times10^{-2}}{2}} = 1.23 mH/km$$

6. **What is meant by disruptive critical voltage?[Nov/Dec '13][Nov/Dec'11][R]**

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

7. **Give expression for capacitance of three phase transmission line with unsymmetrical spacing. (Transposed conductors)[Nov/Dec'13][R]**
The capacitance of the 3 phase unsymmetrically spaced transmission lines is given by,

$$C_{an} = \frac{2\pi\varepsilon}{\ln(\frac{D_{eq}}{r})} F/m$$

Where $D_{eq} = 3\sqrt{D_{12}D_{23}D_{31}}$

8. **What is meant by transposition of line conductors?[April/May'11][R]**
Transposition is the periodic swapping of positions of the conductors of a transmission line, so that each conductor occupies the original position of every other conductor over an equal distance so as to achieve balance in the three phases.

9. **What is the need of transposition?[Nov/Dec'11][May/June'16][R]**
Ref.8

10. **What are the advantages of using bundled conductors?[Nov/Dec'11][R]**
   a. Reduction in corona loss
   b. Minimization of interference with communication circuit.
   c. Reduction in voltage drop which increases circuit capacity and boosting of operating voltage.
   d. Low reactance, increase in capacitance and surge impedance loading.

11. **What is corona?[May/June'16][R]**
The phenomenon of corona (a sort of electric discharge around the high tension line) produces a hissing noise which is audible when habitation is in close proximity. At the towers great attention must be paid to tightness of joints, avoidance of sharp edges and use of earth screen shielding to limit audible noise to acceptable levels.

12. **Distinguish between self and mutual GMD.[Nov/Dec'15][R]**

Self GMD	Mutual GMD
The denominator of argument of log, which is the m^2 root of m^2 distances, i.e, the distances of the various conductors from one conductor and the radius of the same conductor, is called geometric mean radius (GMR also called self GMD) and denoted by D_s.	The numerator of argument of natural log (mnth root of the product of the mndistances between m conductors of wire-A and n conductors of wire-B) is called geometric mean distance(GMD, often called GMD) and denoted by D_m.

13. **Mention the advantages of transposition of conductors.[Nov/Dec'15][R]**
Transposition of Conductors refers to the exchanging of position of conductors of a three phase system along the transmission distance in such a manner that each conductors occupies the original position of every other conductor over an equal distance.
When conductors are not transposed at regular intervals, the inductance and capacitance of the conductors will not be equal. When conductors such as telephone lines are run in parallel to transmission lines, there is a possibility of high voltages induced in the telephone lines. This can result in acoustic shock or noise. Transposition greatly reduces this undesired phenomenon.

14. **How inductance and capacitance of a transmission line are affected by the spacing between the conductors?[May/June'16][R]**

15. **How will you reduce the corona loss?[Nov/Dec'15][R]**
   a. Increasing the conductor size.
   b. Increasing the conductor spacing

c. Using hollow and bundled conductor.

16. What are the factors to be considered while designing a transmission line?[R]

The various factors to be considered while designing a transmission line are

(i) Type and size of conductor
(ii) Voltage level
(iii) Power flow capability, stability and efficiency of transmission
(iv) Line regulation and control of voltage
(v) Power system structure
(vi) Economic aspects

17. What are the advantages of double circuit lines?[R]

The advantages of double circuit lines are

(i) Continuity of supply is possible
(ii) More reliable.
(iii) Less spacing of conductors required
(iv) Less inductance and reactance. Efficiency is enhanced as compared with single circuit lines.

18. What is mean by corona effect?[April/May'08][R]

It can be noticed that near the overhead lines there exists is hissing noise and sometimes a faint violet glow. The effect due to which such phenomenon exists surrounding the overhead lines is called corona effect.

19. What are the factors affecting corona?[April/May'12][R]

i. Electrical factors such as supply frequency
ii. Line voltages
iii. Atmospheric conditions like pressure, temperature etc.
iv. Size of the conductor
v. Surface conditions whether rough, smooth, dry or wet
vi. Shape of the conductor
vii. Spacing between conductors
viii. Number of conductors per phase
ix. Clearance from ground.
x. Load current.

20. What are the disadvantages of corona loss?[April/May'05][R]

a. The corona power loss is the biggest disadvantage which reduces the transmission efficiency.
b. The third harmonic components produced due to corona makes the current non sinusoidal. This increases the corona loss.
c. The ozone gas formed due to corona chemically reacts with the conductor and can cause corrosion.

UNIT II

Classification of lines - short line, medium line and long line - equivalent circuits, phasor diagram, attenuation constant, phase constant, surge impedance; transmission efficiency and voltage regulation, real and reactive power flow in lines, Power - circle diagrams, surge impedance loading, methods of voltage control; Ferranti effect.

Real and Reactive power Flow in lines

Deduce an expression for the sending end and receiving end power of a line in terms of voltages and ABCD constants. Show that the real power transferred is dependent on the power angle and reactive power transferred is dependent on the voltage drop in the line. [16][April/May'11]

Or

Explain the real and reactive power flow in lines. [16][April/May'15]

Or

Show that the real power transferred is dependent on the power angle and the reactive power transferred is dependent on the voltage drop in the line. [16][Nov/Dec'15]

Or

Derive the power flow performance equation of a three phase transmission line in the form of sending-end receiving-end complex power and voltages at the two ends of the line. [08][May/June'16]

The transmission line performance equation was presented in the form of voltage and current relationships between sending and receiving ends. Since loads are more often expressed in terms of real (watts/kW) and reactive (VARs/kVAR) power, it is convenient to deal with transmission line equations in the form of sending and receiving end complex power and voltages. The principles involved are illustrated here through a single transmission line (2-node/2-bus system) as shown in Fig.1

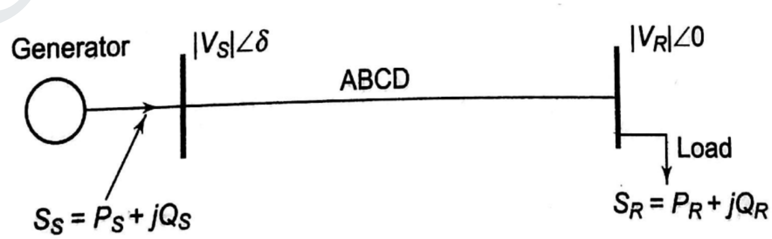


Fig.1 A two bus system

Let us take receiving-end voltage as a reference phasor ($V_R = |V_R|$at an angle 0^o) and let the sending end voltage lead it by an angle δ (V_s=$|V_s|$ at an angle δ). The angle δ is known as the torque angle.

The complex power leaving the receiving-end and entering the sending-end of the transmission line can be expressed as (on per phase basis)

$$S_R = P_R + jQ_R = V_R I_R^* \qquad (1)$$

$$s_S = P_S + jQ_s = V_s I_S^* \qquad (2)$$

Receiving and sending end currents can, however, be expressed in terms of receiving and sending end voltage as (Equations)

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_R \\ I_R \end{bmatrix}$$

$$I_R = \frac{1}{B} V_s - \frac{A}{B} V_R \qquad (3)$$

$$I_S = \frac{D}{B} V_S - \frac{1}{B} V_R \qquad (4)$$

Let A, B, D the transmission line constants, be written as

$$A = |A| \underline{|\alpha}, B = |B| \underline{|\beta}, D = |D| \underline{|\alpha} \text{ (Since A=D)}$$

Therefore, we can write

$$I_R = \left|\frac{1}{B}\right| |V_S| \underline{|(\delta - \beta)} - \left|\frac{A}{B}\right| |V_R| \underline{|(\alpha - \beta)}$$

$$I_S = \left|\frac{D}{B}\right| |V_S| \underline{|(\alpha + \delta - \beta)} - \left|\frac{1}{B}\right| |V_R| \underline{|-\beta}$$

Substituting for I_R in Equation (1), we get

$$S_R = |V_R| \underline{|0} \left[\left|\frac{1}{B}\right| |V_S| \underline{|(\beta - \delta)} - \left|\frac{A}{B}\right| |V_R| \underline{|(\beta - \alpha)} \right]$$

$$S_R = \frac{|V_S||V_R|}{|B|} \underline{|(\beta - \alpha)} - \left|\frac{A}{B}\right| |V_R|^2 \underline{|(\beta - \alpha)} \qquad (5)$$

Similarly,

$$S_S = \left|\frac{D}{B}\right| |V_S|^2 \angle(\beta-\alpha) - \frac{|V_S||V_R|}{|B|} \angle(\beta+\alpha) \qquad (6)$$

In the above equations S_R and S_S are per phase complex volt-amperes, while V_R and V_S are expressed in per phase volts. If V_R and V_S are expressed in kV line, then the three-phase receiving-end complex power is given by

$$S_R(3-\phi VA) = 3\left\{ \frac{|V_S||V_R| \times 10^6}{\sqrt{3}\times\sqrt{3}|B|} \angle(\beta-\delta) - \left|\frac{A}{B}\right| \frac{|V_R|^2 \times 10^6}{3} \angle(\beta-\alpha) \right\}$$

$$S_R(3-\phi MVA) = \frac{|V_S||V_R|}{|B|} \angle(\beta-\delta) - \left|\frac{A}{B}\right| \frac{|V_R|^2 \times 10^6}{3} \angle(\beta-\alpha) \qquad (7)$$

This indeed is the same as equation (5). The same result holds for S_S. Thus we see that Equations (5) and (6) give the three-phase MVA if V_S and V_R are expressed in kV line.

If equation (5) is expressed in real and imaginary parts, we can write the real and reactive powers at the receiving-end as

$$P_R = \frac{|V_S||V_R|}{|B|} \cos(\beta-\delta) - \left|\frac{A}{B}\right| |V_R|^2 \cos(\beta-\delta) \qquad (8)$$

$$Q_R = \frac{|V_S||V_R|}{|B|} \sin(\beta-\delta) - \left|\frac{A}{B}\right| |V_R|^2 \sin(\beta-\delta) \qquad (9)$$

Similarly, the real and reactive powers at sending-end are

$$P_S = \left|\frac{D}{B}\right| |V_S|^2 \cos(\beta-\delta) - \frac{|V_S||V_R|}{|B|} \cos(\beta+\delta) \qquad (10)$$

$$Q_S = \left|\frac{D}{B}\right| |V_S|^2 \sin(\beta-\delta) - \frac{|V_S||V_R|}{|B|} \sin(\beta+\delta) \qquad (11)$$

It is easy to see from equation (8) that the received power P_R will be maximum at

$$\delta = \beta$$

Such that

$$P_R(\max) = \frac{|V_S||V_R|}{|B|} - \frac{|A||V_R|^2}{|B|} \cos(\beta-\alpha) \qquad (12)$$

The corresponding Q_R (at max P_R) is

$$Q_R = -\frac{|A||V_R|^2}{|B|}\sin(\beta - \alpha)$$

Thus the load must draw this much leading MVAR in order to receive the maximum real power.

Consider now the special case of a short line with a series impedance Z, Now

$$A = D = 1\angle 0;\ B = Z = |Z|\angle\theta$$

Substituting these in equations (8) to (11), we get the simplified results for the short line as

$$P_R = \frac{|V_S||V_R|}{|Z|}\cos(\theta - \delta) - \frac{|V_R|^2}{|Z|}\cos\theta \qquad (13)$$

$$Q_R = \frac{|V_S||V_R|}{|Z|}\sin(\theta - \delta) - \frac{|V_R|^2}{|Z|}\sin\theta \qquad (14)$$

For the receiving-end and for the sending end

$$P_S = \frac{|V_S|^2}{|Z|}\cos\theta - \frac{|V_S||V_R|}{|Z|}\cos(\theta + \delta) \qquad (15)$$

$$Q_S = \frac{|V_S|^2}{|Z|}\sin\theta - \frac{|V_S||V_R|}{|Z|}\sin(\theta + \delta) \qquad (16)$$

The above short line equation will also apply for a long line when the line is replaced by its equivalent-π(or nominal-π) and the shunt admittances are lumped with the receiving-end load and sending-end generation. In fact, this technique is always used in the load flow studies.

From equation (13), the maximum receiving-end power is received, when δ-Θ, so that

$$P_R(\max) = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|}\cos\theta$$

Now $\cos\theta = \frac{R}{|Z|}$,

$$\therefore P_R(\max) = \frac{|V_S||V_R|}{|Z|} - \frac{|V_R|^2}{|Z|^2}R \qquad (17)$$

Normally the resistance of a transmission line is small compared to its reactance (since it is necessary to maintain a high efficiency of transmission), so that $\theta = \tan^{-1} X/R \approx 90^o$; where Z=R+jX. The receiving-end Equations (13) and (14) can then be approximated as

$$P_R = \frac{|V_S||V_R|}{X}\sin\delta \qquad (18)$$

$$Q_R = \frac{|V_S||V_R|}{X}\cos\delta - \frac{|V_R|^2}{X} \qquad (19)$$

Equation (19) can be further simplified by assuming cos δ=1, since δ is normally small. Thus

$$Q_R = \frac{|V_R|}{X}(|V_S| - |V_R|) \qquad (20)$$

Let $|V_S| - |V_R| = |\Delta V|$, the magnitude of voltage drop across the transmission line.

$$Q_R = \frac{|V_R|}{X}|\Delta V| \qquad (21)$$

Several important conclusions that easily follow from Equations (18) to (21) are enumerated below:

1. For R≈0(Which is a valid approximation for a transmission line) the real power transferred to the receiving-end is proportional to sin δ(≈δ for small values of δ), while the reactive power is proportional to the magnitude of the voltage drop across the line.
2. The real power received is maximum for $\delta=90^0$ and has a value $|V_S||V_R|/X$. Of course, δ is restricted to values well below 90^0 from considerations of stability.
3. Maximum real power transferred for a given line (fixed X) can be increased by raising its voltage level. It is from this consideration that voltage levels are being progressively pushed up to transmit large chunks of power over longer distances warranted by large size generating stations.

   For very long lines, voltage level cannot be raised beyond the limits placed by present-day voltage technology. To increase power transmitted in such cases, the only choice is to reduce the line reactance. This is accomplished by adding series capacitors in the line. Series capacitors would be course increase the severity of line over voltage under switching conditions.

4. The VARs (lagging reactive power) delivered by a line is proportional to the line voltage drop and is independent of δ. Therefore, in a transmission system if the VARs demand of the load is large, the voltage profile at that point tends to sag rather sharply. To maintain

a desired voltage profile, the VARs demand of the load must be met locally by employing positive VAR generators (condensers).

A somewhat more accurate yet approximate result expressing line voltage drop in terms of active and reactive powers can be written directly from

$$|\Delta V| = |I_R| R\cos\phi + |I_R| X\sin\phi$$

$$= \frac{|V_R||I_R| R\cos\phi + |V_R||I_R| X\sin\phi}{|V_R|}$$

$$= \frac{RP_R + XQ_R}{|V_R|} \qquad (22)$$

This result reduces to that of equation (21) if R =0

Power - circle diagrams

Explain the step-by-step procedure for construction of receiving end power circle diagram.[08][May/June’16][R]

Or

Write a short note on the following: (i) concept and procedure to draw circle diagram (ii) Power transfer capability of the transmission lines.[16][Nov/Dec’15][U]

It has been shown above that the flow of active and reactive power over a transmission line can be handled computationally. It will now be shown that the locus of complex sending-end and receiving-end power is a circle. Since circles are convenient to draw, the circle diagrams are useful aid to visualize the load flow problem over a single transmission line.

The expressions for complex number receiving and sending-end powers are reproduced below from equations (5) and (6),

$$S_R = \frac{|V_S||V_R|}{|B|}\underline{|(\beta-\alpha)} - \left|\frac{A}{B}\right||V_R|^2\underline{|(\beta-\alpha)} \qquad (5)$$

$$S_S = \left|\frac{D}{B}\right||V_S|^2\underline{|(\beta-\alpha)} - \frac{|V_S||V_R|}{|B|}\underline{|(\beta+\alpha)} \qquad (6)$$

The units of SR and SS are MVA (three-phase) with voltages in kV line.

As per the above equations, SR and SS are each composed of two phasor components—one constant phasor and the other a phasor of fixed magnitude but variable angle. The loci for SR and SS would, therefore, be circles drawn from the tip of constant phasor as centers.

It follows from equation (5) that the centre of receiving-end circle is located at the tip of the phasor

$$-\left|\frac{A}{B}\right||V_R|^2 \underline{|(\beta-\alpha)} \qquad (23)$$

In polar coordinates or in terms of rectangular coordinates.

Horizontal coordinate of the centre

$$= -\left|\frac{A}{B}\right||V_R|^2 \cos\underline{|(\beta-\alpha)} MW \qquad (24)$$

Vertical coordinate of the centre

$$= -\left|\frac{A}{B}\right||V_R|^2 \sin\underline{|(\beta-\alpha)} MVAR \qquad (25)$$

The radius of the receiving end circle is

$$\frac{|V_S||V_R|}{|B|} MVA \qquad (26)$$

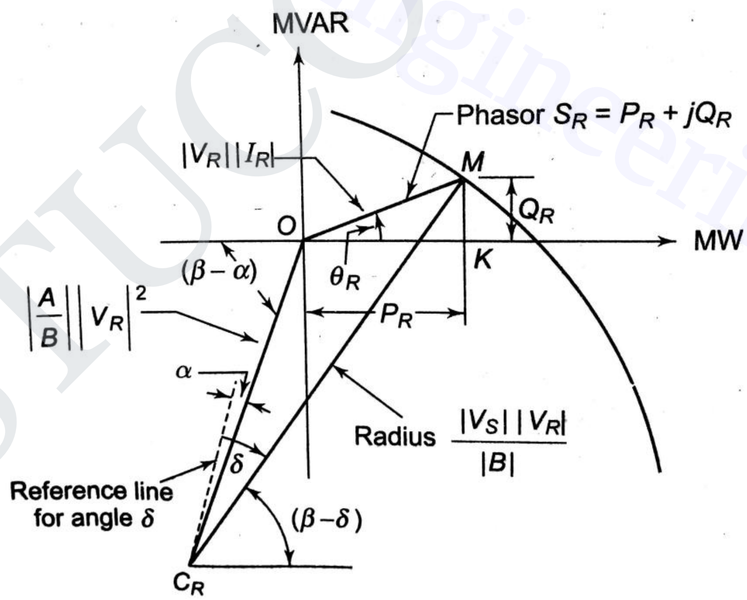


Fig 2 Receiving end circle diagram

The receiving end circle diagram is drawn in Fig 2.

The centre is located by drawing OC_R at an angle (β-δ) in the positive direction from the negative MW-axis.

From the centre C_R the receiving end circle is drawn with the radius $|V_S||V_R|/|B|$.

The operating point M is located on the circle by means of the received real power PR.

The corresponding Q_R (or Θ_R) can be immediately read from the circle diagram.

The torque angle δ can be read in accordance with the positive direction indicated from the reference line.

For constant $|V_R|$, the centre C_R remains fixed and concentric circles result for varying $|V_S|$. However, for the case of constant $|V_S|$ and varying $|V_R|$ the centers of circles move along the line OC_R and have radii in accordance to $|V_S|\ |V_R|/|B|$.

Similarly, it follows from Equation (6) that the centre of the sending-end circle is located at the tip of the phasor in the polar coordinates or in terms of rectangular coordinates.

$$\left|\frac{D}{B}\right||V_S|^2 \angle(\beta-\alpha) \qquad (27)$$

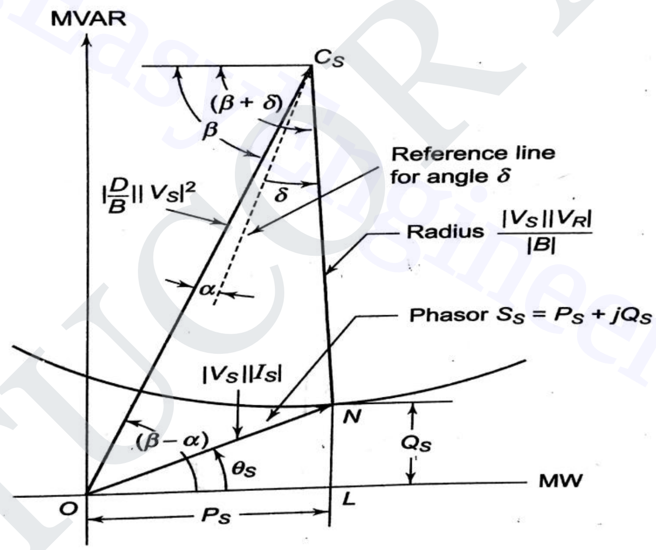


Fig 3 Sending end circle diagram

Horizontal coordinate of the centre

$$=\left|\frac{D}{B}\right||V_S|^2 \cos\angle(\beta-\alpha) MW \qquad (28)$$

Vertical coordinate of the centre

$$=\left|\frac{D}{B}\right||V_S|^2 \sin\angle(\beta-\alpha) MVAR \qquad (29)$$

The radius of the sending end circle is

$$\frac{|V_S||V_R|}{|B|} \qquad (30)$$

The sending end circle diagram is shown in Fig.3. The centre is located by drawing OCS at angle (β-δ) from the positive MW-axis.

From the centre the sending end circle is drawn with a radius $|V_S||V_R|/|B|$ (same as in the case of receiving-end).

The operating point N is located by measure the torque angle δ (as read from the receiving-end circle diagram) in the direction indicated from the reference axis.

For constant $|V_S|$ the centre C_S remains fixed and concentric circles result for varying $|V_R|$. However, if $|V_R|$ is fixed and $|V_S|$ varies, the centers of the circles move along the line OC_S and have radii in accordance to $|V_S||V_R|/|B|$.

For the case of a short line with a series impedance |Z| at angle of Θ, the simplified circle diagrams can be easily drawn by recognizing.

$$|A| = |D| = 1, \alpha = 0$$
$$|B| = |Z|, \beta = \theta$$

The corresponding receiving and sending end circle diagrams have been drawn in Figures (4) and (5)

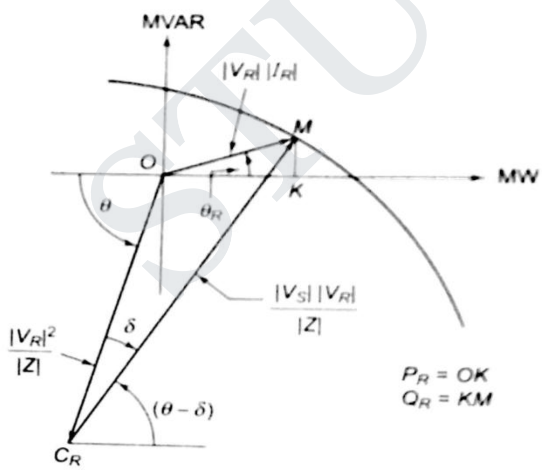


Fig.4

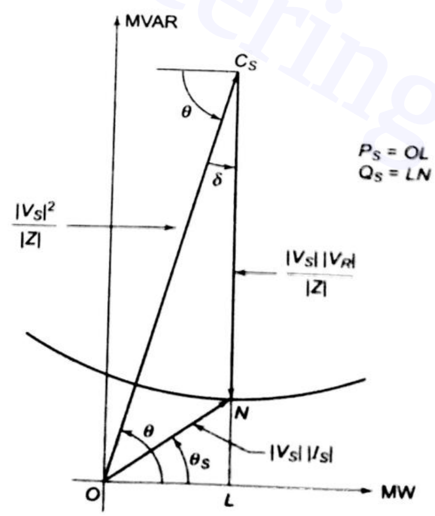


Fig.5

Receiving end and Sending End circle diagram for a short line

Surge Impedance Loading

Surge Impedance Loading (SIL) of a transmission line is defined as the power delivered by a line to purely resistive load equal in value to the surge impedance of the line. Thus for a line having 400 ohms surge impedance,

$$SIL = \sqrt{3}\frac{|V_R|}{\sqrt{3} \times 400}|V_R| \times 1000kW = 2.5|V_R|^2\ kW$$

Where $|V_R|$ is the line-to-line receiving-end voltage in kV. Sometimes , it is found convenient to express line loading in per unit of SIL, i.e. as the ratio of the power transmitted to surge impedance loading.

Explain the method of voltage control in transmission lines.

Voltage control

Importance of Voltage Control

When the load on the supply system changes, the voltage at the consumer's terminals also changes. The variations of voltage at the consumer's terminals are undesirable and must be kept within prescribed limits for the following reasons :

(*i*) In case of lighting load, the lamp characteristics are very sensitive to changes of voltage. For instance, if the supply voltage to an incandescent lamp decreases by 6% of rated value, then illuminating power may decrease by 20%. On the other hand, if the supply voltage is 6% above the rated value, the life of the lamp may be reduced by 50% due to rapid deterioration of the filament.

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

(*iii*) Too wide variations of voltage cause excessive heating of distribution transformers. This may reduce their ratings to a considerable extent.

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

Location of Voltage Control Equipment

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

Firstly, the power network is very extensive and there is a considerable voltage drop in transmission and distribution systems.

Secondly, the various circuits of the power system have dissimilar load characteristics. For these reasons , it is necessary to provide individual means of voltage control for each circuit or group of circuits. In practice, voltage control equipment is used at :

(***i***) generating stations
(***ii***) transformer stations
(***iii***) the feeders if the drop exceeds the permissible limits

Methods of Voltage Control

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

Method (*i*) is used at the generating station only whereas methods (*ii*) to (*v*) can be used for transmission as well as primary distribution systems. However, methods (*vi*) is reserved for the voltage control of a transmission line. We shall discuss each method separately in the next sections.

Excitation Control

When the load on the supply system changes, the terminal voltage of the alternator also varies due to the changed voltage drop in the synchronous reactance of the armature. The voltage of the alternator can be kept constant by changing the field current of the alternator in accordance with the load. This is known as *excitation control* method.

The excitation of alternator can be controlled by the use of automatic or hand operated regulator acting in the field circuit of the alternator. The first method is preferred in modern practice. There are two main types of automatic voltage regulators *viz.*

(***i***) Tirril Regulator
(***ii***) Brown-Boveri Regulator

These regulators are based on the "overshooting the mark principle" to enable them to respond quickly to the rapid fluctuations of load. When the load on the alternator increases, the regulator produces an increase in excitation more than is ultimately necessary. Before the voltage has the time to increase to the value corresponding to the increased excitation, the regulator reduces the excitation to the proper value.

Tirril Regulator

In this type of regulator, a fixed resistance is cut in and cut out of the exciter field circuit of the alternator. This is achieved by rapidly opening and closing a shunt circuit across the exciter rheostat. For this reason, it is also known as vibrating type voltage regulator.

Construction.

Fig.6 shows the essential parts of a Tirril voltage regulator. A rheostat R is provided in the exciter circuit and its value is set to give the required excitation. This rheostat is put in and out of the exciter circuit by the regulator, thus varying the exciter voltage to maintain the desired voltage of the alternator.

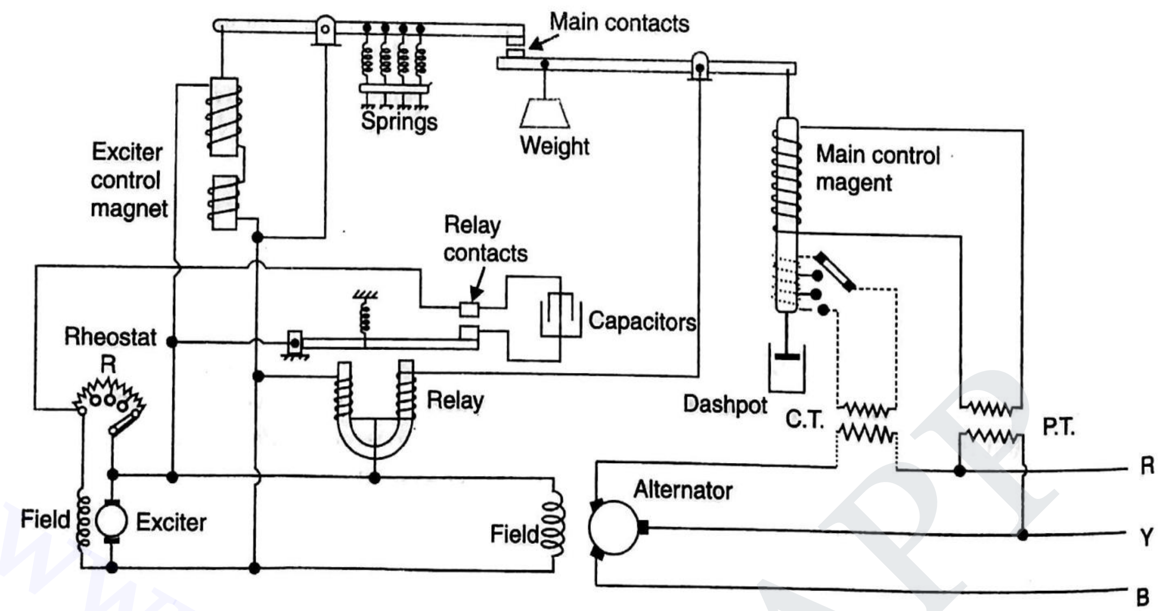


Fig 6 Tirril Regulator

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

(*ii*) *Exciter magnet.* This magnet is of the ordinary solenoid type and is connected across the exciter mains. It's exciting current is, therefore, proportional to the exciter voltage. The counter balancing force for the exciter magnet is provided by four coil springs.

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

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

Operation.

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

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

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

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

Brown-Boveri Regulator

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

Construction.

Fig.7 shows the schematic diagram of a Brown-Boveri voltage regulator. It also works on the "overshooting the mark principle" and has the following four important parts :

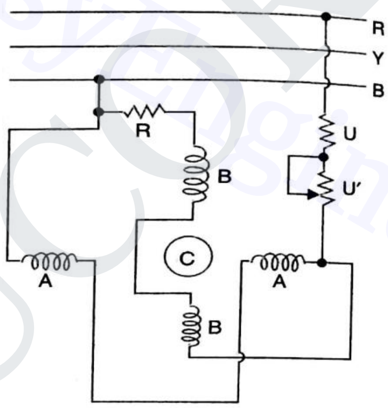


Fig.7

(i) Control system.

The control system is built on the principle of induction motor. It consists of two windings *A* and *B* on an annular core of laminated sheet steel. The winding *A* is excited from two of the generator terminals through resistances *U* and *U′* while a resistance *R*is inserted in the circuit of winding *B*. The ratio of resistance to reactance of the two windings are suitably adjusted so as to create a phase difference of currents in the two windings. Due to the phase difference of currents in the two windings, rotating magnetic field is set up. This produces electromagnetic torque on the thin aluminum drum *C* carried by steel spindle ; the latter being supported at both ends by jewel bearings. The torque on drum *C* varies with the terminal voltage of the alternator. The variable resistance *U′* can also vary the torque on the drum. If the resistance is increased, the torque is decreased and vice versa.

Therefore, the variable resistance *U′* provides a means by which the regulator may be set to operate at the desired voltage.

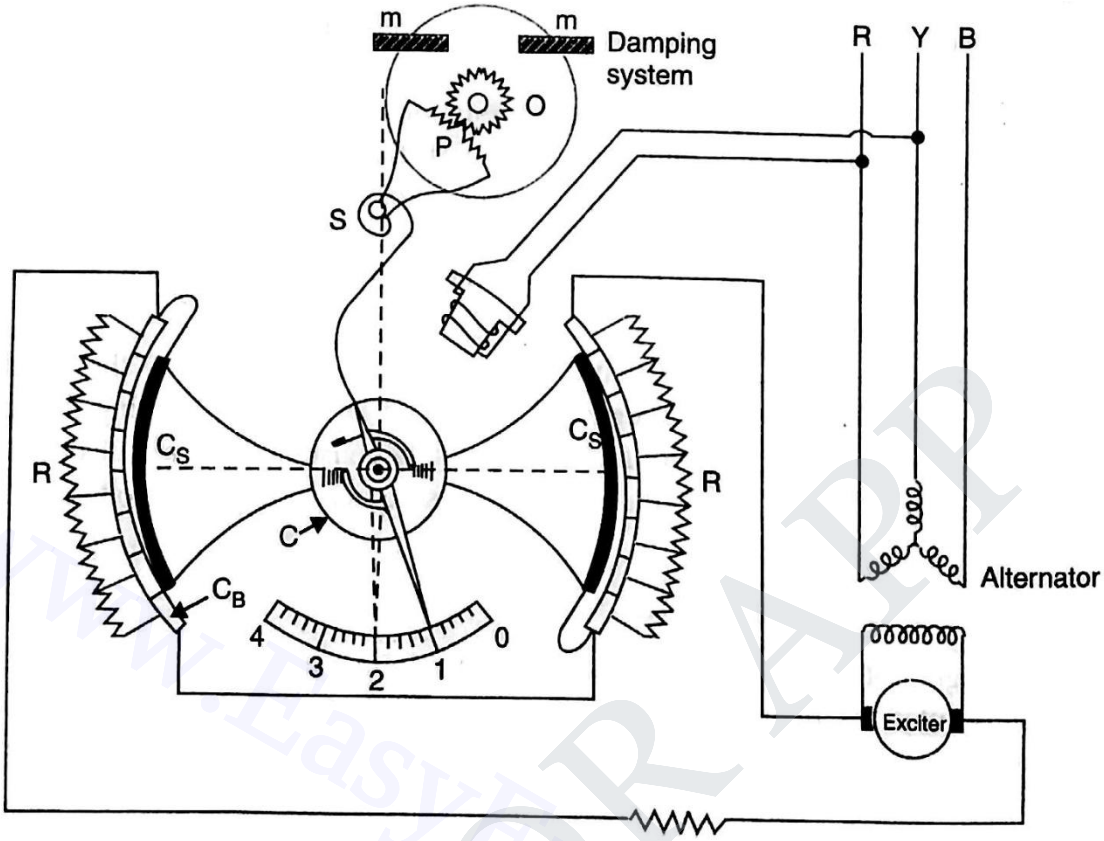


Fig.8

(*ii*) *Mechanical control torque.* The electric torque produced by the current in the split phase winding is opposed by a combination of two springs (main spring and auxiliary spring) which produce a constant mechanical torque irrespective of the position of the drum. Under steady deflected state, mechanical torque is equal and opposite to the electric torque.

(*iii*) *Operating system.* It consists of a field rheostat with contact device. The rheostat consists of a pair of resistance elements connected to the stationary contact blocks *CB*. These two resistance sectors *R* are connected in series with each other and then in series with the field circuit of the exciter. On the inside surface of the contact blocks roll the contact sectors *CS*. When the terminal voltage of the alternator changes, the electric torque acts on the drum. This causes the contact sectors to roll over the contact blocks, cutting in or cutting out rheostat resistance in the exciter field circuit.

(*iv*) *Damping torque.* The regulator is made stable by damping mechanism which consists of an aluminum disc *O* rotating between two permanent magnets *m*. The disc is geared to the rack of an aluminum sector *P* and is fastened to the aluminum drum *C* by means of a flexible spring *S* acting as the recall spring. If there is a change in the alternator voltage, the eddy currents induced in the disc *O* produce the necessary damping torque to resist quick response of the moving system.

Operation. Suppose that resistances *U* and *U′* are so adjusted that terminal voltage of the alternator is normal at position 1. In this position, the electrical torque is counterbalanced by the mechanical torque and the moving system is in equilibrium. It is assumed that electrical torque rotates the shaft in a clockwise direction.

Now imagine that the terminal voltage of the alternator rises due to decrease in load on the supply system. The increase in the alternator voltage will cause an increase in electrical torque which becomes greater than the mechanical torque. This causes the drum to rotate in clockwise direction, say to position 3.

As a result, more resistance is inserted in the exciter circuit, thereby decreasing the field current and hence the terminal voltage of the alternator. Meanwhile, the recall spring *S* is tightened and provides a counter torque forcing the contact roller back to position 2 which is the equilibrium position. The damping system prevents the oscillations of the system about the equilibrium position.

Tap-Changing Transformers

The excitation control method is satisfactory only for relatively short lines. However, it is not suitable for long lines as the voltage at the alternator terminals will have to be varied too much in order that the voltage at the far end of the line may be constant. Under such situations, the problem of voltage control can be solved by employing other methods. One important method is to use tap-changing transformer and is commonly employed where main transformer is necessary. In this method, a number of tapings are provided on the secondary of the transformer. The voltage drop in the line is supplied by changing the secondary e.m.f. of the transformer through the adjustment of its number of turns.

(*i*) Off load tap-changing transformer.

Fig. 9 shows the arrangement where a number of tappings have been provided on the secondary. As the position of the tap is varied, the effective number of secondary turns is varied and hence the output voltage of the secondary can be changed. Thus referring to Fig.9, when the movable arm makes contact with stud 1, the secondary voltage is minimum and when with stud 5, it is maximum. During the period of light load, the voltage across the primary is not much below the alternator voltage and the movable arm is placed on stud 1. When the load increases, the voltage across the primary drops, but the secondary voltage can be kept at the previous value by placing the movable arm on to a higher stud. Whenever a tapping is to be changed in this type of transformer, the load is kept off and hence the name off load tap-changing transformer.

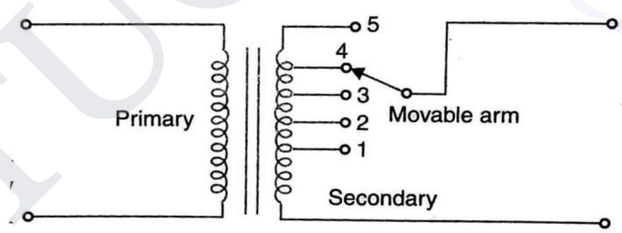


Fig.9

The principal disadvantage of the circuit arrangement shown in Fig.4 is that it cannot be used for tap-changing on load. Suppose for a moment that tapping is changed from position 1 to position 2 when the transformer is supplying load. If contact with stud 1 is broken before contact with stud 2 is made, there is break in the circuit and arcing results. On the other hand, if contact with stud 2 is made before contact with stud 1 is broken, the coils connected between these two tapping's are short circuited and carry damaging heavy currents. For this reason, the above circuit arrangement cannot be used for tap-changing on load.

(*ii*) On-load tap-changing transformer. In supply system, tap-changing has normally to be performed on load so that there is no interruption to supply.

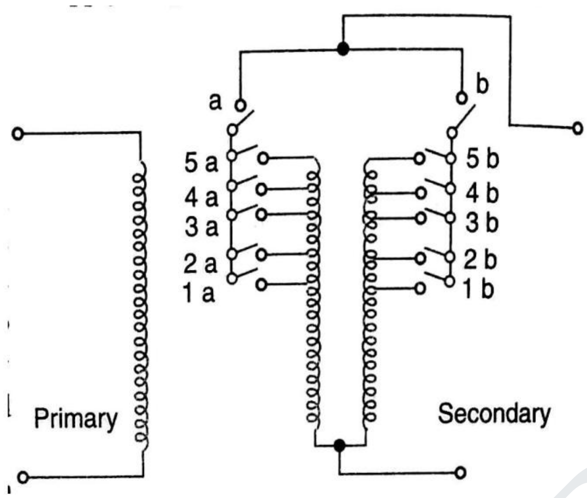


Fig 10

Fig. 10 shows diagrammatically one type of on-load tap-changing transformer. The secondary consists of two equal parallel windings which have similar tapping's 1*a* ...... 5*a* and 1*b* .... 5*b*. In the normal working conditions, switches *a*, *b* and tapping's with the same number remain closed and each secondary winding carries one-half of the total current.

Referring to Fig. 10, the secondary voltage will be maximum when switches *a*, *b* and 5*a*, 5*b* are closed. However, the secondary voltage will be minimum when switches *a*, *b* and 1*a*, 1*b* are closed. Suppose that the transformer is working with tapping position at 4*a*, 4*b* and it is desired to alter its position to 5*a*, 5*b*. For this purpose, one of the switches *a* and *b*, say *a*, is opened. This takes the secondary winding controlled by switch *a* out of the circuit. Now, the secondary winding controlled by switch *b* carries the total current which is twice its rated capacity.

Then the tapping on the disconnected winding is changed to 5*a* and switch *a* is closed. After this, switch *b* is opened to disconnect its winding, tapping position on this winding is changed to 5*b* and then switch *b* is closed. In this way, tapping position is changed without interrupting the supply.

This method has the following disadvantages:

(*i*) During switching, the impedance of transformer is increased and there will be a voltage surge.
(*ii*) There are twice as many tappings as the voltage steps.

Auto-Transformer Tap-changing

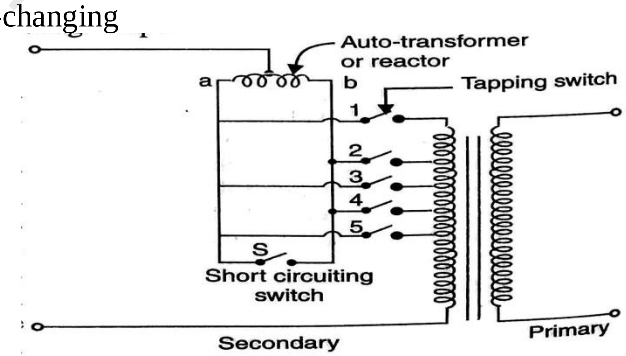


Fig 11

Fig.11 shows diagrammatically auto-transformer tap changing. Here, a mid-tapped auto-transformer or reactor is used. One of the lines is connected to its mid-tapping. One end, say *a* of this transformer is connected to a series of switches across the odd tapping's and the other end *b* is connected to switches across even tapping's. A short-circuiting switch *S* is connected across the auto-transformer and remains in the closed position under normal operation. In the normal operation, there is no inductive voltage drop across the auto-transformer. Referring to Fig. 11, it is clear that with switch 5 closed, minimum secondary turns are in the circuit and hence the output voltage will be the lowest.

On the other hand, the output voltage will be maximum when switch 1 is closed. Suppose now it is desired to alter the tapping point from position 5 to position 4 in order to raise the output voltage. For this purpose, short-circuiting switch *S* is opened, switch 4 is closed, then switch 5 is opened and finally short-circuiting switch is closed. In this way, tapping can be changed without interrupting the supply.

It is worthwhile to describe the electrical phenomenon occurring during the tap changing. When the short-circuiting switch is opened, the load current flows through one-half of the reactor coil so that there is a voltage drop across the reactor. When switch 4 is closed, the turns between points 4 and 5 are connected through the whole reactor winding. A circulating current flows through this local circuit but it is limited to a low value due to high reactance of the reactor.

Booster Transformer

Sometimes it is desired to control the voltage of a transmission line at a point far away from the main transformer. This can be conveniently achieved by the use of a booster transformer as shown in Fig.12. The secondary of the booster transformer is connected in series with the line whose voltage is to be controlled. The primary of this transformer is supplied from a regulating transformer fitted with on-load tap-changing gear. The booster transformer is connected in such a way that its secondary injects a voltage in phase with the line voltage.

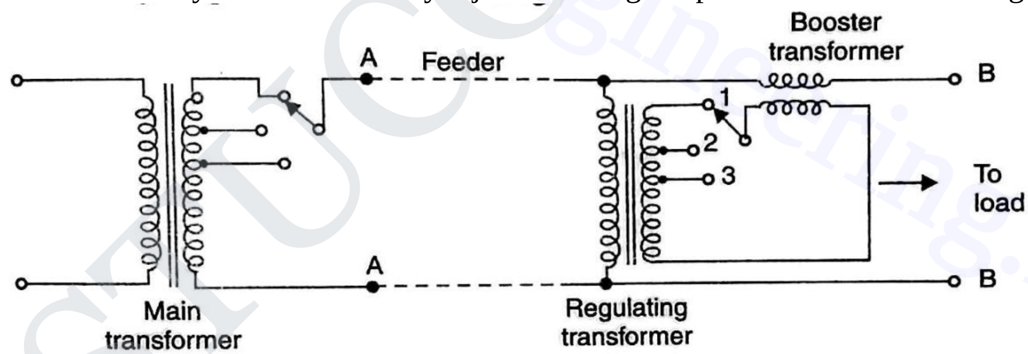


Fig.12

The voltage at *AA* is maintained constant by tap-changing gear in the main transformer. However, there may be considerable voltage drop between *AA* and *BB* due to fairly long feeder and tapping of loads. The voltage at *BB* is controlled by the use of regulating transformer and booster transformer. By changing the tapping on the regulating transformer, the magnitude of the voltage injected into the line can be varied. This permits to keep the voltage at *BB* to the desired value. This method of voltage control has three disadvantages.

Firstly, it is more expensive than the on-load tap-changing transformer.

Secondly, it is less efficient owing to losses in the booster and thirdly more floor space is required. Fig.8 shows a three-phase booster transformer.

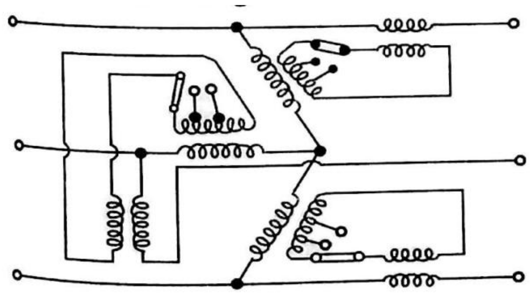


Fig.13

Induction Regulators

An induction regulator is essentially a constant voltage transformer, one winding of which can be moved *w.r.t.* the other, thereby obtaining a variable secondary voltage. The primary winding is connected across the supply while the secondary winding is connected in series with the line whose voltage is to be controlled. When the position of one winding is changed w.r.t. the other, the secondary voltage injected into the line also changes. There are two types of induction regulators *viz.* single phase and 3-phase.

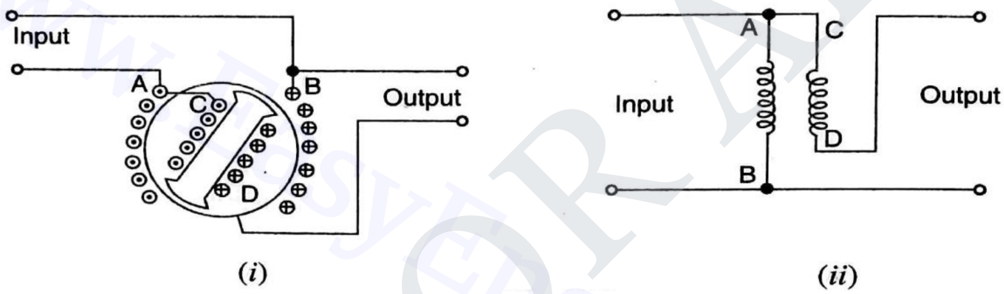


Fig.14

(*i*) Single-phase induction regulator. A single phase induction regulator is illustrated in Fig.14. In construction, it is similar to a single phase induction motor except that the rotor is not allowed to rotate continuously but can be adjusted in any position either manually or by a small motor. The primary winding *AB* is wound on the stator and is connected across the supply line. The secondary winding *CD* is wound on the rotor and is connected in series with the line whose voltage is to be controlled.

The primary exciting current produces an alternating flux that induces an alternating voltage in the secondary winding *CD*. The magnitude of voltage induced in the secondary depends upon its position *w.r.t.* the primary winding. By adjusting the rotor to a suitable position, the secondary voltage can be varied from a maximum positive to a maximum negative value. In this way, the regulator can add or subtract from the circuit voltage according to the relative positions of the two windings.

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

(*ii*) Three-phase induction regulator. In construction, a 3-phase induction regulator is similar to a 3-phase induction motor with wound rotor except that the rotor is not allowed to rotate continuously but can be held in any position by means of a worm gear. The primary windings either in star or delta are wound on the stator and are connected across the supply. The secondary windings are wound on the rotor and the six terminals are brought out since these windings are to be connected in series with the line whose voltage is to be controlled.

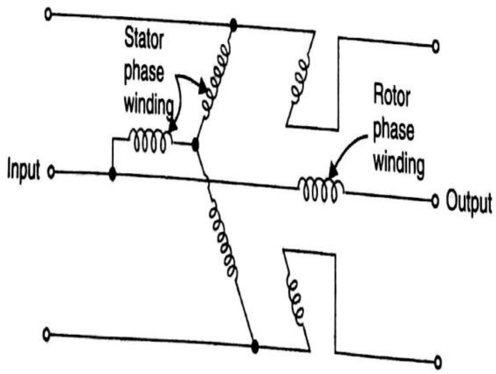


Fig.15

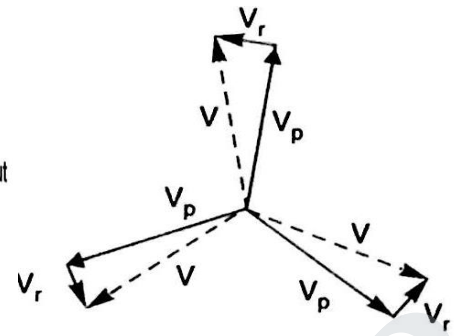


Fig.16

When polyphase currents flow through the primary windings, a rotating field is set up this induces an e.m.f. in each phase of rotor winding. As the rotor is turned, the magnitude of the rotating flux is not changed; hence the rotor e.m.f. per phase remains constant. However, the variation of the position of the rotor will affect the phase of the rotor e.m.f. *w.r.t.* the applied voltage as shown in Fig.11. The input primary voltage per phase is V_p and the boost introduced by the regulator is V_r. The output voltage V is the vector sum of V_p and V_r. Three phase induction regulators are used to regulate the voltage of feeders and in connection with high voltage oil testing transformers.

Voltage Control by Synchronous Condenser

The voltage at the receiving end of a transmission line can be controlled by installing specially designed synchronous motors called synchronous condensers at the receiving end of the line. The synchronous condenser supplies wattless leading kVA to the line depending upon the excitation of the motor. This wattless leading kVA partly or fully cancels the wattless lagging kVA of the line, thus controlling the voltage drop in the line. In this way, voltage at the receiving end of a transmission line can be kept constant as the load on the system changes. For simplicity, consider a short transmission line where the effects of capacitance are neglected. Therefore, the line has only resistance and inductance. Let V_1 and V_2be the per phase sending end and receiving end voltages respectively. Let I_2 be the load current at a lagging power factor of cos φ_2.

***(i)* Without synchronous condenser.** Fig. 17 (*i*) shows the transmission line with resistance *R* and inductive reactance *X* per phase. The load current I_2 can be resolved into two rectangular components *viz* $I_p$in phase with V_2 and $I_q$at right angles to V_2 [See Fig. 72 (*ii*)]. Each component will produce resistive and reactive drops ; the resistive drops being in phase with and the reactive drops in quadrature leading with the corresponding currents. The vector addition of these voltage drops to V_2 gives the sending end voltage V_1.

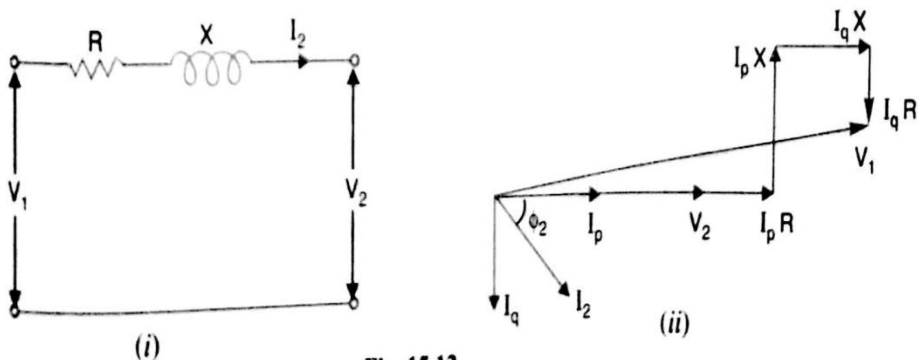


Fig.17

***(ii)* With synchronous condenser.** Now suppose that a synchronous condenser taking a leading Current I_m is connected at the receiving end of the line. The vector diagram of the circuit becomes as shown in Fig. 18. Note that since I_m and I_q are in direct opposition and that I_m must be greater than I_q, the four drops due to these two currents simplify to:

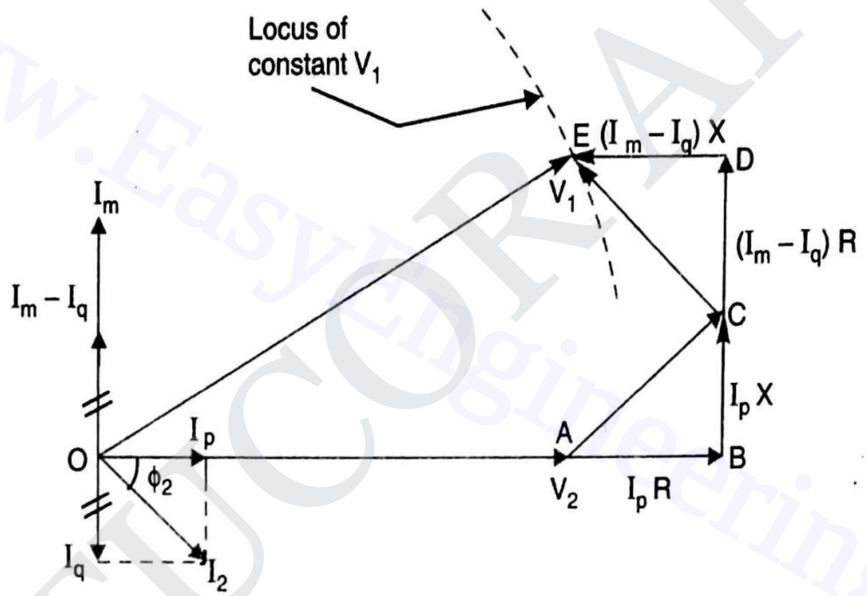


Fig.18

$(I_m - I_q)R$ in phase with I_m and $(I_m - I_q)X$ in quadrature leading with I_m

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

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

Or

$$V_1^2 = [V_2 + I_pR - (I_m - I_q)X]^2 + [I_pX + (I_m - I_q)R]^2$$

From this equation, the value of I_m can be calculated to obtain any desired ratio of V_1/V_2 for a given load current and power factor.

kVAR capacity of condenser $=(3V_2I_m)/1000$

Ferranti Effect

A long or medium transmission line has considerable capacitance and so draws leading charging current from the generating-end even when loaded. Moreover, receiving-end voltage V_R under no-load condition is found to be greater than sending-end voltage V_S. This phenomenon is known as Ferranti Effect.

Fig 19(a) shows the distributed parameters of such a line. It may be replaced by the circuit of Fig 19(b) where these distributed parameters have been lumped. As shown in diagram of Fig.2, the charging current I_c leads V_R by 90^o and produces a phase voltage drop $=I_cZ=I_c(R+jX_L)$.

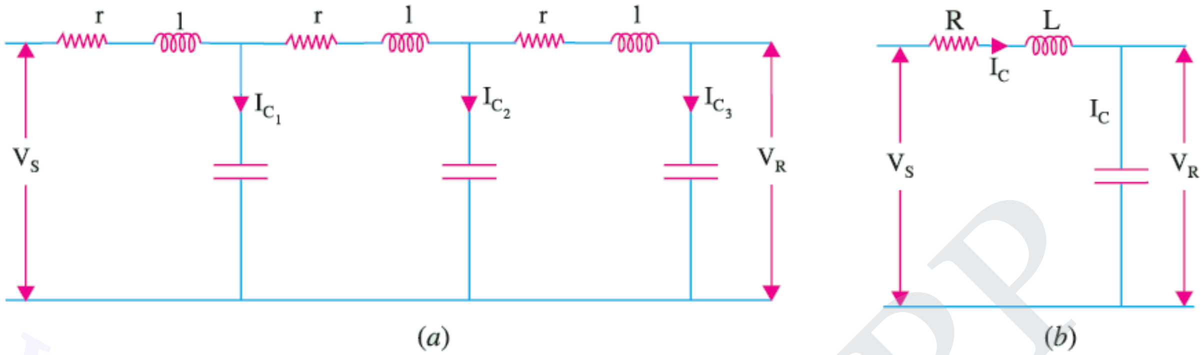


Fig.19

Obviously, $V_s<V_R$ Now, $I_c = V_R\omega C$

As seen from Fig 20

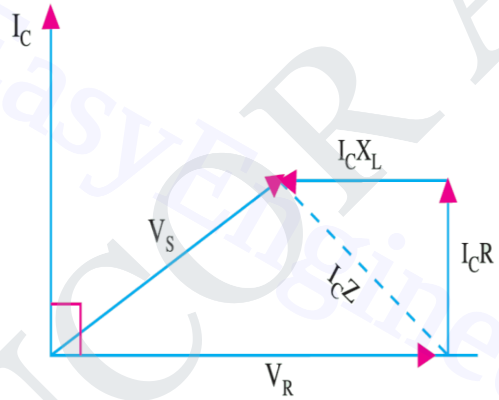


Fig.20

$$V_s = \sqrt{(V_R - I_cX_L)^2 + (I_cR)^2}$$

If R is negligible, then

$$V_s = (V_R - I_cX_L) or\ V_R = V_s + I_cX_L$$

PART-A

1. What is the importance of voltage control? [April/May ‘15][R]

When the load on the supply system changes, the voltage at the consumer’s terminals also changes. The variations of voltage at the consumer’s terminals are undesirable and must be kept within prescribed limits for the following reasons:

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

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

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

(iii) Too wide variations of voltage cause excessive heating of distribution transformers. This may reduce their ratings to a considerable extent.

2. Define voltage regulation in connection with transmission lines. [Nov/Dec '12](or) Define voltage regulation of transmission line. [Nov/Dec '13][R]
   Voltage regulation of a transmission line is defined as the difference in voltage at the receiving end of the transmission line at the no load and full load expressed as a percentage of the voltage at the receiving end with supply frequency and voltage at sending end remaining unchanged. Mathematically it is given as,
   $$\%\text{Voltage Regulation} = \frac{V_{\text{No load}} - V_{\text{Full load}}}{V_{\text{Full load}}} \times 100$$
3. What is the range of surge impedance in case of underground cables?[Nov/Dec '12][U]
   The approximate value of surge impedance for underground cables is 40Ω while typically it is in the range of 40Ω to 60Ω.
4. What is Ferranti effect?[May/June'13][Nov/Dec '13][Nov/Dec'11][Nov/Dec'10][April/May '15][May/June'16][Nov/Dec'15][U]
   In long transmission lines and cables, receiving end voltage is greater than sending end voltage during light load or no-load operation. Under no load or light load, the capacitance associated with the line generate more reactive power than the reactive power which is absorbed, hence V_R>V_S. This effect is known as Ferranti effect...
5. What is the range of surge impedance of an OH transmission line?[May/June'13][R]
   The approximate value of surge impedance for overhear lines is 400Ω while typically it is in the range of 400Ω to 600Ω.
6. What is the surge impedance loading of a line?[April/May'11][R]
   Surge impedance loading of a line is the maximum power transmitted when a lossless line operating at its nominal voltage, is terminated with a resistance equal to surge impedance of the line.
   $$P_R = \frac{|V_{RL}|^2}{Z_C} MW$$
   Where V_{RL} = Line voltage at the receiving end
   Z_C = surge impedance = $\sqrt{\frac{L}{C}}$
   P_R = surge impedance loading

7. Distinguish between attenuation and phase constant.[Nov/Dec'11][R]

Attenuation constant	Phase constant
It is the real part of the propagation constant γ.	It is the imaginary part of the propagation constant γ.
It is denoted by the symbol α.	It is denoted by the symbol β.
It is measured in nepers per unit length (meter)	It is measured in radians per unit length(meter)
It represents the attenuation of an electromagnetic wave propagating through a medium per unit distance from the source.	It represents the change in phase per meter along the path travelled by the wave at any instant.

8. What is shunt compensation?[Nov/Dec'10][R]

   Compensation of a line with the help of a shunt capacitor across the line in order to improve the power factor and voltage profile as well as to reduce the losses is known as shunt compensation.

9. Mention the significance of surge impedance loading.(SIL)[May/June'16][U]

   The surge impedance Loading (SIL) of a line is defined as the power delivered by a line to a purely resistive load equal to its surge or characteristics impedance. SIL is called natural power of the line. It helps in expressing power transmitted by a line in terms of per unit of SIL which is the ratio of the power transmitted to the surge impedance loading. The permissible loading of a transmission line can be expressed as a fraction of its SIL and it provides a comparison of load carrying capabilities of lines.

10. Define transmission efficiency.[Nov/Dec'15][U]

    The transmission efficiency is defined as the ratio of power at the receiving end to the power at the sending end expressed as a percentage. Mathematically it is given as,

$$\%\, Tranmission\ efficiency = \frac{Power\ \ at\ receiving\ \ end\ \ (P_R)}{Power\ \ at\ sending\ \ end\ \ (P_S)} \times 100$$

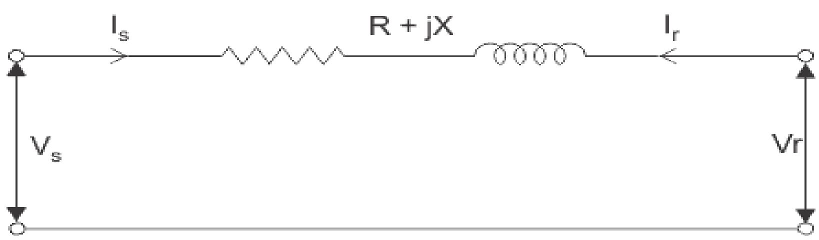
11. Write the formula for finding surge impedance of transmission line.[Nov/Dec'15][U]

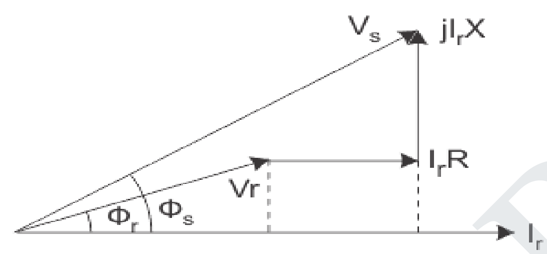
$$Z_C = \text{surge impedance} = \sqrt{\frac{L}{C}}$$

12. Mention the range of surge impedance value for a overhead transmission line and a underground cable.[May/June'16][U]

    The approximate value of surge impedance for overhear lines is 400Ω while typically it is in the range of 400Ω to 600Ω.The approximate value of surge impedance for underground cables is 40Ω while typically it is in the range of 40Ω to 60Ω

13. Draw equivalent circuit and phasor diagram for short transmission line.[May/June'16][[R]





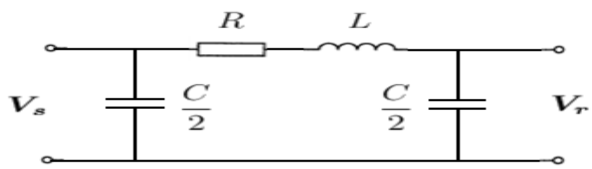
14. Define voltage stability.[Nov/Dec'15][R]

Voltage stability is the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance. A system enters a state of voltage instability when a disturbance increase in load demand, or change in system condition causes a progressive and uncontrollable drop in voltage.

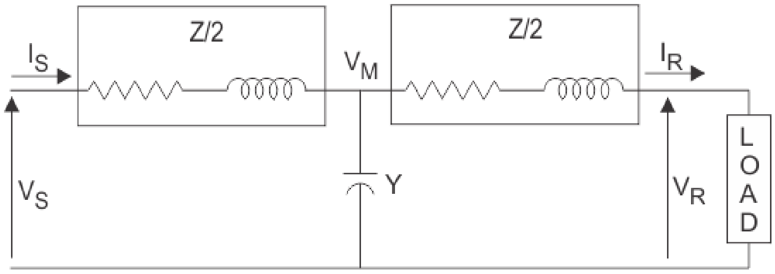
15. What is power circle diagram?[R]

The real and reactive powers at sending and receiving end can be computed mathematically and the transmission line characteristics can be represented graphically. By taking sending end or receiving end voltage or current as a reference, these characteristics can be plotted which represent circle and the corresponding diagram is called circle diagram. The real power is plotted on X axis while the reactive power is on Y axis.

16. Draw the nominal π representation of a transmission line.[R]



17. Draw the nominal T representation of a transmission line.[R]



Nominal T representation of a medium transmission line

18. What are the factors which govern the performance of a transmission line?[R]

The transmission line performance is mainly governed by its four parameters series resistance and inductance, shunt capacitance and conductance where the shunt conductance is often neglected as it is very small. All these parameters are distributed over the length of the line. Based on these parameters measures of transmission lines are the transmission efficiency and voltage regulation both expressed as percentage.

19. What are the advantages of series compensation?[R]

The advantages of series compensation are

i. Increase in power transmission capacity of line
ii. Improvement in system stability
iii. Improved voltage stability
iv. Load division between parallel circuits
v. Damping of power swings and transients

20. Distinguish between voltage stability and rotor angle stability[U]

Voltage stability	Rotor angle stability
It refers to load stability	It refers to generator stability
It is mainly related to reactive power transfer	It is mainly related to real power transfer
Problems occur in the event of fault	Problems occur during and after faults

UNIT IV

Insulators - Types, voltage distribution in insulator string, improvement of string efficiency, testing of insulators. Underground cables - Types of cables, Capacitance of Single-core cable, Grading of cables, Power factor and heating of cables, Capacitance of 3-core belted cable, D.C cables.

Introduction

The overhead line conductors should be supported on the poles or towers in such a way that currents from conductors do not flow to earth through supports *i.e.*, line conductors must be properly insulated from supports. This is achieved by securing line conductors to supports with the help of *insulators*.

The insulators provide necessary insulation between line conductors and supports and thus prevent any leakage current from conductors to earth. In general, the insulators should have the following desirable properties:

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

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

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

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

(*v*) High ratio of puncture strength to flashover.

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

Types of Insulators

Discuss briefly on the following: (a) Pin type insulator (b) Suspension type insulator.[16][Nov/Dec/10]

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

1. Pin type insulators. The part section of a pin type insulator is shown in Fig. 4.1 (*i*). As the name suggests, the pin type insulator is secured to the cross-arm on the pole.

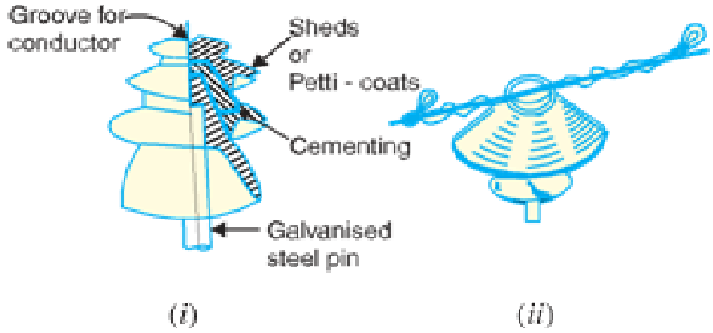


Fig 4.1 Pin-type Insulator

There is a groove on the upper end of the insulator for housing the conductor. The conductor passes through this groove and is bound by the annealed wire of the same material as the conductor [See Fig. 4.1 (*ii*)]. Pin type insulators are used for transmission and distribution of electric power at voltages upto 33 kV. Beyond operating voltage of 33 kV, the pin type insulators become too bulky and hence uneconomical.

Causes of insulator failure. Insulators are required to withstand both mechanical and electrical stresses. The latter type is pirmarily due to line voltage and may cause the breakdown of the insulator. The electrical breakdown of the insulator can occur either by *flash-over* or *puncture.* In flashover, an arc occurs between the line conductor and insulator pin (*i.e.*, earth) and the discharge jumps across the air gaps, following shortest distance. Fig. 4.2 shows the arcing distance (*i.e.* $a + b + c$) for the insulator.

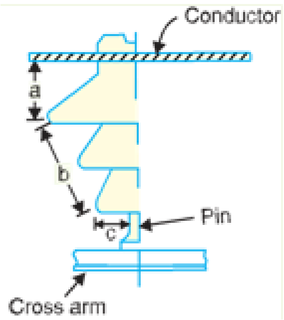


Fig 4.2

In case of flash-over, the insulator will continue to act in its proper capacity unless extreme heat produced by the arc destroys the insulator. In case of puncture, the discharge occurs from conductor to pin through the body of the insulator. When such breakdown is involved, the insulator is permanently destroyed due to excessive heat. In practice, sufficient thickness of porcelain is provided in the insulator to avoid puncture by the line voltage. The ratio of puncture strength to flashover voltage is known as safety factor *i.e.*,

Safety factor of insulator = Puncture strength/Flash - over voltage

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

2 Suspension type insulators. The cost of pin type insulator increases rapidly as the working voltage is increased. Therefore, this type of insulator is not economical beyond 33 kV. For high voltages (>33 kV), it is a usual practice to use suspension type insulators shown in Fig. 4.3.

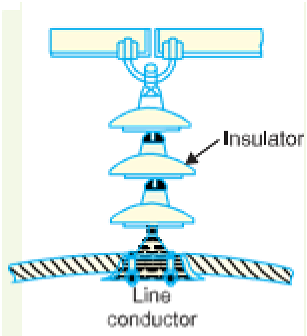


Fig 4.3

They consist of a number of porcelain discs connected in series by metal links in the form of a string. The conductor is suspended at the bottom end of this string while the other end of the string is secured to the cross-arm of the tower. Each unit or disc is designed for low voltage, say 11 kV. The number of discs in series would obviously depend upon the working voltage. For instance, if the working voltage is 66 kV, then six discs in series will be provided on the string.

Advantages

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

(*ii*) Each unit or disc of suspension type insulator is designed for low voltage,usually 11 kV. Depending upon the working voltage, the desired number of discs can be connected in series.

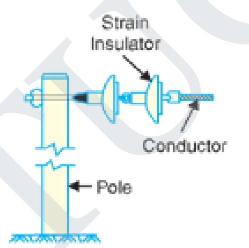
(*iii*) If any one disc is damaged, the whole string does not become useless because the damaged disc can be replaced by the sound one.

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

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

(*vi*) The suspension type insulators are generally used with steel towers. As the conductors run below the earthed cross-arm of the tower, therefore, this arrangement provides partial protection from lightning.

3. Strain insulators. When there is a dead end of the line or there is corner or sharp curve, the line is subjected to greater tension. In order to relieve the line of excessive tension, strain insulators are used. For low voltage lines (< 11 kV), shackle insulators are used as strain insulators. However, for high voltage transmission lines, strain insulator consists of an assembly of suspension insulators as shown in Fig. 4.4. The discs of strain insulators are used in the vertical plane. When the tension in lines is exceedingly high, as at long river spans, two or more strings are used in parallel.



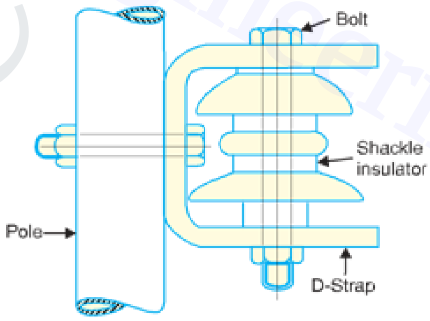


Fig 4.4 Strain Insulator

Fig 4.5

4. Shackle insulators. In early days, the shackle insulators were used as strain insulators. But now a days, they are frequently used for low voltage distribution lines. Such insulators can be used either in a horizontal position or in a vertical position. They can be directly fixed to the pole with a bolt or to the cross arm. Fig. 4.5 shows a shackle insulator fixed to the pole. The conductor in the groove is fixed with a soft binding wire.

Voltage distribution in insulator string

A string of suspension insulators consists of a number of porcelain discs connected in series through metallic links. Fig. 4.6 (*i*) shows 3-disc string of suspension insulators. The porcelain portion of each disc is in between two metal links. Therefore, each disc forms a capacitor *C* as shown in Fig. 4.6 (*ii*). This is known as *mutual capacitance* or *self-*

capacitance. If there were mutual capacitance alone, then charging current would have been the same through all the discs and consequently voltage across each unit would have been the same *i.e.*, $V/3$ as shown in Fig. 4.6 (*ii*). However, in actual practice, capacitance also exists between metal fitting of each disc and tower or earth. This is known as *shunt capacitance* C_1. Due to shunt capacitance, charging current is not the same through all the discs of the string [See Fig. 4.6 (*iii*)]. Therefore, voltage across each disc will be different. Obviously, the disc nearest to the line conductor will have the maximum voltage. Thus referring to Fig. 4.6 (*iii*), V_3 will be much more than V_2 or V_1.

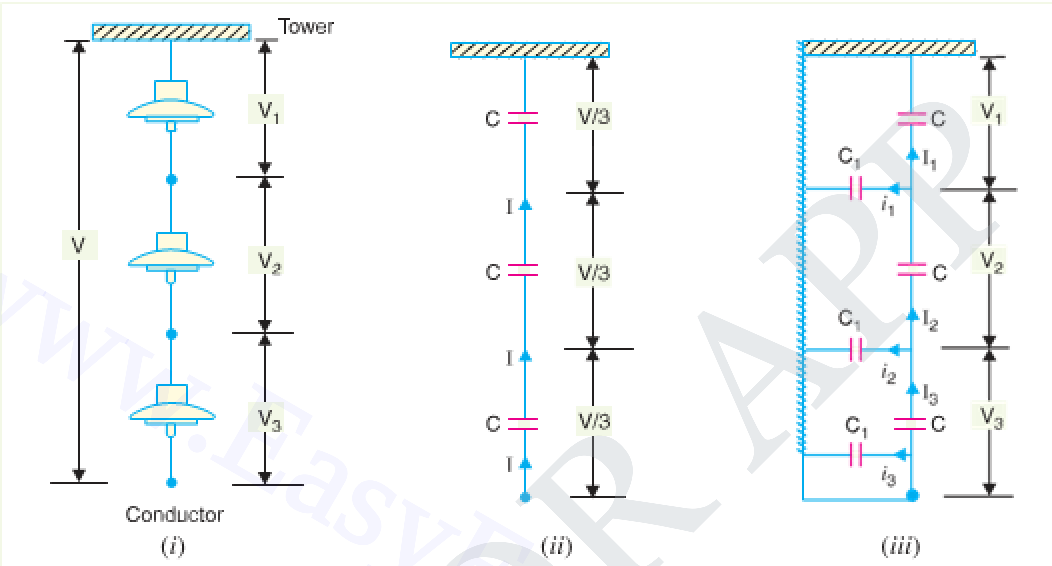


Fig 4.6

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

(i) The voltage impressed on a string of suspension insulators does not distribute itself uniformly across the individual discs due to the presence of shunt capacitance.

(ii) The disc nearest to the conductor has maximum voltage across it. As we move towards the cross-arm, the voltage across each disc goes on decreasing.

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

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

String Efficiency

Define 'string efficiency' and calculate its value for a string of 3 insulators units if the capacitance of each unit to earth and line be 20% and 5% of the self capacitance of the unit. Derive any formula that might be used.[16][May/June'13]

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

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

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

where n = number of discs in the string.

String efficiency is an important consideration since it decides the potential distribution along the string. The greater the string efficiency, the more uniform is the voltage distribution. Thus 100% string efficiency is an ideal case for which the volatge across each disc will be exactly the same. Although it is impossible to achieve 100% string efficiency, yet efforts should be made to improve it as close to this value as possible.

Mathematical expression. Fig. 4.7 shows the equivalent circuit for a 3-disc string. Let us suppose that self capacitance of each disc is C. Let us further assume that shunt capacitance C_1 is some fraction K of self capacitance *i.e.*, $C_1 = KC$. Starting from the cross-arm or tower, the voltage across each unit is V_1, V_2 and V_3 respectively as shown.

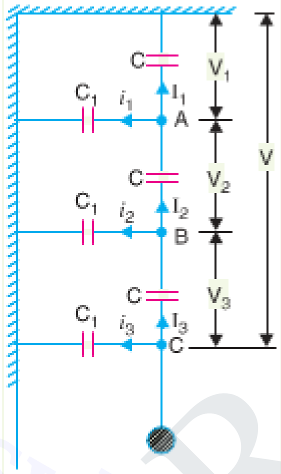


Fig 4.7

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

$$I_2 = I_1 + i_1$$

Or $$V_2\omega C = V_1\omega C + V_1\omega C_1$$

Or $$V_2\omega C = V_1\omega C + V_1\omega KC$$

∴ $$V_2 = V_1(1+K) \qquad \text{(i)}$$

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

$$I_3 = I_2 + i_2$$

Or $$V_3\omega C = V_2\omega C + (V_1+V_2)\omega C_1$$

Or $$V_3\omega C = V_2\omega C + (V_1+V_2)\omega KC$$

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

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

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

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

$$V_3=V_1[1+3K+K^2] \qquad \text{(ii)}$$

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

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

$$V=V_1(1+K)(3+K) \qquad \text{(iii)}$$

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

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

∴ Voltage across top unit, $V_1=\dfrac{V}{(1+K)(3+K)}$

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

Voltage across third unit from top, $V_3=V_1[1+3K+K^2]$

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

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

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

(*i*) If K = 0·2 (Say), then from exp. (*iv*), we get, V_2 = 1·2 V_1 and V_3 = 1·64 V_1. This clearly shows that disc nearest to the conductor has maximum voltage across it; the voltage across other discs decreasing progressively as the cross-arm in approached.

(*ii*) The greater the value of K (= C_1/C), the more non-uniform is the potential across the discs and lesser is the string efficiency.

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

METHODS OF IMPROVING STRING EFFICIENCY

Explain in detail the different methods of improving the string efficiency.[16][Nov/Dec '12][May/June'16]

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

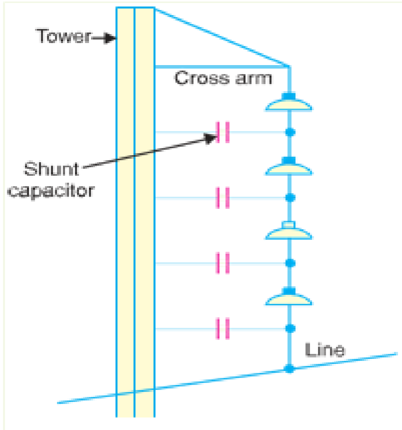


Fig 4.8

(*i*) *By using longer cross-arms*. The value of string efficiency depends upon the value of K *i.e.*, ratio of shunt capacitance to mutual capacitance. The lesser the value of K, the greater is the string efficiency and more uniform is the voltage distribution. The value of K can be decreased by reducing the shunt capacitance. In order to reduce shunt capacitance, the distance of conductor from tower must be increased *i.e.*, longer cross-arms should be used. However, limitations of cost and strength of tower do not allow the use of very long cross-arms. In practice, $K = 0{\cdot}1$ is the limit that can be achieved by this method.

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

(*iii*) *By using a guard ring*. The potential across each unit in a string can be equalised by using a guard ring which is a metal ring electrically connected to the conductor and surrounding the bottom insulator as shown in the Fig. 4.9. The guard ring introduces capacitance between metal fittings and the line conductor. The guard ring is contoured in such a way that shunt capacitance currents i_1, i_2 etc. are equal to metal fitting line capacitance currents i'_1, i'_2 etc. The result is that same charging current I flows through each unit of string. Consequently, there will be uniform potential distribution across the units.

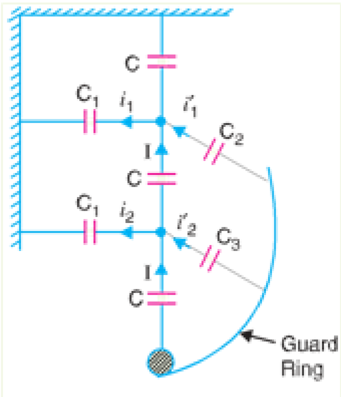


Fig 4.9

Important Points

While solving problems relating to string efficiency, the following points must be kept in mind:

(i) The maximum voltage appears across the disc nearest to the conductror (*i.e.*, line conductor).

(ii) The voltage across the string is equal to phase voltage *i.e.*,

Voltage across string = Voltage between line and earth = Phase Voltage

(iii) Line Voltage = 3 × Voltage across string

Testing of insulators

An insulator should have good mechanical strength to withstand the load conditions. It should not have any pores or voids which may lead to breakdown. Its electrical strength should be large enough to withstand the normal voltage and usual overvoltages but the insulator should flashover at such voltages which are likely to cause damage to other equipment. The following tests are performed on the insulators:

1. Mechanical strength, electrical insulation tests, environmental tests.
2. Porosity, galvanizing test
3. Power frequency dry flashover voltage
4. Power frequency wet flashover voltage
5. Impulse voltage withstand flashover test
6. Puncture voltage test
7. Corona and radio interference test

Mechanical tests

Tensile strength, Compression test, torsional test, bending minimum test, mechanical vibration test.

Electrical insulation tests

The insulators are subjected to normal continuous power frequency over voltage and impulse voltage test. These voltages have different wave forms and durations.

For these standard test requirements and test procedures relevant standards are followed. For special requirements, the tests are decided jointly by customer and the supplier.

Flash over tests are further classified as,

1. 50 Cycle Dry Flash-over test: In this test, the voltage is applied between the electrodes of the insulator and is gradually increased. The voltage at which the surrounding air breaks down is called the flash-over voltage. This voltage must be greater than the specified limit. Insulator must sustain the minimum voltage for one minutes.
2. 50 Cycle Wet Test: The test is conducted similar to the dry test but in addition to the applied voltage, the water is sprayed over the surface at an angle of 45°, resembling the raining condition. The insulator must be capable of withstanding the minimum standard voltage for 30 seconds under wet conditions. The wet test is applicable only to the outdoor insulators.

Other electrical tests include,

1. Power frequency withstand test: Normal power frequency voltage is continuously applied to the insulator. This caused dust particles to align on the surface causing leakage current. The flash-over is avoided. The voltage magnitude is twice the specified rated voltage. It is applied for 1 minute. There should not be flash-over or puncture.
2. Impulse voltage withstand test: In this test, standard impulse voltage surge is applied to the insulator. Such surges are caused due to the lightning in practice. The standard lighting impulse wave is of 1.2 μsec wave front and 50 μsec wave tail hence called 1.2/50 impulse wave. For this test, the generator developing the lightning voltage surges is used.

   The impulse voltage at very high frequency of several hundred thousand Hz is applied to the insulator and the spark over voltage is noted down. The impulse ratio is defined as,

$$Impulse\ ratio = \frac{Impulse\ spark\ over\ voltage}{50\ cycles\ per\ \sec\ spark\ over\ voltage}$$

   This ratio should be 1.4 for pin type while 1.3 for suspension type insulators.

3. Puncture voltage test: In this test, the insulator is suspended in the oil and certain minimum voltage is applied. This value in case of suspension insulator is 1.3 times the dry flash over voltage. The insulator should not puncture under this test.

Environment and Temporary Cycle Tests

In these tests the insulator is subjected to the alternate temperature cycles, sudden temperature changes, pollution and some other environmental stresses. Out of these tests, for extra high voltage insulators sudden temperature drop test, extremely low temperature test and pollution test are compulsory tests.

In temperature cycle test, the insulator is heated in water at 70°C for one hour and is then immediately cooled in water at 70°C for another hour. Such three cycles are repeated. Then the insulator is dried. After this test, the glaze of the insulator should not be damaged.

Corona and Radio interference test

When the voltage stress level increases beyond corona inspection level, corona discharge starts. The corona discharge means the violet glow, hissing noise and production of ozone gas around a line. This causes inductive interferences with neighbouring communication lines. By providing suitable voltage grading rings, smooth surface and higher size of conductors, corona discharge and radio interference can be eliminated for certain voltage range.

Other important tests

These test include,

1. Porosity test: This is also called destructive test. The insulator under test is broken into pieces and immersed in a 1% solution of dye in alcohol under a pressure of 140 kg/cm^2 for about a day. Then the samples are removed and inspected. The porosity is indicated by the deep penetration of the dye into it.
2. Proof of load test: All types of the insulators are assembled and a tensile load of 20% in excess of specified load is applied, for about one minute.
3. Galvanising test: In this test, galvanised metal parts of the insulator are tested for the strength of galvanization.
4. Corrosion test: The insulator is tested against the corrosion. In this test, insulator is suspended in a copper sulphate solution at 15.6°C for one minute. Then it is removed, dried, cleaned and again put it in the solution. The cycle is repeated for four times and there should not be any type of deposition on the metal. Out of these tests, proof load and corrosion are routine tests. For special type of insulators, some more tests may be performed as per the decision of supplier and the consumer,

Type test:

These are mechanical and electrical tests to prove the quality, material and mechanical properties.

Sample tests:

These are mechanical tests to prove the quality, material and mechanical properties.

Routine tests: These are performed on every insulator.

Introduction

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

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

Underground Cables

An **underground cable** *essentially consists of one or more conductors covered with suitable insulation and surrounded by a protecting cover.*

Although several types of cables are available, the type of cable to be used will depend upon the working voltage and service requirements. In general, a cable must fulfil the following necessary requirements:

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

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

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

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

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

Construction of Cables

Describe the general construction of an underground cable with a neat sketch.[8][Nov/Dec '12][May/June'16]

State the classification of cables and discuss their general construction.[8][Nov/Dec '12]

Fig. 4.1 shows the general construction of a 3-conductor cable. The various parts are :

(*i*) *Cores or Conductors.* A cable may have one or more than one core (conductor) depending upon the type of service for which it is intended. For instance, the 3-conductor cable shown in Fig. 4.1 is used for 3-phase service. The conductors are made of tinned copper or aluminium and are usually stranded in order to provide flexibility to the cable.

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

(*iii*) *Metallic sheath.* In order to protect the cable from moisture, gases or other damaging liquids (acids or alkalies) in the soil and atmosphere, a metallic sheath of lead or aluminium is provided over the insulation as shown in Fig. 4.10

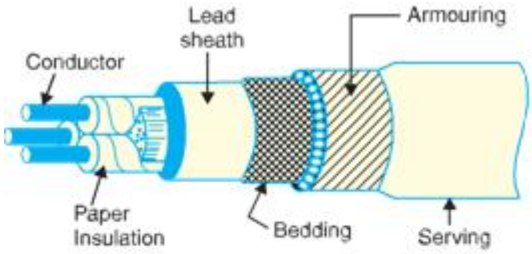


Fig 4.10 Construction of a Cable

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

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

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

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

Insulating Materials for Cables

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

(*i*) High insulation resistance to avoid leakage current.

(*ii*) High dielectric strength to avoid electrical breakdown of the cable.

(*iii*) High mechanical strength to withstand the mechanical handling of cables.

(*iv*) Non-hygroscopic *i.e.*, it should not absorb moisture from air or soil. The moisture tends to decrease the insulation resistance and hastens the breakdown of the cable. In case the insulating material is hygroscopic, it must be enclosed in a waterproof covering like lead sheath.

(*v*) Non-inflammable.

(*vi*) Low cost so as to make the underground system a viable proposition.

(*vii*) Unaffected by acids and alkalies to avoid any chemical action. No one insulating material possesses all the above mentioned properties. Therefore, the type of insulating material to be used depends upon the purpose for which the cable is required and the quality of insulation to be aimed at. The principal insulating materials used in cables are rubber, vulcanised India rubber, impregnated paper, varnished cambric and polyvinyl chloride.

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

2. Vulcanised India Rubber (*V.I.R.*). It is prepared by mixing pure rubber with mineral matter such as zine oxide, red lead etc., and 3 to 5% of sulphur. The compound so formed is

rolled into thin sheets and cut into strips. The rubber compound is then applied to the conductor and is heated to a temperature of about 150ºC. The whole process is called *vulcanisation* and the product obtained is known as vulcanised India rubber.
Vulcanised India rubber has greater mechanical strength, durability and wear resistant property than pure rubber. Its main drawback is that sulphur reacts very quickly with copper and for this reason, cables using *VIR* insulation have tinned copper conductor. The *VIR* insulation is generally used for low and moderate voltage cables.
3. Impregnated paper. It consists of chemically pulped paper made from wood chippings and impregnated with some compound such as paraffinic or napthenic material. This type of insulation has almost superseded the rubber insulation. It is because it has the advantages of low cost, low capacitance, high dielectric strength and high insulation resistance. The only disadvantage is that paper is hygroscopic and even if it is impregnated with suitable compound, it absorbs moisture and thus lowers the insulation resistance of the cable. For this reason, paper insulated cables are always provided with some protective covering and are never left unsealed. If it is required to be left unused on the site during laying, its ends are temporarily covered with wax or tar.

Since the paper insulated cables have the tendency to absorb moisture, they are used where the cable route has a few joints. For instance, they can be profitably used for distribution at low voltages in congested areas where the joints are generally provided only at the terminal apparatus. However, for smaller installations, where the lengths are small and joints are required at a number of places, *VIR* cables will be cheaper and durable than paper insulated cables.
4. Varnished cambric. It is a cotton cloth impregnated and coated with varnish. This type of insulation is also known as *empire tape*. The cambric is lapped on to the conductor in the form of a tape and its surfaces are coated with petroleum jelly compound to allow for the sliding of one turn over another as the cable is bent. As the varnished cambric is hygroscopic, therefore, such cables are always provided with metallic sheath. Its dielectric strength is about 4 kV/mm and permittivity is 2.5 to 3.8.
5. Polyvinyl chloride (*PVC*). This insulating material is a synthetic compound. It is obtained from the polymerisation of acetylene and is in the form of white powder. For obtaining this material as a cable insulation, it is compounded with certain materials known as plasticizers which are liquids with high boiling point. The plasticizer forms a gell and renders the material plastic over the desired range of temperature. Polyvinyl chloride has high insulation resistance, good dielectric strength and mechanical toughness over a wide range of temperatures. It is inert to oxygen and almost inert to many alkalies and acids. Therefore, this type of insulation is preferred over *VIR* in extreme enviormental conditions such as in cement factory or chemical factory. As the mechanical properties (*i.e.*, elasticity etc.) of *PVC* are not so good as those of rubber, therefore, *PVC* insulated cables are generally used for low and medium domestic lights and power installations.

Classification of Cables

Cables for underground service may be classified in two ways according to (*i*) the type of insulating
material used in their manufacture (*ii*) the voltage for which they are manufactured. However, the latter method of classification is generally preferred, according to which cables can be divided into the following groups :

(*i*) Low-tension (L.T.) cables — upto 1000 V
(*ii*) High-tension (H.T.) cables — upto 11,000 V
(*iii*) Super-tension (S.T.) cables — from 22 kV to 33 kV
(*iv*) Extra high-tension (E.H.T.) cables — from 33 kV to 66 kV

(*v*) Extra super voltage cables — beyond 132 kV

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

(*i*)single-core

(*ii*) two-core

(*iii*) three-core

(*iv*) four-core etc.

For a 3-phase service, either 3-single-core cables or three-core cable can be used depending upon the operating voltage and load demand.

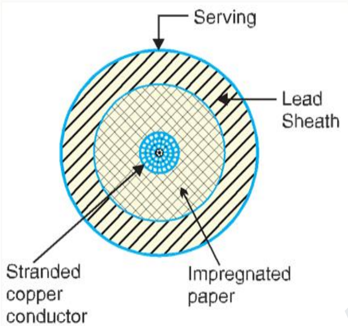


Fig 4.11

Fig. 4.11 shows the constructional details of a single-core low tension cable. The cable has ordinary construction because the stresses developed in the cable for low voltages (upto 6600 V) are generally small. It consists of one circular core of tinned stranded copper (or aluminium) insulated by layers of impregnated paper. The insulation is surrounded by a lead sheath which prevents the entry of moisture into the inner parts. In order to protect the lead sheath from corrosion, an overall serving of compounded fibrous material (jute etc.) is provided. Single-core cables are not usually armoured in order to avoid excessive sheath losses. The principal advantages of single-core cables are simple construction and availability of larger copper section.

Cables for 3-phase service

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

1. Belted cables — upto 11 kV

2. Screened cables — from 22 kV to 66 kV

3. Pressure cables — beyond 66 kV.

1. Belted cables. These cables are used for voltages upto 11kV but in extraordinary cases, their use may be extended upto 22kV. Fig. 4.12 shows the constructional details of a 3-core belted cable. The cores are insulated from each other by layers of impregnated paper. Another layer of impregnated paper tape, called *paper belt* is wound round the grouped insulated cores. The gap between the insulated cores is filled with fibrous insulating material (jute etc.) so as to give circular cross-section to the cable. The cores are generally stranded and may be of noncircular shape to make better use of available space. The belt is covered with lead sheath to protect the cable against ingress of moisture and mechanical injury. The lead sheath is covered with one or more layers of armouring with an outer serving (not shown in the figure). The belted type construction is suitable only for low and medium voltages as the electrostatic stresses developed in the cables for these voltages are more or less radial *i.e.*, across the insulation.

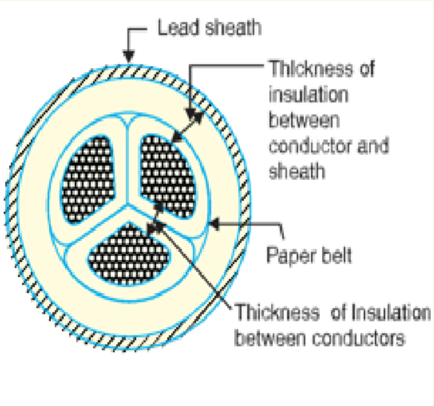


Fig 4.12

However, for high voltages (beyond 22 kV), the tangential stresses also become important. These stresses act along the layers of paper insulation. As the insulation resistance of paper is quite small along the layers, therefore, tangential stresses set up leakage current along the layers of paper insulation. The leakage current causes local heating, resulting in the risk of breakdown of insulation at any moment. In order to overcome this difficulty, *screened cables* are used where leakage currents are conducted to earth through metallic screens.

2. Screened cables. These cables are meant for use upto 33 kV, but in particular cases their use may be extended to operating voltages upto 66 kV. Two principal types of screened cables are H-type cables and S.L. type cables.

(*i*) *H-type cables.* This type of cable was first designed by H. Hochstadter and hence the name.

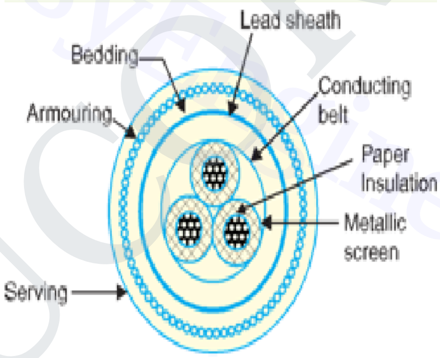


Fig 4.13

Fig. 4.13 shows the constructional details of a typical 3-core, *H*-type cable. Each core is insulated by layers of impregnated paper. The insulation on each core is covered with a metallic screen which usually consists of a perforated aluminium foil. The cores are laid in such a way that metallic screens make contact with one another. An additional conducting belt (copper woven fabric tape) is wrapped round the three cores. The cable has no insulating belt but lead sheath, bedding, armouring and serving follow as usual. It is easy to see that each core screen is in electrical contact with the conducting belt and the lead sheath. As all the four screens (3 core screens and one conducting belt) and the lead sheath are at †earth potential, therefore, the electrical stresses are purely radial and consequently dielectric losses are reduced.

Two principal advantages are claimed for *H*-type cables.

Firstly, the perforations in the metallic screens assist in the complete impregnation of the cable with the compound and thus the possibility of air pockets or voids (vacuous spaces) in the dielectric is eliminated. The voids if present tend to reduce the breakdown strength of the cable and may cause considerable damage to the paper insulation.

Secondly, the metallic screens increase the heat dissipating power of the cable.

(*ii*) *S.L. type cables.* Fig. 4.14 shows the constructional details of a 3-core *S.L. (separate lead) type cable.

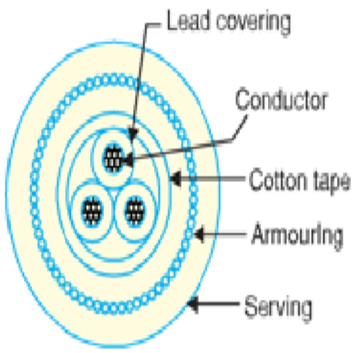


Fig 4.14

It is basically *H*-type cable but the screen round each core insulation is covered by its own lead sheath. There is no overall lead sheath but only armouring and serving are provided. The S.L. type cables have two main advantages over *H*-type cables. Firstly, the separate sheaths minimise the possibility of core-to-core breakdown. Secondly, bending of cables becomes easy due to the elimination of overall lead sheath. However, the disadvantage is that the three lead sheaths of S.L. cable are much thinner than the single sheath of *H*-cable and, therefore, call for greater care in manufacture.

Limitations of solid type cables.

All the cables of above construction are referred to as solid type cables because solid insulation is used and no gas or oil circulates in the cable sheath. The voltage limit for solid type cables is 66 kV due to the following reasons :

(*a*) As a solid cable carries the load, its conductor temperature increases and the cable com-pound (*i.e.*, insulating compound over paper) expands. This action stretches the lead sheath which may be damaged.

(*b*) When the load on the cable decreases, the conductor cools and a partial vacuum is formed within the cable sheath. If the pinholes are present in the lead sheath, moist air may be drawn into the cable. The moisture reduces the dielectric strength of insulation and may eventually cause the breakdown of the cable.

(*c*) In practice, †voids are always present in the insulation of a cable. Modern techniques of manufacturing have resulted in void free cables. However, under operating conditions, the voids are formed as a result of the differential expansion and contraction of the sheath and impregnated compound. The breakdown strength of voids is considerably less than that of the insulation. If the void is small enough, the electrostatic stress across it may cause its breakdown. The voids nearest to the conductor are the first to break down, the chemical and thermal effects of ionisation causing permanent damage to the paper insulation.

3. Pressure cables For voltages beyond 66 kV, solid type cables are unreliable because there is a danger of breakdown of insulation due to the presence of voids. When the operating voltages are greater than 66 kV, *pressure cables* are used. In such cables, voids are eliminated by increasing the pressure of compound and for this reason they are called pressure cables. Two types of pressure cables *viz* oil-filled cables and gas pressure cables are commonly used.

(*i*) *Oil-filled cables.* In such types of cables, channels or ducts are provided in the cable for oil circulation. The oil under pressure (it is the same oil used for impregnation) is kept constantly supplied to the channel by means of external reservoirs placed at suitable distances (say 500 m) along the route of the cable. Oil under pressure compresses the layers of paper insulation and is forced into any voids that may have formed between the layers. Due to the elimination of voids, oil-filled cables can be used for higher voltages, the range being from 66 kV upto 230 kV. Oil-filled cables are of three types *viz.*, single-core conductor channel, single-core sheath channel and three-core filler-space channels.

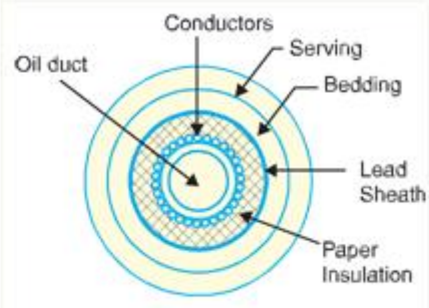


Fig 4.15 Single-core conductor channel Oil filled cable

Fig. 4.15 shows the constructional details of a single-core conductor channel, oil filled cable. The oil channel is formed at the centre by stranding the conductor wire around a hollow cylindrical steel spiral tape. The oil under pressure is supplied to the channel by means of external reservoir. As the channel is made of spiral steel tape, it allows the oil to percolate between copper strands to the wrapped insulation. The oil pressure compresses the layers of paper insulation and prevents the possibility of void formation. The system is so designed that when the oil gets expanded due to increase in cable temperature, the extra oil collects in the reservoir. However, when the cable temperature falls during light load conditions, the oil from the reservoir flows to the channel. The disadvantage of this type of cable is that the channel is at the middle of the cable and is at full voltage *w.r.t.* earth, so that a very complicated system of joints is necessary.

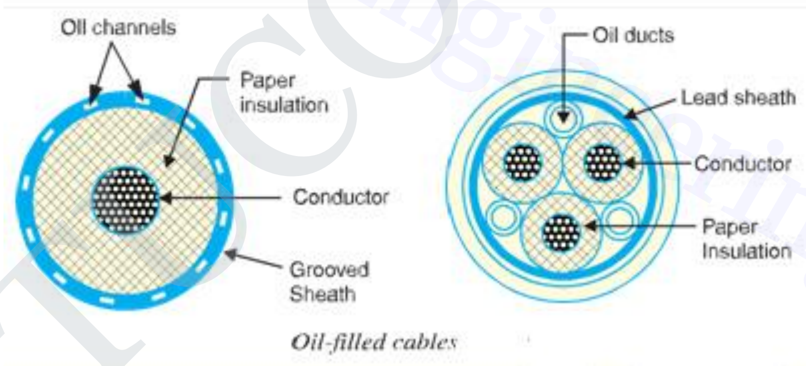


Fig 4.16 Fig 4.17

Fig. 4.16 shows the constructional details of a single core sheath channel oil-filled cable. In this type of cable, the conductor is solid similar to that of solid cable and is paper insulated. However, oil ducts are provided in the metallic sheath as shown. In the 3-core oil-filler cable shown in Fig. 4.17, the oil ducts are located in the filler spaces. These channels are composed of perforated metal-ribbon tubing and are at earth potential. The oil-filled cables have three principal advantages. Firstly, formation of voids and ionisation are avoided. Secondly, allowable temperature range and dielectric strength are increased. Thirdly, if there is leakage, the defect in the lead sheath is at once indicated and the possibility of earth faults is decreased. However, their major disadvantages are the high initial cost and complicated system of laying.

(ii) *Gas pressure cables.* The voltage required to set up ionisation inside a void increases as the pressure is increased. Therefore, if ordinary cable is subjected to a sufficiently high pressure, the ionisation can be altogether eliminated. At the same time, the increased pressure produces radial compression which tends to close any voids. This is the underlying principle of gas pressure cables.

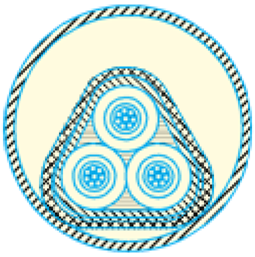


Fig 4.18

Fig. 4.18 shows the section of external pressure cable designed by Hochstadter, Vogal and Bowden. The construction of the cable is similar to that of an ordinary solid type except that it is of triangular shape and thickness of lead sheath is 75% that of solid cable. The triangular section reduces the weight and gives low thermal resistance but the main reason for triangular shape is that the lead sheath acts as a pressure membrane. The sheath is protected by a thin metal tape. The cable is laid in a gas-tight steel pipe. The pipe is filled with dry nitrogen gas at 12 to 15 atmospheres. The gas pressure produces radial compression and closes the voids that may have formed between the layers of paper insulation. Such cables can carry more load current and operate at higher voltages than a normal cable. Moreover, maintenance cost is small and the nitrogen gas helps in quenching any flame. However, it has the disadvantage that the overall cost is very high.

Laying of Underground Cables

The reliability of underground cable network depends to a considerable extent upon the proper laying and attachment of fittings *i.e.*, cable end boxes, joints, branch connectors etc. There are three main methods of laying underground cables *viz.*, direct laying, draw-in system and the solid system.

1. Direct laying. This method of laying underground cables is simple and cheap and is much favoured in modern practice. In this method, a trench of about 1·5 metres deep and 45 cm wide is dug. The trench is covered with a layer of fine sand (of about 10 cm thickness) and the cable is laid over this sand bed. The sand prevents the entry of moisture from the ground and thus protects the cable from decay.

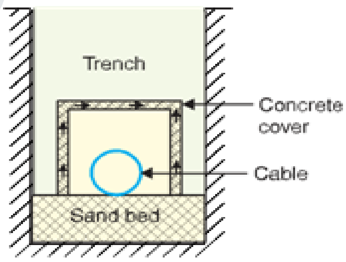


Fig 4.19

After the cable has been laid in the trench, it is covered with another layer of sand of about 10 cm thickness. The trench is then covered with bricks and other materials in order to protect the cable from mechanical injury. When more than one cable is to be laid in the same trench, a horizontal or vertical inter axial spacing of at least 30 cm is provided in order to reduce the effect of mutual heating and also to ensure that a fault occurring on one cable does not damage the adjacent cable. Cables to be laid in this way must have serving of bituminised paper and hessian tape so as to provide protection against corrosion and electrolysis.

Advantages

(*i*) It is a simple and less costly method.

(*ii*) It gives the best conditions for dissipating the heat generated in the cables.

(iii) It is a clean and safe method as the cable is invisible and free from external disturbances.

Disadvantages

(i) The extension of load is possible only by a completely new excavation which may cost as much as the original work.

(ii) The alterations in the cable netwok cannot be made easily.

(iii) The maintenance cost is very high.

(iv) Localisation of fault is difficult.

(v) It cannot be used in congested areas where excavation is expensive and inconvenient.

This method of laying cables is used in open areas where excavation can be done conveniently and at low cost.

2. Draw-in system. In this method, conduit or duct of glazed stone or cast iron or concrete are laid in the ground with manholes at suitable positions along the cable route. The cables are then pulled into position from manholes.

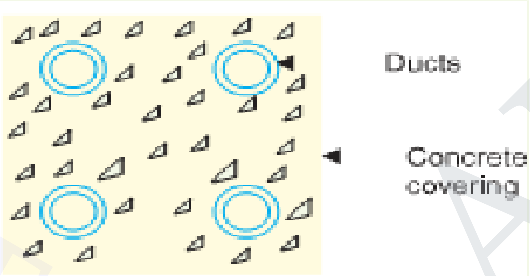


Fig 4.20

Fig. 4.20 shows section through four-way underground duct line. Three of the ducts carry transmission cables and the fourth duct carries relay protection connection, pilot wires. Care must be taken that where the duct line changes direction ; depths, dips and offsets be made with a very long radius or it will be difficult to pull a large cable between the manholes. The distance between the manholes should not be too long so as to simplify the pulling in of the cables. The cables to be laid in this way need not be armoured but must be provided with serving of hessian and jute in order to protect them when being pulled into the ducts.

Advantages

(i) Repairs, alterations or additions to the cable network can be made without opening the ground.

(ii) As the cables are not armoured, therefore, joints become simpler and maintenance cost is reduced considerably.

(iii) There are very less chances of fault occurrence due to strong mechanical protection provided by the system.

Disadvantages

(i) The initial cost is very high.

(ii) The current carrying capacity of the cables is reduced due to the close grouping of cables and unfavourable conditions for dissipation of heat. This method of cable laying is suitable for congested areas where excavation is expensive and inconvenient, for once the conduits have been laid, repairs or alterations can be made without opening the ground. This method is generally used for short length cable routes such as in workshops, road crossings where frequent digging is costlier or impossible.

3. Solid system. In this method of laying, the cable is laid in open pipes or troughs dug out in earth along the cable route. The troughing is of cast iron, stoneware, asphalt or treated wood. After the cable is laid in position, the troughing is filled with a bituminous or asphaltic compound and covered over. Cables laid in this manner are usually plain lead covered because troughing affords good mechanical protection.

Disadvantages

(i) It is more expensive than direct laid system.
(ii) It requires skilled labour and favourable weather conditions.
(iii) Due to poor heat dissipation facilities, the current carrying capacity of the cable is reduced.

In view of these disadvantages, this method of laying underground cables is rarely used now-a-days.

Capacitance of Single-Core Cable

Derive the expression for the insulation resistance, capacitance, electric stress and dielectric loss of a single core cable.[16][Nov/Dec'10]

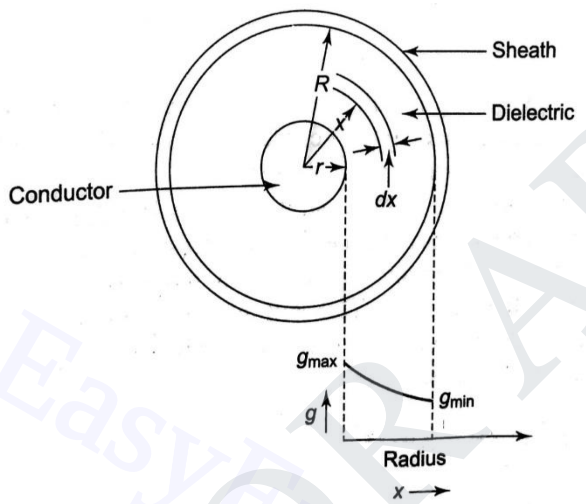


Fig 4.21 Electric stress in a single-core cable

In a single-core cable, the conductor is surrounded by the dielectric material with an outer metallic sheath as shown in Fig 4.21. The dielectric is stressed to about $1/5^{th}$ of the breakdown value. It is easy to visualize that in this type of construction; the electric field is confined to the space between the conductor and the sheath, and has circular symmetry.

Let r be the radius of the conductor, R the inner radius of the sheath, k the permittivity of the dielectric, q the charge in c/m of axial length, V the potential of the conductor with respect to the sheath and g the electric field intensity (gradient) at a distance x from the centre of the conductor within the dielectric material.

$$g = \frac{q}{2\pi kx} V/m \qquad (1)$$

Now

$$V = \int_r^R g.dx = \int_r^R \frac{q}{2\pi kx} dx = \frac{q}{2\pi k} \ln \frac{R}{r} \qquad (2)$$

And the capacitance between core and sheath is

$$c = \frac{2\pi k_o k_r}{\ln R/r} F/m \qquad (3)$$

For equations (1) and (2)

$$g = \frac{V}{x \ln R/r} \qquad (4)$$

The maximum electric stress in the cable dielectric will occur at the surface of the conductor, i.e at x_{min} = r and is given by

$$g_{max} = \frac{V}{r \ln R / r} \quad (5)$$

And the gradient is minimum at x_{max} = R, i.e

$$g_{min} = \frac{V}{R \ln R / r} \quad (6)$$

And $\frac{g_{max}}{g_{min}} = \frac{R}{r}$ (7)

In order to keep a fixed overall size of the cable (R) for given V, there is a particular r which minimizes gmax, i.e. we have to maximize r ln R/r, which occurs when ln R/r =1 or R/r = e = 2.71882.

Since the insulation can only be stressed to its limiting operating voltage gradient at the conductor surface, and is understressed as we move away from the conductor, it is advantageous to try to have a more uniform stress distribution across the dielectric. This will minimize the quantity of insulation (dielectric) needed for a given r and operating cable voltage. This technique is known as grading of cables.

GRADING OF CABLES

Explain the following with respect to cables. (i) capacitance grading (ii) Intersheath grading. [16][May/June'13]

As stated above, in a cable with single homogeneous layer of insulation, much of the dielectric is being operated at a very much less than the maximum allowable stress. The grading of cables means the subdivision of a cable in such a way that (g_{max}~g_{min}) is minimized, with the result that less dielectric is required and overall dia (2R) is reduced. It must mentioned here that there is little application of methods of grading because of constructional reasons. However, we discuss them briefly here to illustrate important basic principles.

Capacitive Grading

Here we use two or more insulating materials with those having the larger permittivities nearer to the conductor.

We know

$$g = \frac{q}{2\pi k_o k_r x}$$

If the permittivity k_r could be varied continuously at different radii x in such a fashion that

$$k_r \frac{1}{x} = \frac{m}{x} (say)$$

then for any x

$$g = \frac{q}{2\pi k_o m} = \text{a constant}$$

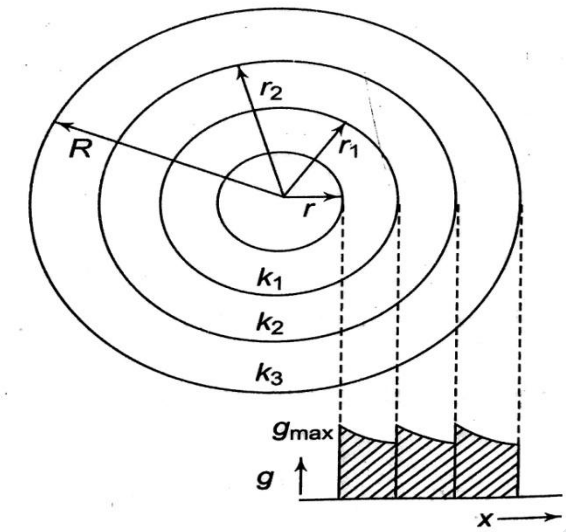


Fig 4.22 Capacitive grading and voltage distribution

An infinite gradation in k is, however, impossible, but practically two or three dielectrics with different values of k, may be used.

Let there be three layers of dielectric of outer radii r_1, r_2 and R and of dielectric strength k_1, k_2 and k_3 as shown in Fig 4.22.

Let the dielectric strengths of the three materials to G_1, G_2 and G_3 respectively with the same factor of safety.

Gradient at x = r is

$$\frac{q}{2\pi k_1 r} = \frac{G_1}{f}$$

Gradient at x = r_1 is

$$\frac{q}{2\pi k_2 r_1} = \frac{G_2}{f}$$

Gradient at x = r_2 is

$$\frac{q}{2\pi k_3 r_2} = \frac{G_3}{f}$$

Where f = factor is safety.

From these three relations we get

$$q = 2\pi k_1 r \frac{G_1}{f} = 2\pi k_2 r_1 \frac{G_2}{f} = 2\pi k_3 r_2 \frac{G_3}{f}$$

Or

$$k_1 r G_1 = k_2 r_1 G_2 = k_3 r_2 G_3$$

Since $r<r_1<r_2$

$k_1 G_1 > k_2 G_2 > k_3 G_3$ (8)

This clearly shows that the material with the highest product of dielectric strength and permittivity should be placed nearest to the conductor, and other layers should be in the descending order of the product of dielectric strength and permittivity.

The second alternative is to subject all the materials to the same maximum stress. Then

$$g_{\max} = \frac{q}{2\pi k_1 r} = \frac{q}{2\pi k_2 r_1} = \frac{q}{2\pi k_3 r_2}$$

∴ $k_1 r = k_2 r_1 = k_3 r_2$

∴ $k_1 > k_2 > k_3$

The dielectric material with highest permittivity should be kept nearest to the conductor and so on.

Total operating voltage of the cable if g_{max} is the working stress (ref Fig 4.21)

$$V = g_{max} r \ln \frac{r_1}{r} + g_{max} r_1 \ln \frac{r_2}{r_1} + g_{max} r_2 \ln \frac{R}{r_2}$$

$$= g_{max}[r \ln \frac{r_1}{r} + r_1 \ln \frac{r_2}{r_1} + r_2 \ln \frac{R}{r_2}] V \qquad (9)$$

Intersheath Grading

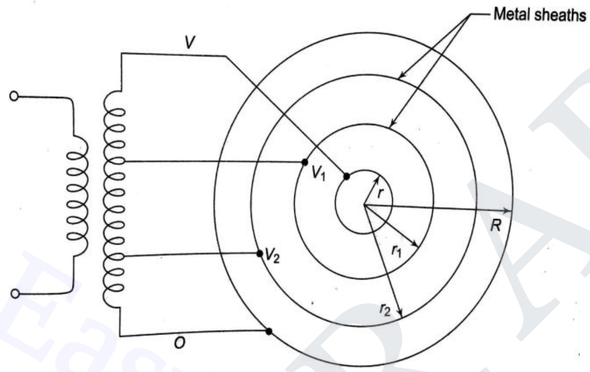


Fig 4.23 Intersheath grading

Here a single insulating material, i.e homogeneous dielectric is separated into two or more layers by thin metallic intersheaths maintained at the appropriate potentials by being connected to tappings on the winding of an auxiliary transformer supplying the cable as shown in Fig 4.23.

There is thus a definite potential difference between the inner and outer radii of each sheath. Each sheath can, therefore, be considered as a homogenous single-core cable. Let the various radii be r, r_1, r_2.......,R as before. We can then write.

$$g_{max1} = \frac{V_1}{r \ln r_1 / r}, g_{max2} = \frac{V_2}{r_1 \ln r_2 / r_1} \text{ and so on.}$$

But the condition of a homogeneous dielectric requires

$$g_{max1} = g_{max2} = g_{max3} = \ldots$$

Or

$$\frac{V_1}{r \ln r_1 / r} = \frac{V_2}{r_1 \ln r_2 / r_1} = \ldots$$

We also have the condition (since all voltages are in phase)

$$V = V_1 + V_2 + V_3 + \ldots$$

If all the n layers have the same thickness t

$$\frac{V_1}{r \ln \frac{r+t}{r}} = \frac{V_2}{(r+t) \ln \frac{r+2t}{r+t}} = \ldots = \frac{V}{M} \qquad (10)$$

Where

$$M = r \ln \ln \frac{r+t}{r} + (r+t) \ln \frac{r+2t}{r+t} + \ldots + [r+(n-1)t] \ln \frac{r+nt}{r+(n-1)t}$$

∴ Peak voltage across the m^{th} layer for uniform g_{max} is

$$\therefore V_m = \frac{V}{M}[r+(m-1)t]\ln\frac{r+mt}{r+(m-1)t} \qquad (11)$$

Now let us consider a cable with one intersheath only. Let r and R be radii of core and outside of dielectric as earlier. Let r_1 be the radius of the intersheath as shown in Fig 4.24.

$$g_{max} = \frac{V_1}{r\ln r_1/r} = \frac{V_2}{r_1 \ln R/r_1}$$

$$V_2 = V - V_1$$

$$\therefore g_{max} r_1 \ln\frac{R}{r_1} = V - g_{max} r \ln\frac{r_1}{r}$$

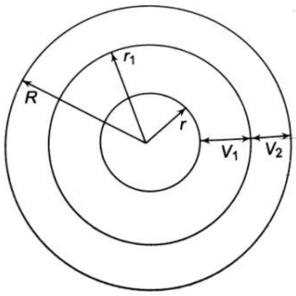


Fig 4.24 one intersheath cable

$$\therefore g_{max} = \frac{V}{r_1 \ln\frac{R}{r_1} + r\ln\frac{r_1}{r}}$$

To find the optimum placing of an intersheath,

$$\frac{dg_{max}}{dr} = 0$$

Which gives

$$\frac{r_1}{r}\ln\frac{r_1}{r} = 1$$

Solving,

$$r_1 = 1.76r$$

$\therefore$ g_{max} for optimum $r_1 = \frac{V}{1.33r}$

For a nonintersheath cable, the corresponding optimal condition is

$$g^1_{max} = \frac{V}{r\ln R/r} = \frac{V}{r\ln e} = \frac{V}{r}$$

Hence for the same overall dimensions, the use of single intersheath has raised the maximum voltage the cable can withstand in the ratio.

$$g^1_{max} / g_{max} = \frac{V/r}{V/1.33r} = 1.33, \text{ an increase of } 33\%$$

The grading theory explained above is only of theoretical interest, as in practice none of the two methods are useful. Capacitance grading is difficult due to the nonavailability of materials in the different permittivities. Also with time the permittivities of the materials may change resulting in nonuniform potential gradient distribution, and may eventually lead to dielectric failure. In the case of intersheath grading, there is a possibility of damage of thin intersheath during the laying operation. The charging currents carried by the intersheaths may cause overheating. For these reasons, modern practice is to avoid grading and use instead the oil-filled and gas-filled cables.

POWER FACTOR AND HEATING OF CABLES

For single-core cable the insulation resistance is given by

$$R_i = \frac{\rho}{2\pi l} \ln \frac{R}{r} \Omega \qquad (12)$$

Here ρ is the specific resistance of the material, and l length of the cable. Assuming ρ to remain constant, the impressed voltage V will send a current (in phase with V) through the insulation.

Capacitive current drawn from the supply $= \omega CV$

Where C is the Cable capacitance.

The charging current leads V by 90°. The phasor diagram is shown in Fig 4.25. the resultant current I leads V by ∅(approx 90°) where cosΦ gives the power factor of the cable. But

$$\cos\phi = \cos(\pi/2 - \delta) = \sin\delta = \delta \ (\because \delta \text{ is very small}) = \tan\ \delta$$

The cable power factor can be expressed as

$$pf = \delta = \frac{V/R_i}{\omega CV} = \frac{1}{\omega CR_i} \qquad (13)$$

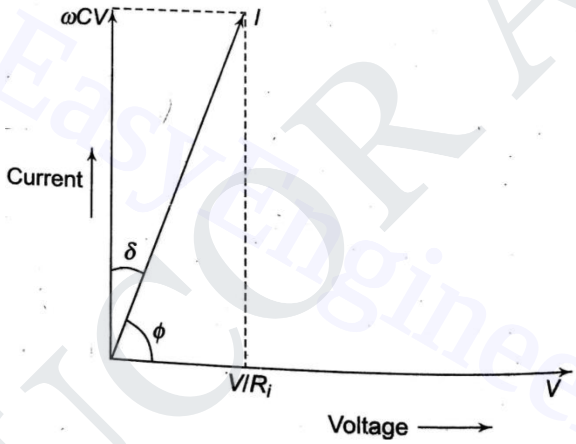


Fig 4.25 The phasor diagram

Dielectric Loss

The breakdown of a cable may be owing to thermal or mechanical and electrical causes. Thermal breakdown is due to a rise in temperature owing to the losses in the cables, i.e core loss (I^2R), dielectric loss and sheath loss. These losses cause heating of cables.

Dielectric loss is caused by dielectric absorption or polarization. It is small for voltage upto 33kV,but for higher voltages has an increasingly important effect on the current rating. The cable is a sort of a capacitor, the phasor diagram is given in Fig 4.25, the equivalent circuit being a parallel combination of leakage resistance R_i and a capacitance C. The loss in the dielectric is due to the loss in the equivalent leakage resistance.

Dielectric loss $= VI\cos\delta = EI\sin\phi = EI\delta$

But $I = V\omega C$

∴ Dielectric loss $= V^2\omega C\delta = 2\pi fCV^2\delta$ per phase at working voltage V (14)

It is sufficient to assume that the loss occurs at conductor surface, and has to flow through the whole thermal resistance. The effect is to reduce the rated current of a 33kV cable by about 1% and of a 400kV cable by about 15%.

Sheath loss

When single core cables are used for AC transmission, the current flowing through the core generates pulsating magnetic field which, linking the sheath, induces currents in it resulting in sheath losses. These are normally negligible as they are about 2% of the core losses.

Ionization

Power factor, and hence the dielectric loss, rises very steeply when ionization occurs. If voids are present due to imperfect impregnation, or as a result of the successive expansions and contractions which occur during a heating cycle, then discharges can take place. The effect of this ionization is a chemical action resulting in a gradual breakdown of the dielectric.

Stability

The term stability is used to denote the characteristic by which a cable will retain its freedom from ionization during worst conditions. Even if the cable is initially void-free (i.e manufacturing is perfect), voids may be formed later when the heating cycle has repeated many times. The presence of voids with subsequent ionization is one of the chief causes of the deterioration of a cable dielectric.

CAPACITANCE OF 3-CORE BELTED CABLE

The expression of capacitance Eq.(3) is valid for circular conductor 3-core H-type cables,in which each core in separately screened or sheathed. A simple circuit of the belted cable is shown in the Fig 4.26. Since the conductor section is normally not circular, and conductors are not grounded by homogeneous insulation of known permittivity, the capacitances C_c between cores and C_s between a core and sheath, cannot be easily calculated and are generally obtained by measurement.

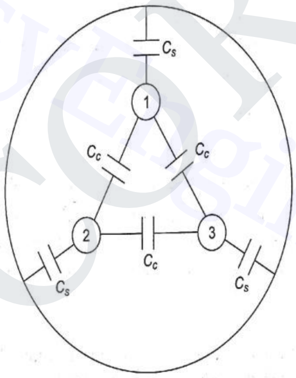


Fig 4.26 Capacitances between cores and to sheath of a 3-core belted cable

The effective capacitances of each core to be earthed neutral is $C = (C_s+3C_c)$ as shown in Fig 4.27. To find C_s and C_c, two measurements are required.

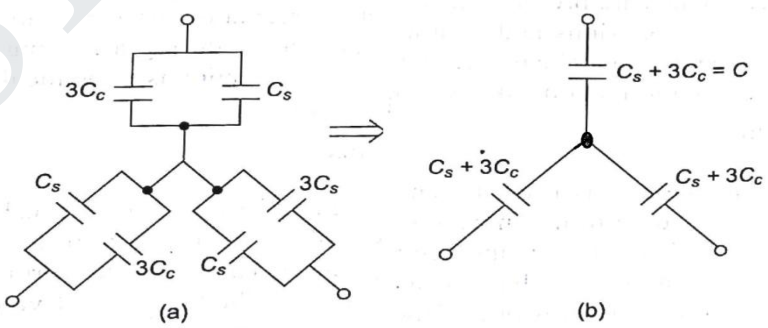


Fig 4.27 Equivalent capacitance of a 3-core cable

(i) The capacitance between the three cores bunched together, and the sheath. Let this be C_a given by $C_a=3C_s$ as shown in Fig 4.28.

(ii) The capacitance between any two cores bunched with sheath and the remaining core. Let this be C_b given in Fig 4.29.

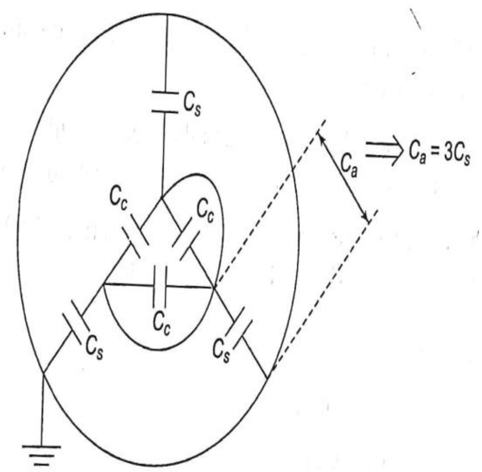


Fig 4.28 Capacitance calculation between core and sheath (C_s)

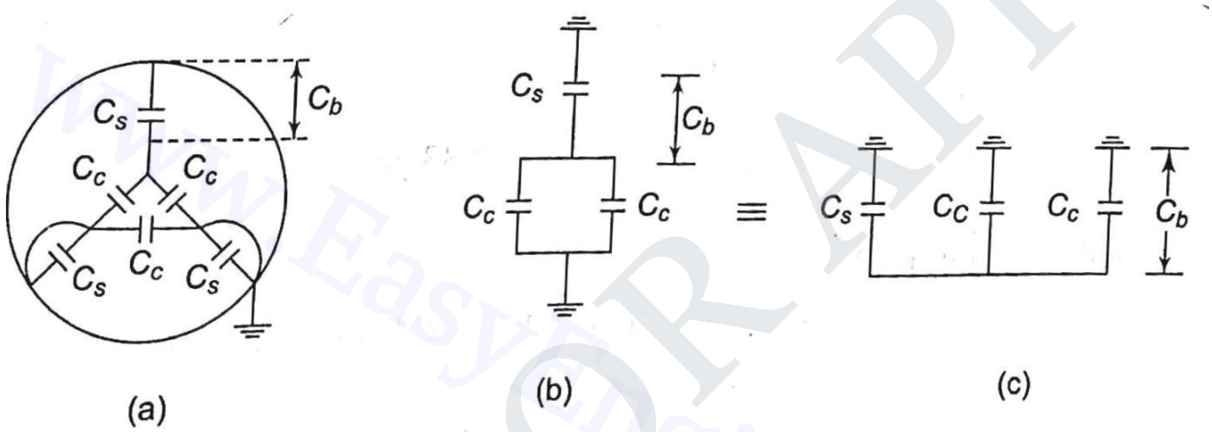


Fig 4.29 Capacitance calculation between core (C_c)

From these two measurements

$$C_s = \frac{C_a}{3} \; and$$

$$C_c = \frac{1}{2}(C_b - C_s) = \frac{1}{2}[C_b - \frac{C_a}{3}]$$

From these values, the effective capacitance to neutral is:

$$C = C_s + 3C_c$$

$$= \frac{C_a}{3} + \frac{3}{2}(C_b - \frac{C_a}{3})$$

$$\Rightarrow \frac{C_a}{3} + \frac{3C_b}{2} - \frac{C_a}{2} \Rightarrow \frac{3C_b}{2} - \frac{C_a}{6} = \frac{9C_b - C_a}{6}$$

D.C. CABLES

The losses in a DC cable are less than those with AC because, for a DC cable (1) there is no skin effect, (2) dielectric loss is small, since it is only due to leakage current, and (3) sheath losses are small as they are only due to leakage and ripple currents so that cross-bonding (similar to transposition in an overhead line case) equipment is not required. Further, there is no continuous charging current so that shunt compensation (reactors at the supply and load end of the cable) is not required. Due to these factors, the current carrying capacity is increased for DC by about 15% so that more power can be transmitted. Dc are now available upto ±600kV.

Joints and Terminations

The maximum length between joints is determined by the size of the reel or drum; for most cable circuits several lengths must be joined. At high voltages the design of the joint is complex and critical, especially as the splice must be applied by hand in situ and hence does not possess the electric strength of the cable insulation because of the presence of moisture. Both from an electrical and thermal standpoint, the joint represents a crucial part of a cable system.

TWO MARKS

1. Define grading of cables.[Nov/Dec '12][Nov/Dec'15]
   The process of obtaining uniform distribution of stress in the insulation of cables is called grading of cables.
2. Mention the insulating materials used in insulators.[May/June '13]
   i. Porcelain
   ii. Glass
   iii. Synthetic resin
   iv. steatite
3. Mention any 4 insulating materials for cables.[May/June'13]
   i. Poly vinyl chloride(PVC)
   ii. Paper
   iii. Cross linked polythene
   iv. Vulcanised india rubber (VIR)
4. What are the methods of improving string efficiency?[May/June'13][Nov/Dec'15]
   i. By using longer cross arms to reduce the ratio of shunt capacitance to self capacitance
   ii. By grading the insulators
   iii. By using a guard ring
5. How does guard ring improve string efficiency?. [Nov/Dec '13]
   The use of guard ring increases the capacitance between the metal plate of insulator and the line. These capacitors are greater for the lower units. Due to this the voltage across these units is reduced. Hence uniform voltage distribution can be obtained which improves the string efficiency.
6. Give the relation for insulation resistance of a cable. [Nov/Dec '13]
   The insulation resistance of a cable is given by,
   $$R_i = \frac{\rho}{2\pi l}\ln\frac{D}{d}$$
   d = Diameter of core
   D = Diameter of sheath
   l = Length of cable
   ρ = Resistivity of the insulating material
7. Why loss angle of a cable should be very small?[April/May'11]
   The dielectric loss in a cable is given by,
   $W=V^2\omega\tan\delta$ where δ = Loss angle
   Smaller the loss angle δ, smaller are the dielectric losses. Hence the loss angle of cable should be very small.
8. What are the causes of failure of insulators?[April/May'11]
   i. Due to lightning strokes
   ii. Due to mechanical stresses

iii. Due to cracking of insulating material
iv. Due to porosity in the insulating material
v. Due to defective insulating material
vi. Improper glazing on the insulator surface due to which moisture sticks on the surface causing flashovers.
vii. Due to overheating caused by flashovers
viii. Due to short circuits.

9. What are the methods of grading of cables?[Nov/Dec'11]
   i. Intersheath grading
   ii. Capacitance grading
10. Define string efficiency.[Nov/Dec'10][Nov/Dec'15][May/June'16]

    The ratio of voltage across the whole string to the product of number of discs and the voltage across the disc nearest to the conductor is known as string efficiency.
11. What is the main purpose of armouring? [April/May '15]

    Armouring is a layer consisting of galvanized steel wires which provide protection to the cable from the mechanical injury.
12. What are the tests performed on the insulators?[May/June'16]
    i. Mechanical tests
    ii. Electrical insulation tests
    iii. Environmental tests
    iv. Temporary cycle tests
    v. Corona and radio interference tests
13. Classify the cables used for three phase service.[May/June'16]

    1. Belted cables — upto 11 kV
    2. Screened cables — from 22 kV to 66 kV
    3. Pressure cables — beyond 66 kV.
14. What are the modern practices adopted to avoiding grading of cables?[May/June'16]
    - Use of intersheath for grading
    - Capacitance grading
15. What is dielectric stress?[April/May'14]

    The insulation of a cable is subjected to an electrostatic force under operating condition which is called dielectric cable.
16. What is shackle insulator?[April/May'14]

    The insulator used at the dead end of the aerial wire of service connection to a house or a factory to reduce the excessive tension is called shackle insulator. It is also used if distribution line changes its angle.
17. What are the properties of insulators?[Nov/Dec'10]
    i. High mechanical strength
    ii. High insulation resistance
    iii. High relative permittivity
    iv. Should not be affected by temperature changes
    v. It should be non porous
    vi. It should be flexible
    vii. It should be non-inflammable

18. Why the potential distribution across the string of insulators is not uniform?[Nov/Dec'06]

    Due to different shunt capacitors, the charging currents through them are different. Hence the potential distribution across the string of insulators is not uniform.

19. What is the economical core diameter to give minimum value of maximum stress?

    The core diameter must be ½.718 times the sheath diameter D so as to give the minimum value of the maximum stress

20. What is bedding?

The metallic sheath in a cable is covered by a layer called bedding which fibrous material like jute cloth which protects the armouring from the atmospheric conditions.

UNIT III

Mechanical design of transmission line – sag and tension calculations for different weather conditions, Tower spotting, Types of towers, Substation Layout (AIS, GIS), Methods of grounding.

SAG AND TENSION CALCULATIONS FOR DIFFERENT WEATHER CONDITIONS

While erecting an overhead line, it is very important that conductors are under safe tension. If the conductors are too much stretched between supports in a bid to save conductor material, the stress in the conductor may reach unsafe value and in certain cases the conductor may break due to excessive tension. In order to permit safe tension in the conductors, they are not fully stretched but are allowed to have a dip or sag.

The difference in level between points of supports and the lowest point on the conductor is called ***sag.***

Fig. 1 (*i*) shows a conductor suspended between two equilevel supports *A* and *B*. The conductor is not fully stretched but is allowed to have a dip. The lowest point on the conductor is *O* and the sag is *S*. The following points may be noted:

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

(*ii*) The tension at any point on the conductor acts tangentially. Thus tension T_O at the lowest point *O* acts horizontally as shown in Fig. 1 (*ii*).

(*iii*) The horizontal component of tension is constant throughout the length of the wire.

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

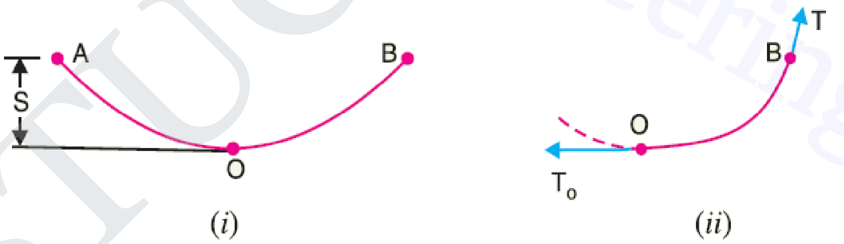


Fig. 1

Conductor sag and tension.

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

Calculation of Sag

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

(*i*) When supports are at equal levels. Considera conductor between two equilevel supports *A* and *B* with *O* as the lowest point as shown in Fig.2 It can be proved that lowest point will be at the mid-span.

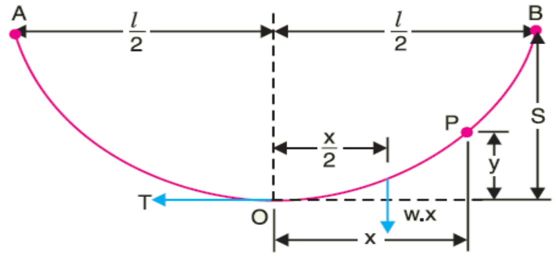


Fig.2

Let

l = Length of span
w = Weight per unit length of conductor
T = Tension in the conductor.

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

(***a***) The weight $w_{ax}$of conductor acting at a distance *x*/2 from *O*.
(***b***) The tension *T* acting at *O*.

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

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

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

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

$$x = l/2 \,\&\, y = S$$

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

(*ii*) When supports are at unequal levels. In hilly areas, we generally come across conductorssuspended between supports at unequal levels. Fig. 3 shows a conductor suspendedbetween two supports *A* and *B* which are at different levels. The lowest point on the conductoris *O*.

Let

l = Span length
h = Difference in levels between two supports
x_1 = Distance of support at lower level (*i.e.*, *A*) from *O*

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

T = Tension in the conductor

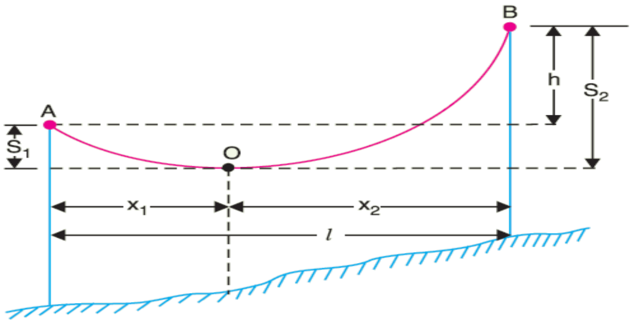


Fig 3

If w is the weight per unit length of the conductor, then,

$$\text{Sag } S_1 = \frac{wx_1^2}{2T}$$

$$\text{Sag } S_2 = \frac{wx_2^2}{2T}$$

Also $$x_1 + x_2 = l \qquad (1)$$

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

$$\therefore S_2 - S_1 = \frac{wl}{2T}(x_2 - x_1) \qquad \because (x_1 + x_2) = l$$

But $S_2 - S_1 = h$

$$\therefore h = \frac{wl}{2T}(x_2 - x_1)$$

Or $$(x_2 - x_1) = \frac{2Th}{wl} \qquad (2)$$

Solving equations (1) and (2), we get,

$$x_1 = \frac{l}{2} - \frac{Th}{wl}$$

$$x_2 = \frac{l}{2} + \frac{Th}{wl}$$

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

EFFECT OF WIND AND ICE LOADING. The above formulae for sag are true only in still air and at normal temperature when the conductor is acted by its weight only. However, in actual practice, a conductor may have ice coating and simultaneously subjected to wind pressure. The weight of ice acts vertically downwards *i.e.*, in the same direction as the weight of conductor. The force due to the wind is assumed to act horizontally *i.e.*, at right angle to the projected surface of the conductor. Hence, the total force on the conductor is the vector sum of horizontal and vertical forces as shown in Fig. 4 (*iii*).

Total weight of conductor per unit length is

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

Where *w* = weight of conductor per unit length

= conductor material density × volume per unit length

wi= weight of ice per unit length

= density of ice × volume of ice per unit length

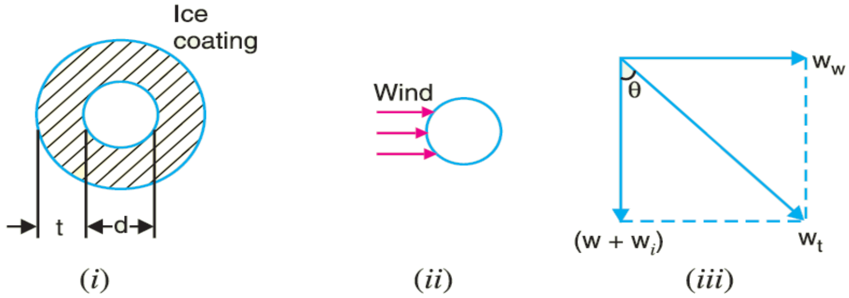


Fig 4

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

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

ww= wind force per unit length

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

= wind pressure × [(*d* + 2*t*) × 1]

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

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

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

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

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

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

(iii) The vertical sag = S cos ϴ

TYPES OF TOWERS

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

(*i*) High mechanical strength to withstand the weight of conductors and wind loads etc.

(*ii*) Light in weight without the loss of mechanical strength.

(*iii*) Cheap in cost and economical to maintain.

(*iv*) Longer life.

(*v*) Easy accessibility of conductors for maintenance.

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

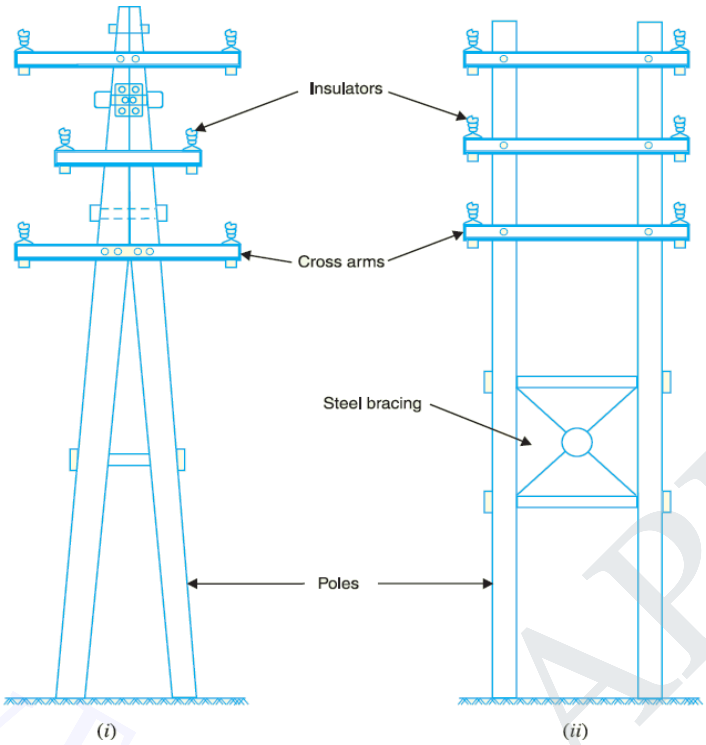


Fig.5 Wooden poles

1. Wooden poles. These are made of seasoned wood (sal or chir) and are suitable for lines of moderate X-sectional area and of relatively shorter spans, say upto 50 meters. Such supports are cheap, easily available, provide insulating properties and, therefore, are widely used for distribution purposes in rural areas as an economical proposition. The wooden poles generally tend to rot below the ground level, causing foundation failure. In order to prevent this, the portion of the pole below the ground level is impregnated with preservative compounds like *creosote oil*. Double pole structures of the '*A*' or '*H*' type are often used (See Fig. 5) to obtain a higher transverse strength than could be economically provided by means of single poles.

The main objections to wooden supports are:

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

2. Steel poles. The steel poles are often used as a substitute for wooden poles. They possess greater mechanical strength, longer life and permit longer spans to be used. Such poles are generally used for distribution purposes in the cities. This type of supports need to be galvanized or painted in order to prolong its life. The steel poles are of three types' *viz.*, **(*i*)** rail poles **(*ii*)** tubular poles and **(*iii*)** rolled steel joints.

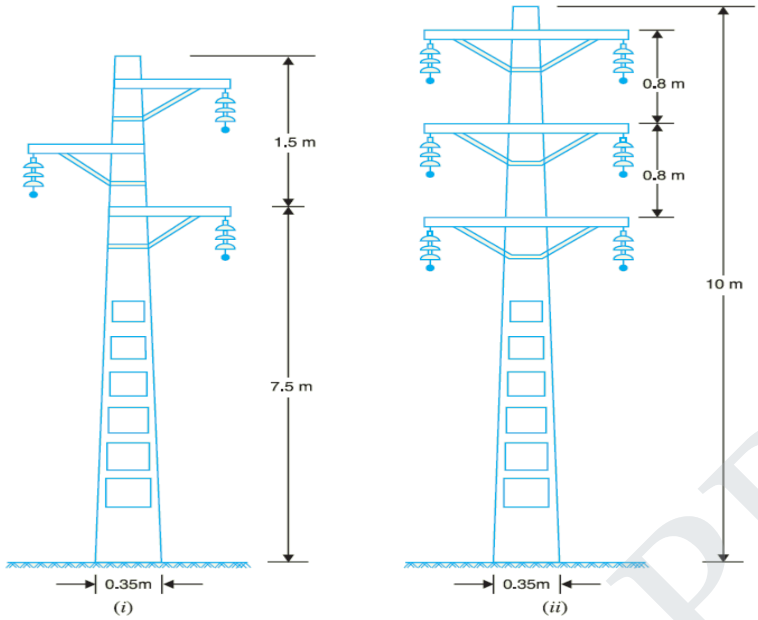


Fig.6

3. RCC poles. The reinforced concrete poles have become very popular as line supports in recent years. They have greater mechanical strength, longer life and permit longer spans than steel poles. Moreover, they give good outlook, require little maintenance and have good insulating properties. Fig. 6 shows R.C.C. poles for single and double circuit. The holes in the poles facilitate the climbing of poles and at the same time reduce the weight of line supports. The main difficulty with the use of these poles is the high cost of transport owing to their heavyweight. Therefore, such poles are often manufactured at the site in order to avoid heavy cost of transportation.

4. Steel towers. In practice, wooden, steel and reinforced concrete poles are used for distribution purposes at low voltages, say up to 11 kV. However, for long distance transmission at higher voltage, steel towers are invariably employed. Steel towers have greater mechanical strength, longer life, can withstand most severe climatic conditions and permit the use of longer spans. The risk of interrupted service due to broken or punctured insulation is considerably reduced owing to longer spans. Tower footings are usually grounded by driving rods into the earth. This minimizes the lightning troubles as each tower acts as a lightning conductor. Fig. 6 (*i*) shows a single circuit tower. However, at a moderate additional cost, double circuit tower can be provided as shown in Fig. 6 (*ii*). The double circuit has the advantage that it ensures continuity of supply. It case there is breakdown of one circuit, the continuity of supply can be maintained by the other circuit

Some Mechanical Principles

Mechanical factors of safety to be used in transmission line design should depend to some extent on the importance of continuity of operation in the line under consideration. In general, the strength of the line should be such as to provide against the worst *probable* weather conditions. We now discuss some important points in the mechanical design of overhead transmission lines.

(*i*) Tower height: Tower height depends upon the length of span. With long spans, relatively few towers are required but they must be tall and correspondingly costly. It is not usually possible to determine the tower height and span length on the basis of direct construction costs because the lightning hazards increase greatly as the height of the conductors above ground is increased. This is one reason that horizontal spacing is favouredinspite of the wider right of way required.

(*ii*) Conductor clearance to ground: The conductor clearance to ground at the time of greatest sag should not be less than some specified distance (usually between 6 and 12 m), depending on the voltage, on the nature of the country and on the local laws. The greatest sag may occur on the hottest day of summer on account of the expansion of the wire or it may occur in winter owing to the formation of a heavy coating of ice on the wires. Special provisions must be made for melting ice from the power lines.

(*iii*) Sag and tension: When laying overhead transmission lines, it is necessary to allow a Reasonable factor of safety in respect of the tension to which the conductor is subjected. The tension is governed by the effects of wind, ice loading and temperature variations. The relationship between tension and sag is dependent on the loading conditions and temperature variations. For example, the tension increases when the temperature decreases and there is a corresponding decrease in the sag. Icing-up of the line and wind loading will cause stretching of the conductor by an amount dependent on the line tension. In planning the sag, tension and clearance to ground of a given span, a maximum stress is selected. It is then aimed to have this stress developed at the worst probable weather conditions (*i.e.* Minimum expected temperature, maximum ice loading and maximum wind). Wind loading increases the sag in the direction of resultant loading but decreases the vertical component. Therefore, in clearance calculations, the effect of wind should not be included unless horizontal clearance is important.

(*iv*) Stringing charts: For use in the field work of stringing the conductors, temperature-sag and temperaturetensioncharts are plotted for the given conductor and loading conditions. Such curves are called stringing charts (see Fig. 7). These charts are very helpful while stringing overhead lines.

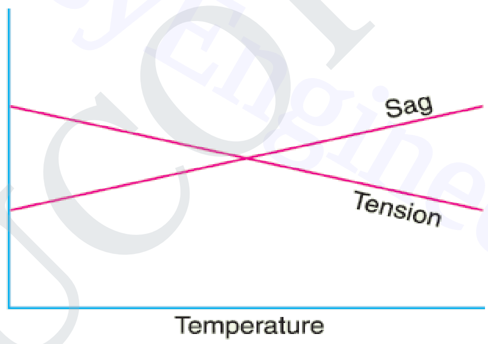


Fig 7

(*v*) Conductor spacing: Spacing of conductors should be such so as to provide safety against flash-over when the wires are swinging in the wind. The proper spacing is a function of span length, voltage and weather conditions. The use of horizontal spacing eliminates the danger caused by unequal ice loading. Small wires or wires of light material are subjected to more swinging by the wind than heavy conductors. Therefore, light wires should be given greater spacing's.

(*vi*) Conductor vibration: Wind exerts pressure on the exposed surface of the conductor. If The wind velocity is small; the swinging of conductors is harmless provided the clearance is sufficiently large so that conductors do not approach within the sparking distance of each other. A completely different type of vibration, called *dancing,* is caused by the action of fairly strong wind on a wire covered with ice, when the ice coating happens to take a form which makes a good air-foil section. Then the whole span may sail up like a kite until it reaches the limit of its slack, stops with a jerk and falls or sails back. The harmful effects of these vibrations occur at the clamps or supports where the conductor suffers fatigue and breaks eventually. In order to protect the conductors, dampers are used.

SUBSTATION LAYOUT (AIS, GIS)

Introduction

The present-day electrical power system isa.c. *i.e.* electric power is generated, transmitted and distributed in the form of alternating current. The electric power is produced at the power stations which are located atfavorable places, generally quite away from the consumers. It is delivered to the consumers through a large network of transmission and distribution.

At many places in the line of the power system, it may be desirable and necessary to change some characteristic (*e.g.* voltage, a.c. to d.c., frequency, p.f. etc.) of electric supply. This is accomplished by suitable apparatus called substation. For example, generation voltage (11 kV or 6·6 kV) at the power station is stepped up to high voltage (say 220 kV or 132 kV) for transmission of electric power. The assembly of apparatus (*e.g.* transformer etc.) used for this purpose is the sub-station.

Similarly, near the consumer's localities, the voltage may have to be stepped down to utilization level. This job is again accomplished by a suitable apparatus called substation. Yet at some places in the line of the power system, it may be desirable to convert large quantities of a.c. power to d.c. power *e.g.* for traction, electroplating, d.c. motors etc. This job is again performed by suitable apparatus (*e.g.* Ignitron) called sub-station.

It is clear that type of equipment needed in a sub-station will depend upon the service requirement. Although there can be several types of sub-stations, we shall mainly confine our attention to only those sub-stations where the incoming and outgoing supplies are a.c. *i.e.* sub-stations which change the voltage level of the electric supply.

Sub-Station

The assembly of apparatus used to change some characteristic (*e.g. voltage, a.c. to d.c., frequency, p.f. etc.*) *of electric supply is called a* **sub-station.**

Sub-stations are important part of power system. The continuity of supply depends to a considerable extent upon the successful operation of sub-stations. It is, therefore, essential to exercise utmost care while designing and building a sub-station. The following are the important points which must be kept in view while laying out a sub-station:

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

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

(*iii*) It should be easily operated and maintained.

(*iv*) It should involve minimum capital cost.

Classification of Sub-Stations

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

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

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

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

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

(*iv*) Frequency changer sub-stations. Those sub-stations which change the supply frequency are known as frequency changer sub-stations. Such a frequency change may be required for industrial utilization.

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

(*vi*) Industrial sub-stations. Those sub-stations which supply power to individual industrial concerns are known as industrial sub-stations.

2. According to constructional features. A sub-station has many components (*e.g.* circuit breakers, switches, fuses, instruments etc.) This must be housed properly to ensure continuous and reliable service. According to constructional features, the sub-stations are classified as:

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

(*i*) Indoor sub-stations. For voltages up to 11 kV, the equipment of the sub-station is installed indoor because of economic considerations. However, when the atmosphere is contaminated with impurities, these sub-stations can be erected for voltages up to 66 kV.

(*ii*) Outdoor sub-stations. For voltages beyond 66 kV, equipment is invariably installed outdoor. It is because for such voltages, the clearances between conductors and the space required for switches, circuit breakers and other equipment becomes so great that it is not economical to install the equipment indoor.

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

(*iv*) Pole-mounted sub-stations. This is an outdoor sub-station with equipment installed overhead on *H*-pole or 4-pole structure. It is the cheapest form of sub-station for voltages not exceeding 11kV (or 33 kV in some cases). Electric power is almost distributed in localities through such substations.

COMPARISON BETWEEN OUTDOOR AND INDOOR SUB-STATIONS

The comparison between outdoor and indoor sub-stations is given below in the tabular form:

S.No.	Particular	Outdoor Sub-station	Indoor Sub-station
1	Space required	More	Less
2	Time required for erection	Less	More
3	Future extension	Easy	Difficult
4	Fault location	Easier beacuse the equipment is in full view	Difficult because the equipment is enclosed
5	Capital cost	Low	High
6	Operation	Difficult	Easier
7	Possibility of fault escalation	Less because greater clearances can be provided	More

From the above comparison, it is clear that each type has its own advantages and disadvantages.

However, comparative economics (*i.e.* annual cost of operation) is the most powerful factor influencing the choice between indoor and outdoor sub-stations. The greater cost of indoor sub-station prohibits its use. But sometimes non-economic factors (*e.g.* public safety) exert considerable influence in choosing indoor sub-station. In general, most of the sub-stations are of outdoor type and the indoor sub-stations are erected only where outdoor construction is impracticable or prohibited by the local laws.

Transformer Sub-Stations

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

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

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

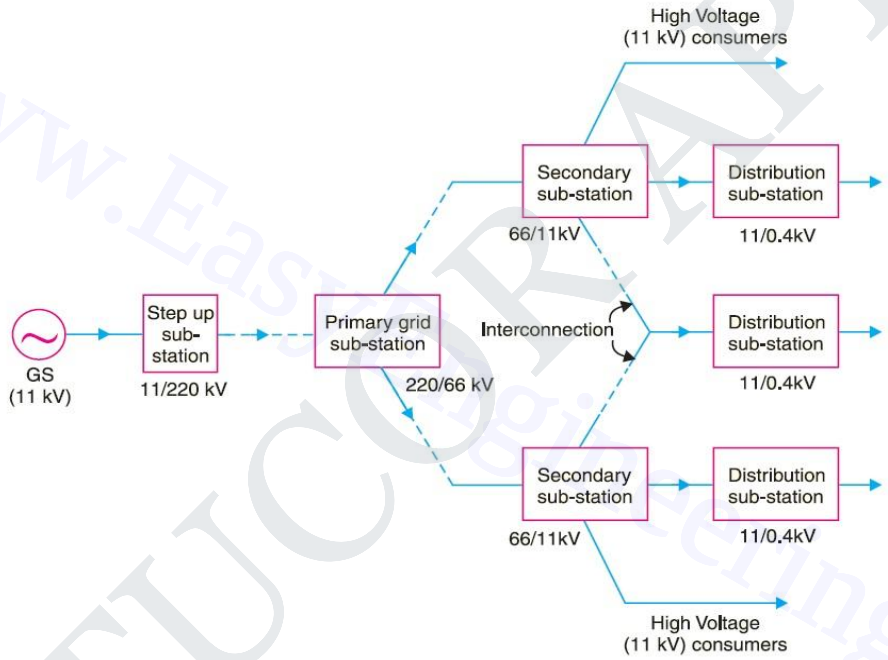


Fig 8

Fig. 8 shows the block diagram of a typical electric supply system indicating the position of above types of sub-stations. It may be noted that it is not necessary that all electric supply schemes include all the stages shown in the figure. For example, in a certain supply scheme there may not be secondary sub-stations and in another case, the scheme may be so small that there are only distribution sub-stations.

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

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

(*iii*) Secondary sub-station. From the primary grid sub-station, electric power is transmitted at66 kV by 3-phase, 3-wire system to various secondary sub-stations located at the strategic points in the city. At a secondary sub-station, the voltage is further stepped down to 11 kV. The 11 kV lines run along the important road sides of the city. It may be noted that big consumers (having demand more than 50 kW) are generally supplied power at 11 kV for further handling with their own sub stations. The secondary sub-stations are also generally of outdoor type.

***(iv)* Distribution sub-station.** The electric power from 11 kV lines is delivered to distribution sub-stations. These sub-stations are located near the consumer's localities and step down the voltage to 400 V, 3-phase, 4-wire for supplying to the consumers. The voltage between any two phase's is400V and between any phase and neutral it is 230 V. The single phase residential lighting load is connected between any one phase and neutral whereas 3-phase, 400V motor load is connected across3-phase lines directly. It may be worthwhile to mention here that majority of the distribution substations are of pole-mounted type.

Pole-Mounted Sub-Station

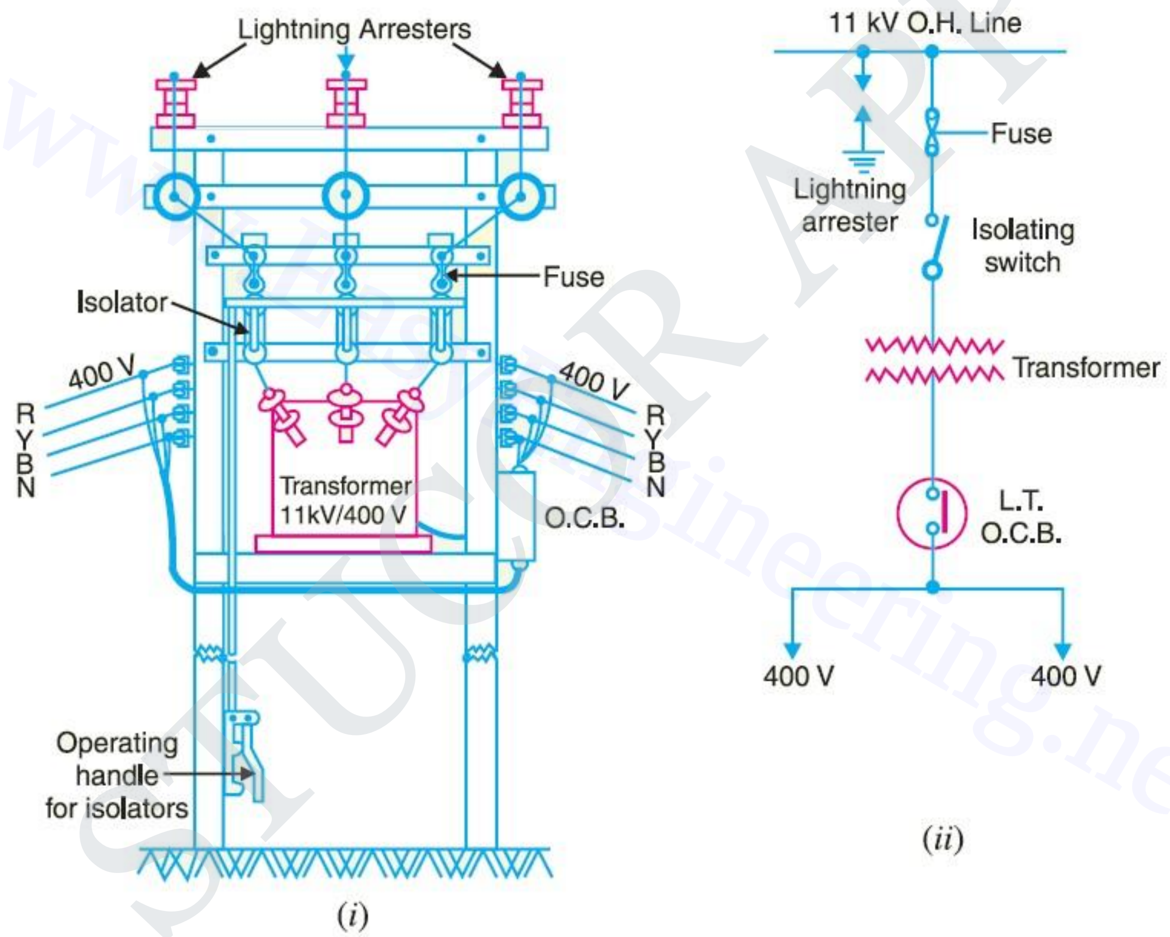


Fig 9

It is a distribution sub-station placed overhead on a pole. It is the cheapest form of sub-station as it does not involve any building work. Fig 9 (*i*) shows the layout of pole-mounted sub-station whereas Fig. 9 (*ii*) shows the schematic connections. The transformer and other equipment are mounted on H-type pole (or 4-pole structure).The 11 kV line is connected to the transformer (11kV /400 V) through gang isolator and fuses. The lightning arresters are installed on the H.T. side to protect the sub-station from lightning strokes. The transformer steps down the voltage to 400V, 3-phase, and 4-wire supply. The voltage between

any two lines are 400V whereas the voltage between any line and neutral is 230 V. The oil circuit breaker (O.C.B.) installed on the L.T. side automatically isolates the transformer from the consumers in the event of any fault. The pole-mounted sub-stations are generally used for transformer capacity up to 200 kVA. The following points may be noted about pole-mounted sub-stations:

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

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

UNDERGROUND SUB-STATION

In thickly populated cities, there is scarcity of land as well as the prices of land are very high. This has led to the development of underground sub-station. In such sub-stations, the equipment is placed underground. Fig. 10 shows a typical underground sub-station.

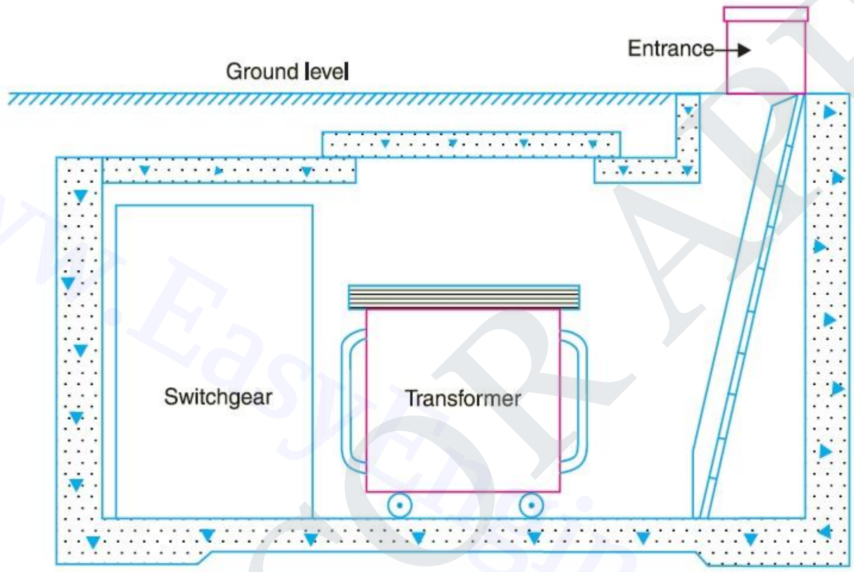


Fig 10

The design of underground sub-station requires more careful consideration than other types of sub-stations. While laying out an underground sub-station, the following points must be kept in view:

(i) The size of the station should be as minimum as possible.

(ii) There should be reasonable access for both equipment and personnel.

(iii) There should be provision for emergency lighting and protection against fire.

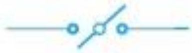
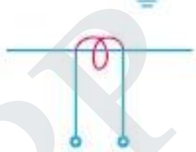
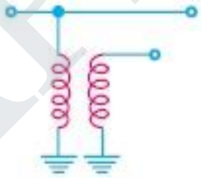
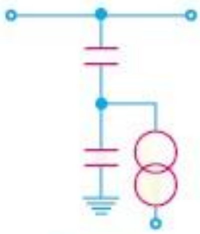
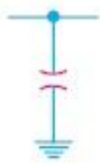
(iv) There should be good ventilation.

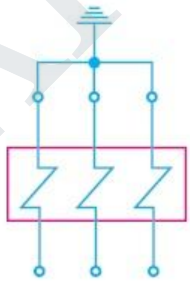
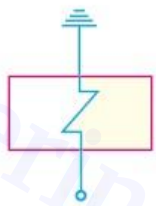
(v) There should be provision for remote indication of excessive rise in temperature so that H.V. supply can be disconnected.

(vi) The transformers, switches and fuses should be air cooled to avoid bringing oil into the premises.

Symbols for Equipment in Sub-Stations

It is a usual practice to show the various elements (*e.g.* transformer, circuit breaker, isolator, instrument transformers etc.) of a sub-station by their graphic symbols in the connection schemes. Symbols of important equipment in sub-station are given below:

S.No.	Circuit element	Symbol
1	Bus-bar	
2	Single-break isolating switch	
3	Double-break isolating switch	
4	On load isolating switch	
5	Isolating switch with earth Blade	
6	Current transformer	
7	Potential transformer	
8	Capacitive voltage transformer	
9	Oil circuit breaker	
10	Air circuit breaker with overcurrent tripping device	
11	Air blast circuit breaker	
12	Lightning arrester (active gap)	
13	Lightning arrester (valve type)	

S.No.	Circuit element	Symbol
14	Arcing horn	
15	3-ϕ Power transformer	
16	Overcurrent relay	
17	Earth fault relay	

Write a short note on sub—station equipment's. [10][Nov/Dec'13][U]

Equipment in a Transformer Sub-Station

The equipment required for a transformer sub-station depends upon the type of sub-station, service requirement and the degree of protection desired. However, in general, a transformer sub-station has the following main equipment:

1. Bus-bars. When a number of lines operating at the same voltage have to be directly connected electrically, bus-bars are used as the common electrical component. Bus-bars are copper or aluminium bars (generally of rectangular *x*-section) and operate at constant voltage. The incoming and outgoing lines in a sub-station are connected to the bus-bars. The most commonly used bus-bar arrangements in sub-stations are:

(i) Single bus-bar arrangement

(ii) Single bus-bar system with sectionalisation

(iii) Double bus-bar arrangement

2. Insulators. The insulators serve two purposes. They support the conductors (or bus-bars) and confine the current to the conductors. The most commonly used material for the manufacture of insulators is porcelain. There are several types of insulators (*e.g.* pin type, suspension type, post insulator etc.) and their use in the sub-station will depend upon the service requirement. For example, post insulator is used for bus-bars. A post insulator consists of a porcelain body, cast iron cap and flanged cast iron base. The hole in the cap is threaded so that bus-bars can be directly bolted to the cap.

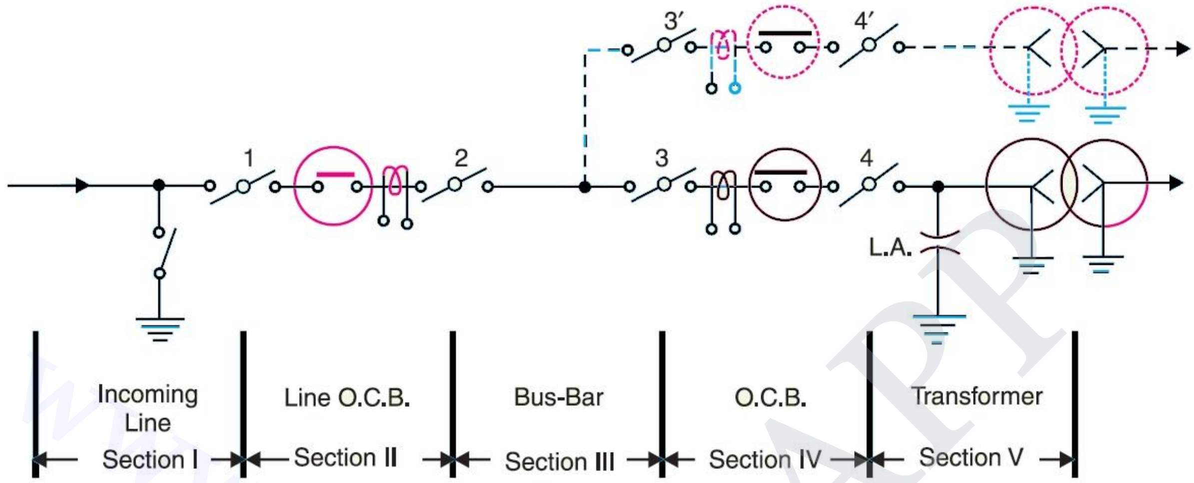


Fig 11

3. Isolating switches. In sub-stations, it is often desired to disconnect a part of the system for general maintenance and repairs. This is accomplished by an isolating switch or isolator. An isolator is essentially a knife switch and is designed to open a circuit under *no load*. In other words, isolator switches are operated only when the lines in which they are connected carry no current. Fig. 11 shows the use of isolators in a typical sub-station. The entire sub-station has been divided into V sections. Each section can be disconnected with the help of isolators for repair and maintenance. For instance, if it is desired to repair section No. II, the procedure of disconnecting this section will be as follows. First of all, open the circuit breaker in this section and then open the isolators 1 and 2. This procedure will disconnect section II for repairs. After the repair has been done, close the isolators 1 and 2 first and then the circuit breaker.

4. Circuit breaker. A circuit breaker is equipment which can open or close a circuit under Normal as well as fault conditions. It is so designed that it can be operated manually (or by remote control) under normal conditions and automatically under fault conditions. For the latter operation, a relay circuit is used with a circuit breaker. Generally, bulk oil circuit breakers are used for voltages up to 66kV while for high (>66 kV) voltages, low oil circuit breakers are used. For still higher voltages, air-blast, vacuum or *SF*6 circuit breakers are used. For detailed discussion of these breakers, the reader may refer to chapter 19.

5. Power Transformers. A power transformer is used in a sub-station to step-up or step-down the voltage. Except at the power station, all the subsequent sub-stations use step-down transformers to gradually reduce the voltage of electric supply and finally deliver it at utilisation voltage. The modern practice is to use 3-phase transformers in sub-stations; although 3 single phase bank of transformers can also be used. The use of 3-phase transformer (instead of 3 single phase bank of transformers) permits two advantages. Firstly, only one 3-phase load-tap changing mechanism can be used. Secondly, its installation is much simpler than the three single phase transformers. The power transformer is generally installed upon lengths of rails fixed on concrete slabs having foundations 1 to 1·5 m deep. For ratings up to 10 MVA, naturally cooled, oil immersed transformers are used. For higher ratings, the transformers are generally air blast cooled.

6. Instrument transformers. The lines in sub-stations operate at high voltages and carry current of thousands of amperes. The measuring instruments and protective devices are designed for low voltages (generally 110 V) and currents (about 5 A). Therefore, they will not work satisfactorily if mounted directly on the power lines. This difficulty is overcome by installing *instrument transformers* on the power lines. The function of these instrument transformers is to transfer voltages or currents in the power lines to values which are convenient for the operation of measuring instruments and relays. There are two types of instrument transformers *viz.*

(*i*) Current transformer (C.T.) (*ii*) Potential transformer (P.T.)

(*i*) Current transformer (C.T.). A current transformer in essentially a step-up transformer which steps down the current to a known ratio. The primary of this transformer consists of one or more turns of thick wire connected in series with the line. The secondary consists of a large number of turns of fine wire and provides for the measuring instruments and relays a current which is constant fraction of the current in the line. Suppose a current transformer rated at 100/5 A is connected in the line to measure current. If the current in the line is 100 A, then current in the secondary will be 5A. Similarly, if current in the line is 50A, then secondary of C.T. will have a current of 2·5 A.Thus the C.T. under consideration will step down the line current by a factor of 20.

(*ii*) Voltage transformer. It is essentially a step down transformer and steps down the voltage to a known ratio. The primary of this transformer consists of a large number of turns of fine wire connected across the line. The secondary winding consists of a few turns and provides for measuring instruments and relays a voltage which is a known fraction of the line voltage. Suppose a potential transformer rated at 66kV/110V is connected to a power line. If line voltage is 66kV, then voltage across the secondary will be 110 V.

7. Metering and Indicating Instruments. There are several metering and indicating instruments (*e.g.* ammeters, voltmeters, energy meters etc.) installed in a sub-station to maintain watch over the circuit quantities. The instrument transformers are invariably used with them for satisfactory operation.

8. Miscellaneous equipment. In addition to above, there may be following equipment in sub-station:

(*i*) fuses
(*ii*) carrier-current equipment
(*iii*) Sub-station auxiliary supplies

BUS-BAR ARRANGEMENTS IN SUB-STATIONS

Draw and explain the single line diagram, showing the location of substation equipment's for the following bus bar arrangements:

(i) Single bus scheme
(ii) Single bus-bar with sectionalizing scheme

State the merits and demerits of each scheme. [16][May/June'16][A]

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

(*i*) Single bus-bar system. As the name suggests, it consists of a single bus-bar and all the incoming and outgoing lines are connected to it. The chief advantages of this type of arrangement are low initial cost, less maintenance and simple operation. However, the principal disadvantage of single bus-bar system is that if repair is to be done on the bus-bar or a fault occurs on the bus, there is a complete interruption of the supply. This arrangement is not used for voltages exceeding 33kV.

The indoor 11kV sub-stations often use single bus-bar arrangement. Fig. 25.5 shows single bus-bar arrangement in a sub-station. There are two 11 kV incoming lines connected to the bus-bar through circuit breakers and isolators. The two 400V outgoing lines are connected to the bus bars through transformers (11kV/400 V) and circuit breakers.

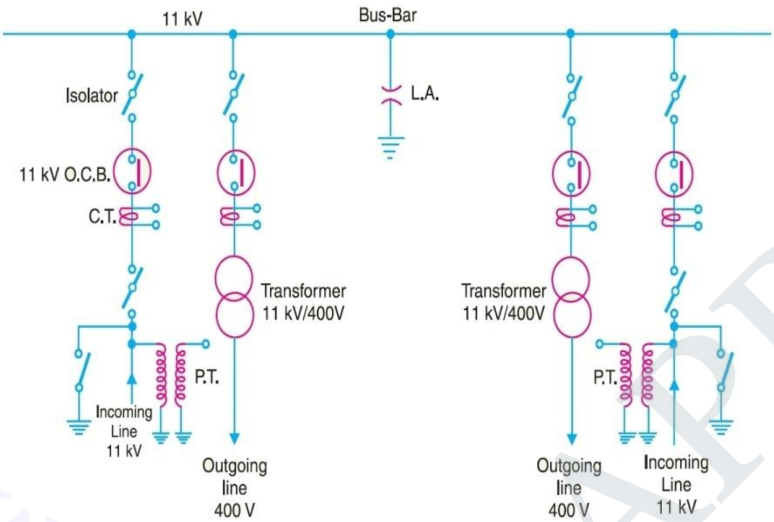


Fig 12

(*ii*) Single bus-bar system with sectionalisation. In this arrangement, the single bus-bar is divided into sections and load is equally distributed on all the sections.

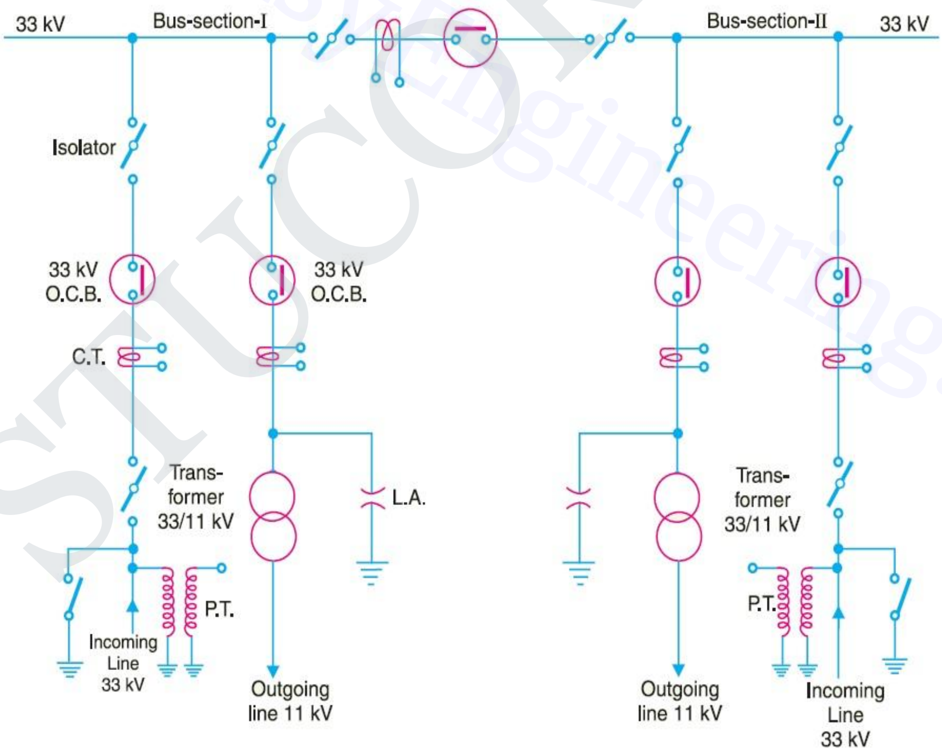


Fig 13

Any two sections of the bus bar are connected by a circuit breaker and isolators. Two principal advantages are claimed for this arrangement. Firstly, if a fault occurs on any section of the bus, that section can be isolated without affecting the supply from other sections. Secondly, repairs and maintenance of any section of the bus bar can be carried out by de-energising that section only, eliminating the possibility of complete shutdown. This arrangement is used for voltages up to 33 kV. Fig. 13 shows bus-bar with sectionalisation where the bus has been divided into two sections. There are two 33 kV incoming lines connected to sections I and II as shown through circuit breaker and isolators. Each 11 kV outgoing line is connected to one section through transformer (33/11 kV) and circuit breaker. It is easy to see that each bus-section behaves as a separate bus-bar.

(*iii*) Duplicate bus-bar system. This system consists of two bus-bars, a "main" bus-bar and a "Spare" bus-bar. Each bus-bar has the capacity to take up the entire sub-station load. The incoming and outgoing lines can be connected to either bus-bar with the help of a bus-bar coupler which consists of a circuit breaker and isolators. Ordinarily, the incoming and outgoing lines remain connected to the main bus-bar. However, in case of repair of main bus-bar or fault occurring on it, the continuity of supply to the circuit can be maintained by transferring it to the spare bus-bar. For voltages exceeding 33kV, duplicate bus-bar system is frequently used.

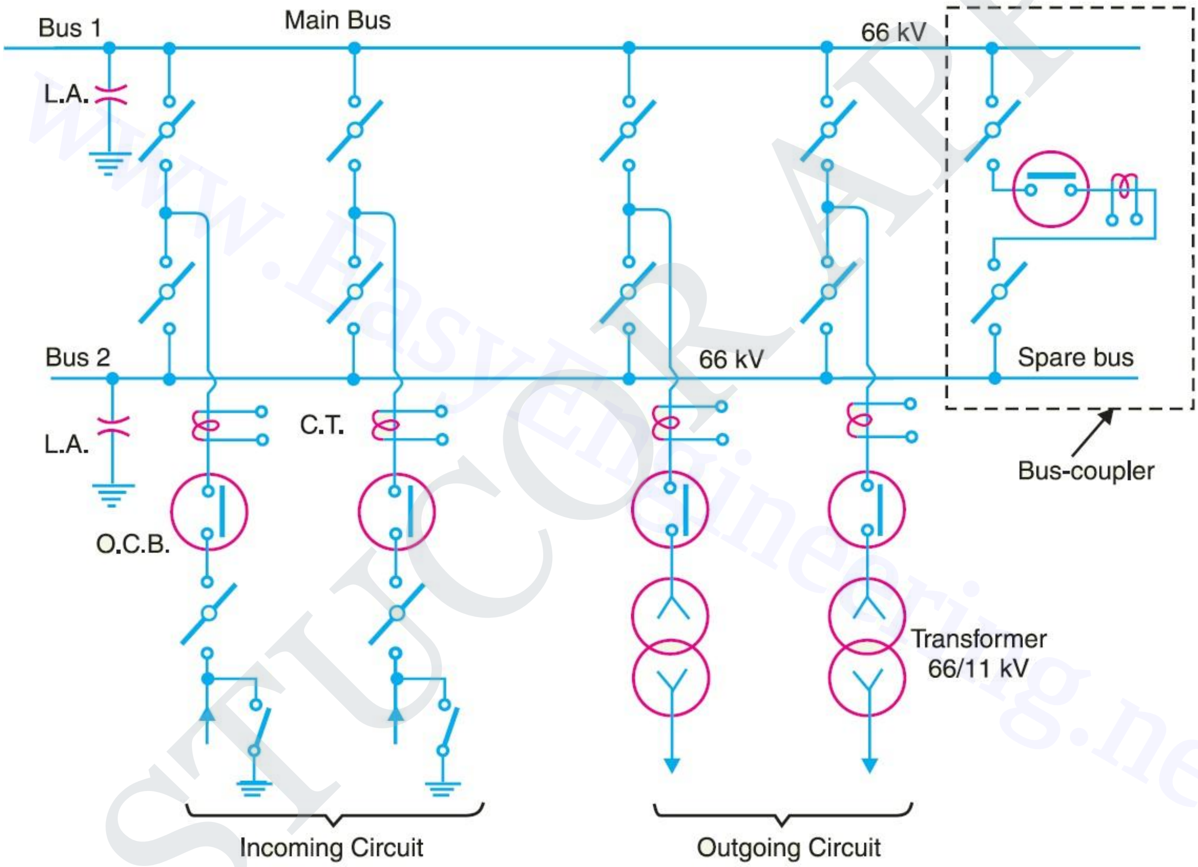


Fig 14

Fig. 14 shows the arrangement of duplicate bus-bar system in a typical sub-station. The two 66kV incoming lines can be connected to either bus-bar by a bus-bar coupler. The two 11 kV outgoing lines are connected to the bus-bars through transformers (66/11 kV) and circuit breakers.

Terminal and Through Sub-Stations

All the transformer sub-stations in the line of power system handle incoming and outgoing lines.

Depending upon the manner of incoming lines, the sub-stations are classified as:

(*i*) Terminal sub-station **(*ii*)** Through sub-station

(*i*) Terminal sub-station. A terminal sub-station is one in which the line supplying to the substation terminates or ends. It may be located at the end of the main line or it may be situated at a point away from main line route. In the latter case, a tapping is taken from the main line to supply to the sub-station. Fig. 15 shows the schematic connections of a terminal sub-station. It is clear that incoming 11 kV main line terminates at the sub-station. Most of the distribution sub-stations are of this type.

(*ii*) Through sub-station. A through sub-station is one in which the incoming line passes 'through' at the same voltage. A tapping is generally taken from the line to feed to the transformer to reduce the voltage to the desired level. Fig. 16 shows the schematic connections of a through substation. The incoming 66 kV line passes through the sub-station as 66kV outgoing line. At the same time, the incoming line is tapped in the sub-station to reduce the voltage to 11 kV for secondary distribution.

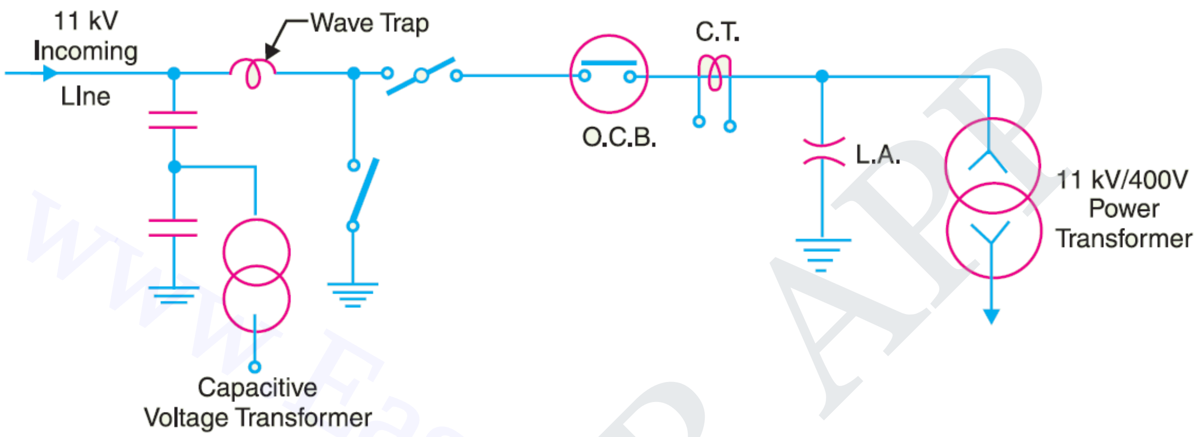


Fig 15

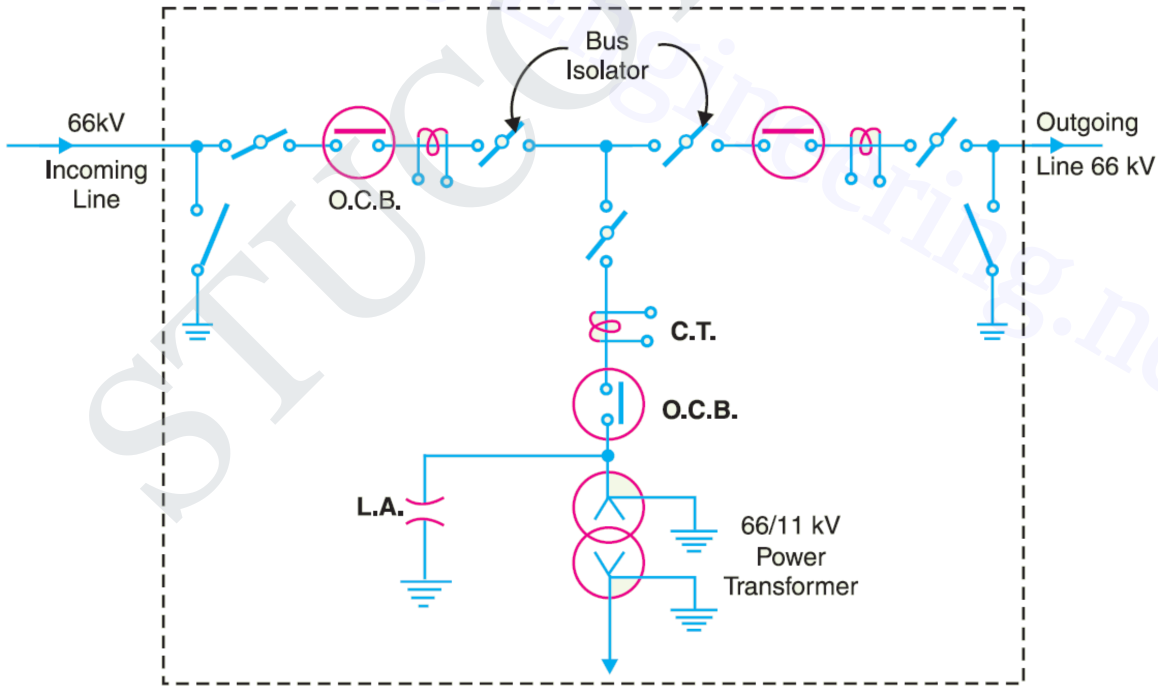


Fig 16

Explain the following substation bus schemes. (i) Main and transfer bus (ii) double bus-bar with bypass isolators.[16]Discuss the design of primary distribution system with respect to following: (i) Selection of voltage[6] (ii) Choice of scheme [5] (iii) Size of feeders[5][April/May'11][U]

KEY DIAGRAM OF 66/11 KV SUB-STATION

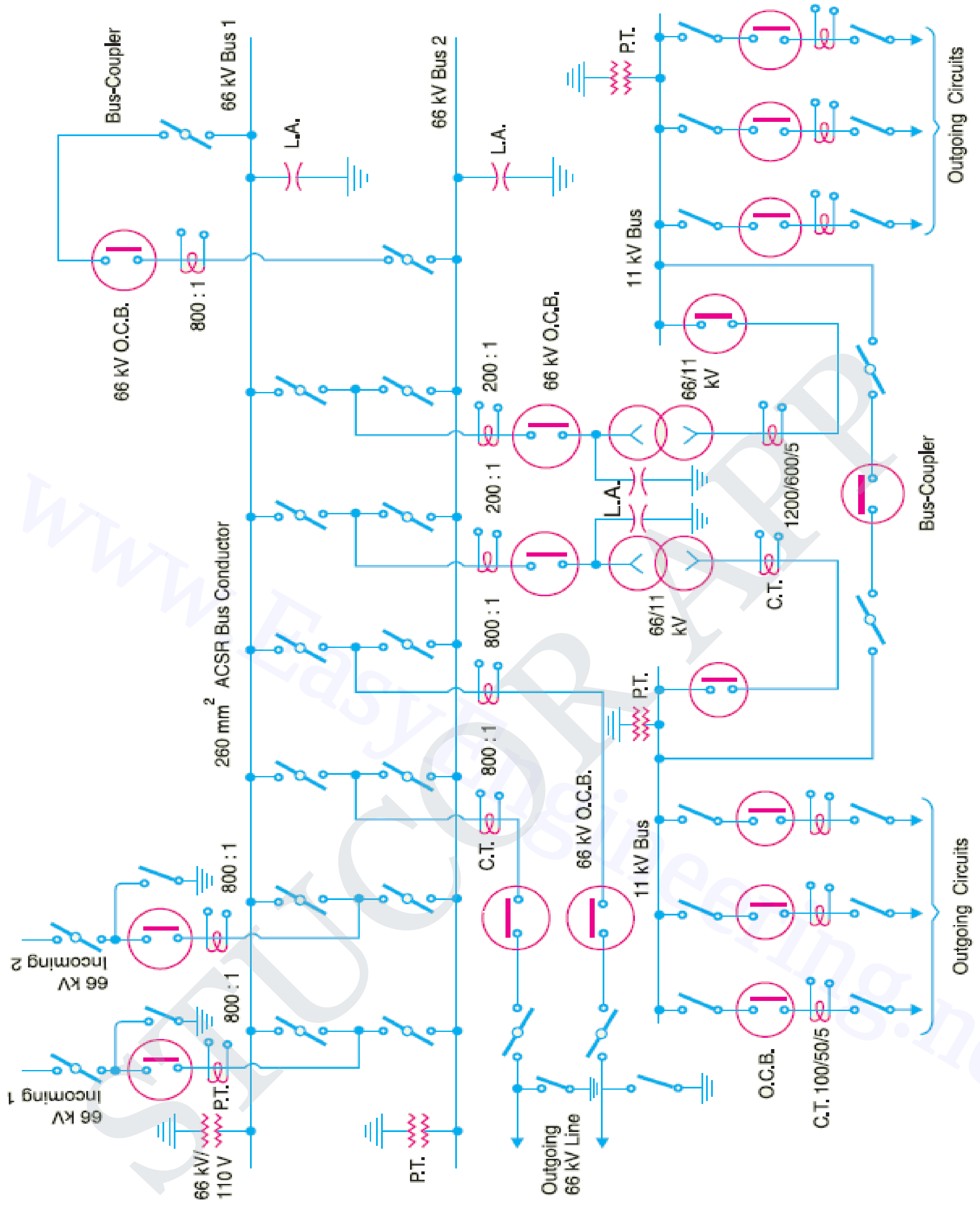


Fig 17

Fig. 17 shows the key diagram of a typical 66/11 kV sub-station. The key diagram of this substation can be explained as under:

(i) There are two 66 kV incoming lines marked 'incoming 1' and 'incoming 2' connected to the bus-bars. Such an arrangement of two incoming lines is called a double circuit. Each incoming line is capable of supplying the rated sub-station load. Either these lines can be loaded simultaneously to share the sub-station load or any one line can be called upon to meet the entire load. The double circuit arrangement increases the reliability of the system. In case there is a breakdown of one incoming line, the continuity of supply can be maintained by the other line.

(*ii*) The sub-station has duplicate bus-bar system; one 'main bus-bar' and the other spare busbar.The incoming lines can be connected to either bus-bar with the help of a bus-coupler this consists of a circuit breaker and isolators. The advantage of double bus-bar system is that if repair is to be carried on one bus-bar, the supply need not be interrupted as the entire load can be transferred to the other bus.
(*iii*) There is an arrangement in the sub-station by which the same 66 kV double circuit supply is going out *i.e.* 66 kV double circuit supply is passing through the sub-station. The outgoing66 kV double circuit line can be made to act as incoming line.
(*iv*) There is also an arrangement to step down the incoming 66 kV supply to 11 kV by two units of 3-phase transformers; each transformer supplying to a separate bus-bar. Generally, one transformer supplies the entire sub-station load while the other transformer acts as a standby unit. If need arises, both the transformers can be called upon to share the sub-station load. The 11 kV outgoing lines feed to the distribution sub-stations located near consumers localities.
(*v*) Both incoming and outgoing lines are connected through circuit breakers having isolators On their either end. Whenever repair is to be carried over the line towers, the line is first switched off and then earthed.
(*vi*) The potential transformers (P.T.) and current transformers (C.T.) and suitably located for supply to metering and indicating instruments and relay circuits (not shown in the figure).The P.T. is connected right on the point where the line is terminated. The CTs are connected at the terminals of each circuit breaker.
(*vii*) The lightning arresters are connected near the transformer terminals (on H.T. side) to protect them from lightning strokes.
(*viii*) There are other auxiliary components in the sub-station such as capacitor bank for power factor improvement, earth connections, local supply connections, d.c. supply connectionist. However, these have been omitted in the key diagram for the sake of simplicity.

KEY DIAGRAM OF 11 KV/400 V INDOOR SUB-STATION

Fig. 18 shows the key diagram of a typical 11 kV/400 V indoor sub-station. The key diagram of this sub-station can be explained as under:
(*i*) The 3-phase, 3-wire 11 kV line is tapped and brought to the gang operating switch installed near the sub-station. The G.O. switch consists of isolators connected in each phase of the 3- phase line.
(*ii*) From the G.O. switch, the 11 kV line is brought to the indoor sub-station as underground cable. It is fed to the H.T. side of the transformer (11 kV/400 V) *via* the 11 kV O.C.B. The transformer steps down the voltage to 400 V, 3-phase, 4-wire.
(*iii*) The secondary of transformer supplies to the bus-bars *via* the main O.C.B. From the bus bars, 400 V, 3-phase, 4-wire supply is given to the various consumers *via* 400 V O.C.B. The voltage between any two phases is 400 V and between any phase and neutral it is 230 V. The single phase residential load is connected between any one phases and neutral whereas 3-phase, 400 V motor loads is connected across 3-phase lines directly.
(*iv*) The CTs are located at suitable places in the sub-station circuit and supply for the metering and indicating instruments and relay circuits.

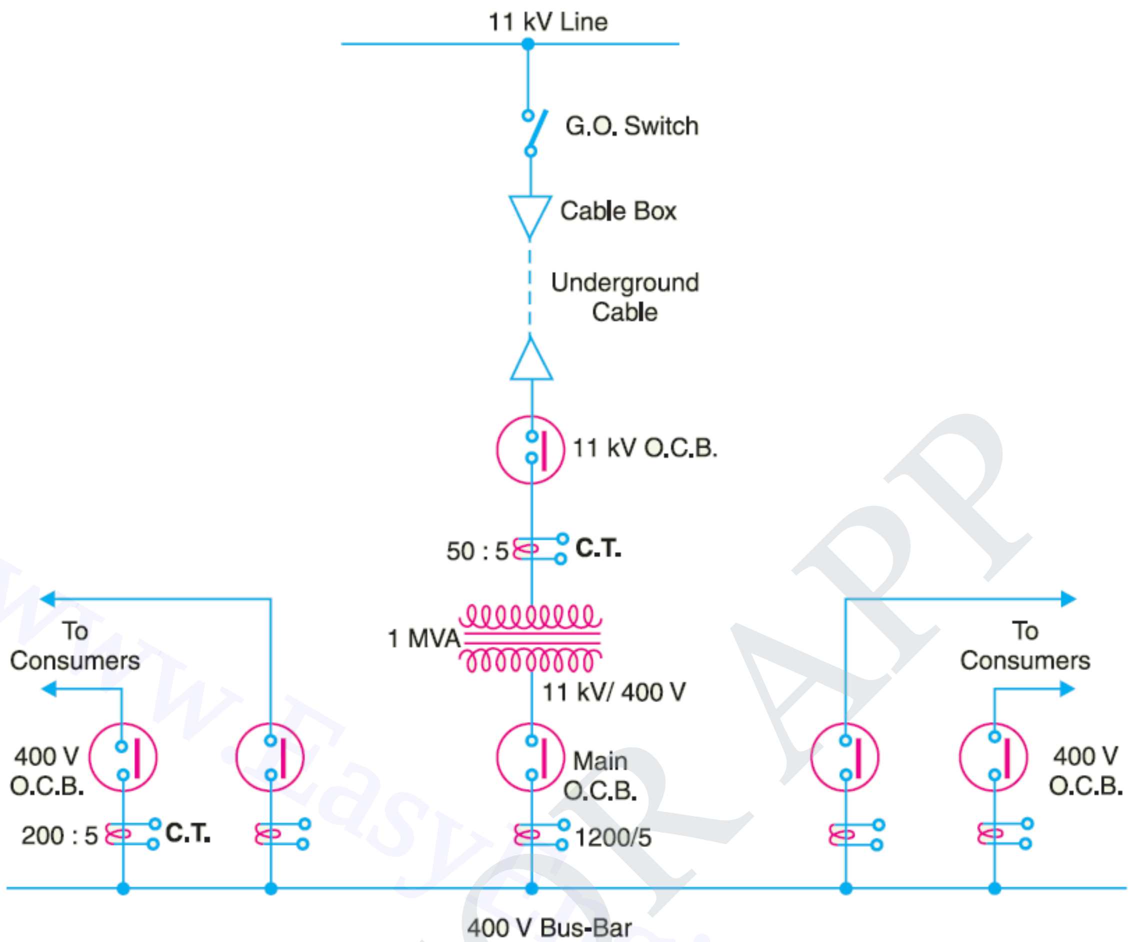


Fig 18

METHODS OF GROUNDING

INTRODUCTION

In power system, *grounding* or *earthing*means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (*e.g.* neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth*i.e.* soil. This connection to earth may be through conductor or some other circuit element (e.g. resistor, a circuit breaker etc.) depending upon the situation. Regardless of the method of connection to earth, grounding or earthingoffers two principal advantages. First, it provides Protection to the power system. For example, if the neutral point of a star-connected system is

Grounded through a circuit breaker and phase to earth fault occurs on any one line, a large fault current will flow through the circuit breaker. The circuit breaker will open to isolate the faulty line. This protects the power system from the harmful effects of the fault. Secondly, earthing of electrical equipment (*e.g.* domestic appliances, hand-held tools, industrial motors etc.) ensures the safety of the persons handling the equipment. For example, if insulation fails, there will be a direct contact of the live conductor with the metallic part (*i.e.* Frame) of the equipment. Any person in contact with the metallic part of this equipment will be subjected to a dangerous electrical shock which can be fatal. In this chapter, we shall discuss the importance of grounding or earthing in the line of power system with special emphasis on neutral grounding.

Grounding or Earthing

The process of connecting the metallic frame (i.e. non-current carrying part) of electrical equipment or some electrical part of the system (e.g. neutral point in a star-connected system, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called **grounding** *or* **earthing.**

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

Equipment Grounding

The process of connecting non-current-carrying metal parts (i.e. metallic enclosure) of the electrical equipment to earth (i.e. soil) in such a way that in case of insulation failure, the enclosure effectively remains at earth potential is called **equipment grounding.**

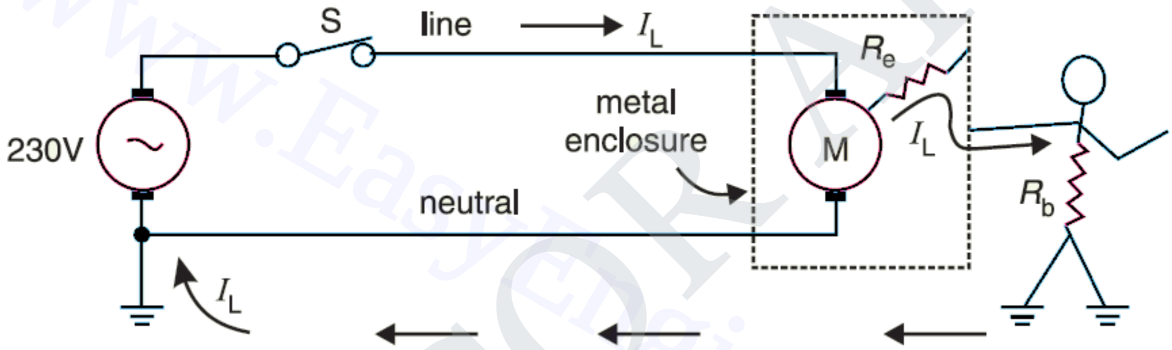


Fig 19

We are frequently in touch with electrical equipment of all kinds, ranging from domestic appliances and hand-held tools to industrial motors. We shall illustrate the need of effective equipment grounding by considering a single-phase circuit composed of a 230 V source connected to a motor M as shown in Fig. 19. Note that neutral is solidly grounded at the service entrance. In the interest of easy understanding, we shall divide the discussion into three heads *viz.* **(*i*)** Ungrounded enclosure **(*ii*)** enclosure connected to neutral wire **(*iii*)** ground wire connected to enclosure.

(*i*) Ungrounded enclosure. Fig. 19 shows the case of ungrounded metal enclosure. If person touches the metal enclosure, nothing will happen if the equipment is functioning correctly. But if the winding insulation becomes faulty, the resistance *Re* between the motor and enclosure drops to a low values (a few hundred ohms or less). A person having a body resistance $R_b$wouldcomplete the current path as shown in Fig. 26.1.If $R_e$is small (as is usually the case when insulation failure of winding occurs), the leakage severe electric shock which may be fatal. Therefore, this system is unsafe.

(*ii*) Enclosure connected to neutral wire. It may appear that the above problem can be solved by connecting the enclosure to the grounded neutral wire as shown in Fig. 20. Now the leakage current$I_L$flows from the motor, through the enclosure and straight back to the neutral wire (See Fig. 20). Therefore, the enclosure remains at earth potential. Consequently, the operator would not experience any electric shock.

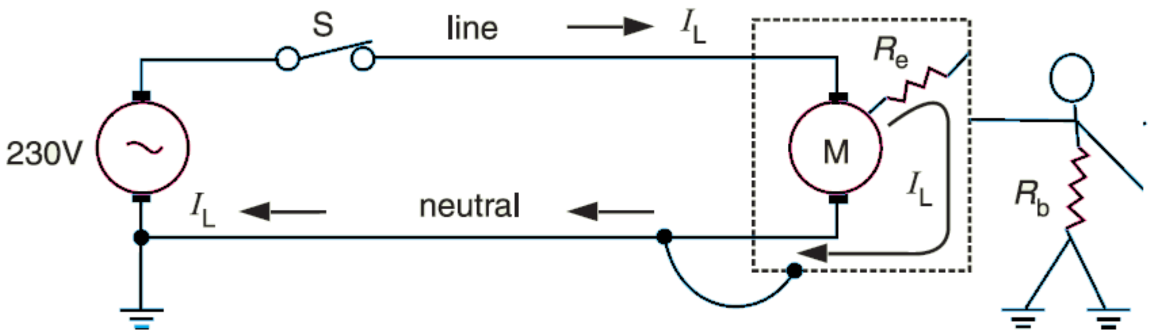


Fig.20

The trouble with this method is that the neutral wire may become open either accidentally ordure to a faulty installation. For example, if the switch is inadvertently in series with the neutral rather than the live wire (See Fig. 21), the motor can still be turned on and off. However, if someone touched the enclosure while the motor is *off*, he would receive a severe electric shock (See Fig. 21). It is because when the motor is off, the potential of the enclosure rises to that of the live conductor.

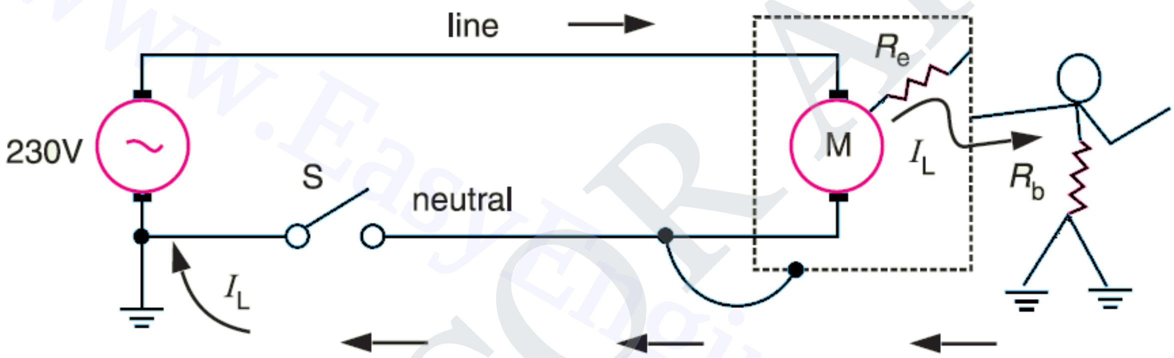


Fig 21

(*iii*) Ground wire connected to enclosure. To get rid of this problem, we install a third wire, Called *ground wire*, between the enclosure and the system ground as shown in Fig. 22 The ground wire may be bare or insulated. If it is insulated, it is colouredgreen.Electrical outlets have three contacts — one for live wire, one for neutral wire and one for ground wire.

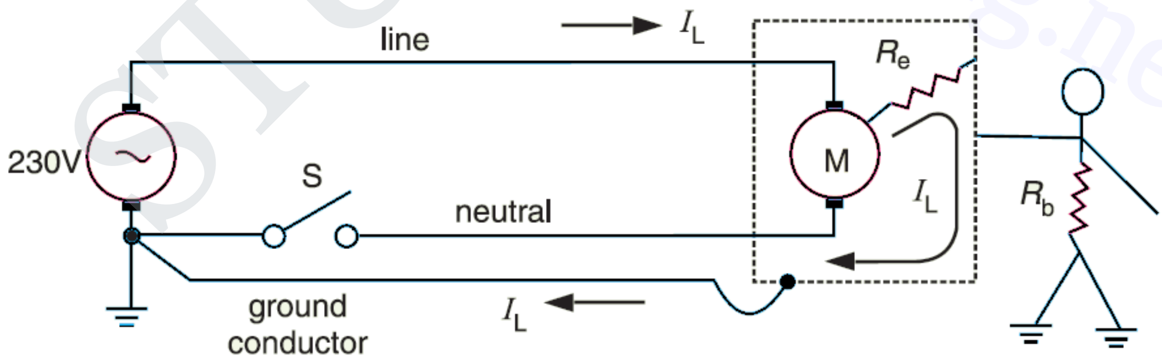


Fig 22

System Grounding

The process of connecting some electrical part of the power system (e.g. neutral point of a starconnectedsystem, one conductor of the secondary of a transformer etc.) to earth (i.e. soil) is called **system grounding.**

The system grounding has assumed considerable importance in the fast expanding power system. By adopting proper schemes of system grounding, we can achieve many advantages including protection, reliability and safety to the power system network. But before discussing the various aspects of *neutral grounding*, it is desirable to give two examples to appreciate the need of system grounding.

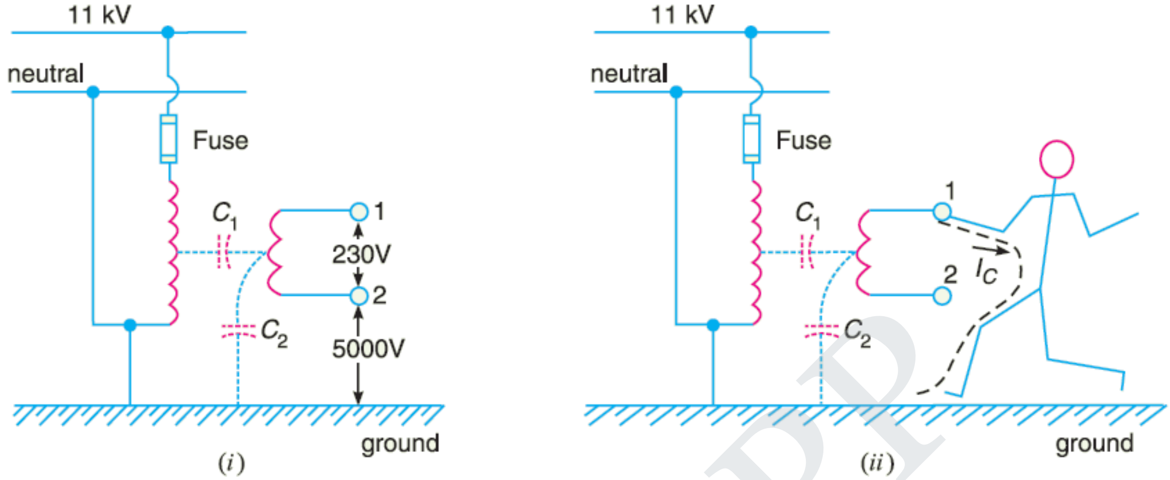


Fig 23

(i) Fig. 23 (*i*) show the primary winding of a distribution transformer connected between the line and neutral of an 11 kV line. If the secondary conductors are *ungrounded*, it would appear that a person could touch either secondary conductor without harm because there is no ground return. However, this is not true. Referring to Fig. 23, there is capacitance C_1between primary and secondary and capacitance C_2 between secondary and ground. This capacitance coupling can produce a high voltage between the secondary lines and the ground.
Depending upon the relative magnitudes of C_1 and C_2, it may be as high as 20% to 40% of the primary voltage. If a person touches either one of the secondary wires, the resulting capacitive current $I_C$lowing through the body could be dangerous even in case of small transformers [See Fig. 23(*ii*)]. For example, if I_C is only 20 mA, the person may get fatal electric shock. If one of the secondary conductors is grounded, the capacitive coupling almost reduces to zero and so is the capacitive current I_C. As a result, the person will experience no electric shock. This explains the importance of system grounding.

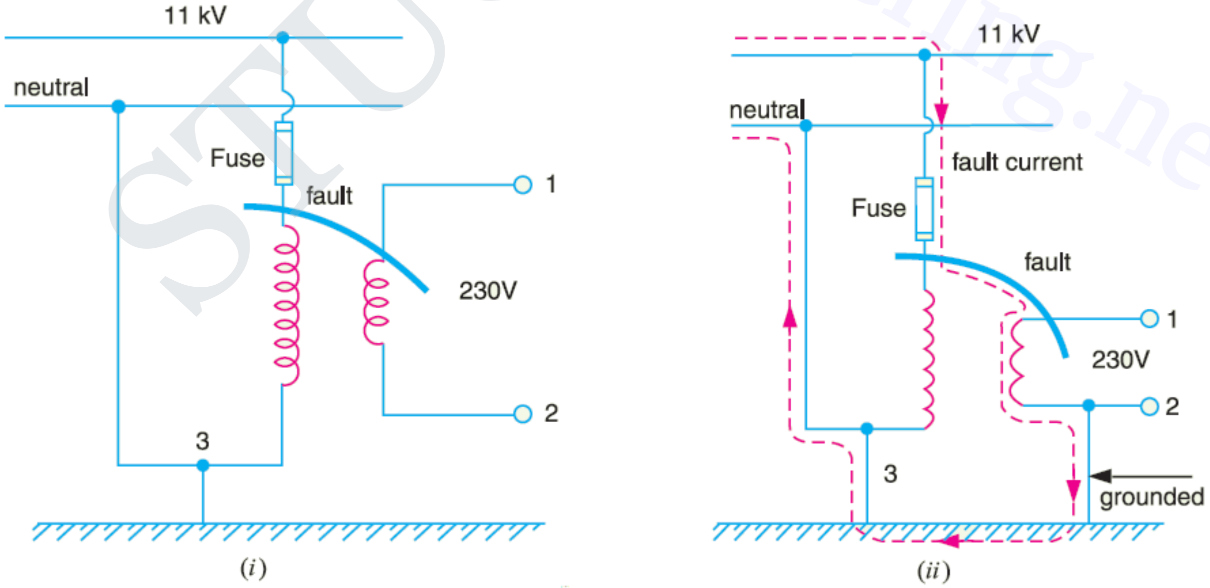


Fig 24

(ii) Let us now turn to a more serious situation. Fig. 24 (*i*) shows the primary winding of distribution transformer connected between the line and neutral of an 11 kV line. The secondary conductors are ungrounded. Suppose that the high voltage line (11 kV in this case) touches the 230 Vconductors as shown in Fig. 24 (*i*). This could be caused by an internal fault in the transformer or by a branch or tree falling across the 11 kV and 230 V lines. Under these circumstances, a very high voltage is imposed between the secondary conductors and ground. This would immediately puncture the 230 V insulation, causing a massive flashover. This flashover could occur anywhere on the secondary network, possibly inside a home or factory. Therefore, ungrounded secondary in this case is a potential fire hazard and may produce grave accidents under abnormal conditions. If one of the secondary lines is grounded as shown in Fig. 24(*ii*), the accidental contact between 11 kV conductors and a 230 V conductor produces a dead short. The short-circuit current (*i.e.* fault current) follows the dotted path shown in Fig. 24 (*ii*). This large current will blow the fuse on the 11 kV side, thus disconnecting the transformer and secondary distribution system from the 11 kV line. This explains the importance of system grounding in the line of the power system.

Ungrounded Neutral System

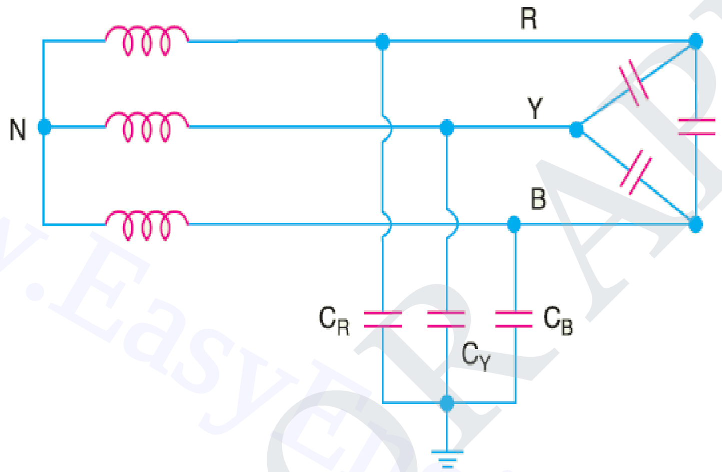


Fig 25

In an ungrounded neutral system, the neutral is not connected to the ground *i.e.* the neutral is isolated from the ground. Therefore, this system is also called *isolated neutral system* or *free neutral system.* Fig. 25shows ungrounded neutral system. The line conductors have capacitances between one another and to ground. The former are delta-connected while the latter are star-connected. The delta-connected capacitances have little effect on the grounding characteristics of the system (*i.e.* these capacitances do not affect the earth circuit) and, therefore, can be neglected. The circuit then reduces to the one shown in Fig. 26(*i*).

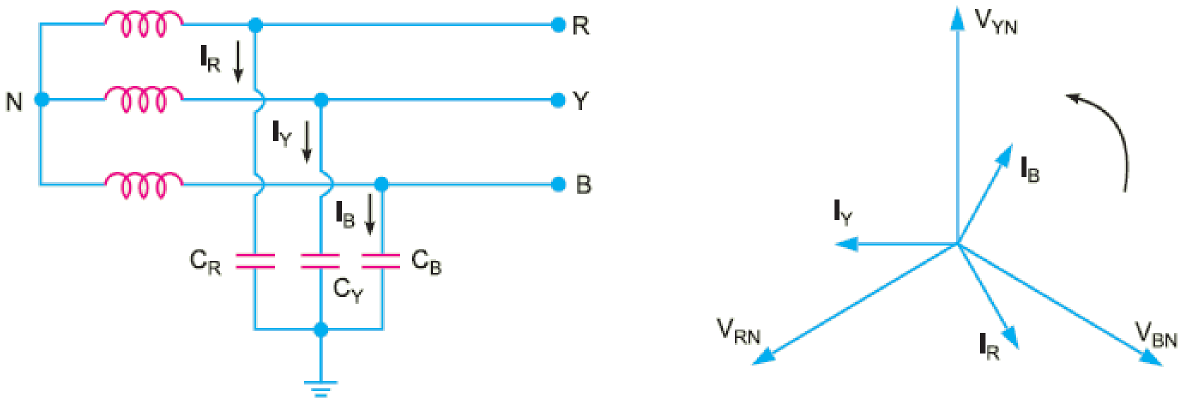
Circuit behavior under normal conditions. Let us discuss the behavior of ungrounded Neutral system under normal conditions (*i.e.* under steady state and balanced conditions). The line is assumed to be perfectly transposed so that each conductor has the same capacitance to ground.

Therefore, $C_R = C_Y = C_B = C$ (say). Since the phase voltages V_{RN}, V_{YN} and V_{BN} have the same magnitude (of course, displaced 120° from one another), the capacitive currents I_R, $I_Y$and $I_B$willhave the same value *i.e.*

$$I_R + I_Y + I_B = \frac{V_{ph}}{X_C} \qquad \text{.....in magnitude}$$

whereV_{ph}= Phase voltage (*i.e.* line-to-neutral voltage)

X_C= Capacitive reactance of the line to ground.

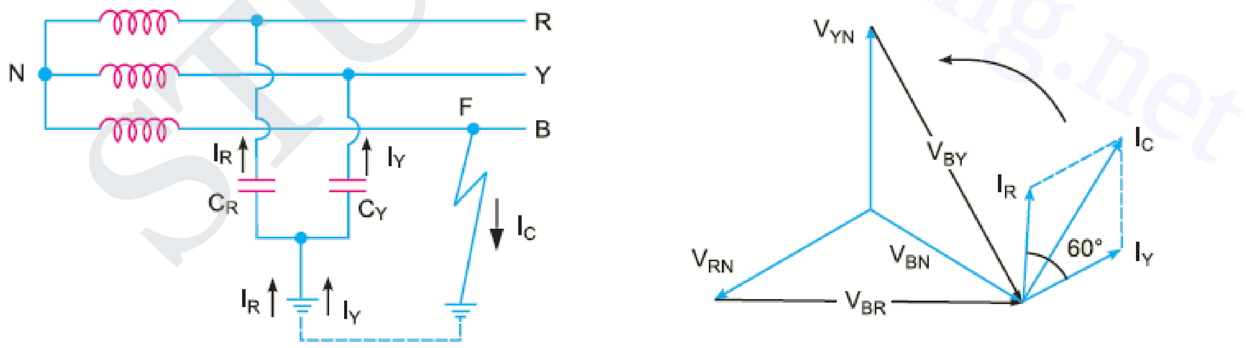


(i) (ii)

Fig 26

The capacitive currents I_R, $I_Y$and $I_B$lead their respective phase voltages V_{RN}, V_{YN} and $V_{BN}$by 90° as shown in the phasor diagram in Fig. 26.8(*ii*). The three capacitive currents are equal in Magnitude and are displaced 120° from each other. Therefore, their phasor sum is zero. As a result, no current flows to ground and the *potential of neutral is the same as the ground potential*. Therefore, ungrounded neutral system poses no problems under normal conditions. However, as we shall see, currents and voltages are greatly influenced during fault conditions.

Circuit behavior under single line to ground-fault. Let us discuss the behavior of ungrounded neutral system when single line to ground fault occurs. Suppose line to ground fault occurs in line *B* at some point *F*.The circuit then becomes as shown in Fig. 27(*i*). The capacitive currents $I_R$and $I_Y$flow through the lines *R* and *Y* respectively. The voltages driving $I_R$and $I_Y$are $V_{BR}$and V_{BY}respectively. Note that $V_{BR}$and $V_{BY}$are the line voltages [See Fig. 27 (*ii*)]. The paths of $I_R$and$I_Y$are essentially capacitive. Therefore, $I_R$leadsV_{BR} by 90° and $I_Y$leads$V_{BY}$by 90° as shown in Fig. 27 (*ii*). The capacitive fault current $I_C$in line *B* is the phasor sum of $I_R$andI_Y.



(i) (ii)

Fig 27

Fault current in line *B*, $I_C = I_R + I_Y$.... Phasor sum

Now, $$I_R = \frac{V_{BR}}{X_C} = \frac{\sqrt{3}V_{ph}}{X_C}$$

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

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

$= \sqrt{3} \times$ Per phase capacitive current under normal conditions

Capacitive fault current in line B is

I_C = Phasor sum of $I_R$andI_Y

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

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

= 3 × per phase capacitive current under normal conditions

Therefore, when single line to ground fault occurs on an ungrounded neutral system, the following effects are produced in the system:

(*i*) The potential of the faulty phase becomes equal to ground potential. However, the voltages of the two remaining healthy phases rise from their normal phase voltages to full line value. This may result in insulation breakdown.

(*ii*) The capacitive current in the two healthy phases increase to 3 times the normal value.

(*iii*) The capacitive fault current (*IC*) becomes 3 times the normal per phase capacitive current.

(*iv*) This system cannot provide adequate protection against earth faults. It is because the capacitive fault current is small in magnitude and cannot operate protective devices.

(*v*) The capacitive fault current *IC* flows into earth. Experience shows that *IC* in excess of 4A is sufficient to maintain an arc in the ionized path of the fault. If this current is once maintained, it may exist even after the earth fault is cleared. This phenomenon of persistent arc is called *arcing ground*. Due to arcing ground, the system capacity is charged and discharged in a cyclic order. These sets up high-frequency oscillations on the wholesystemand the phase voltage of healthy conductors may rise to 5 to 6 times its normal value. The overvoltages in healthy conductors may damage the insulation in the line.

Due to above disadvantages, ungrounded neutral system is not used these days. The modern high-voltage 3-phase systems employ grounded neutral owing to a number of advantages.

Neutral Grounding

Explain the reasons leading to the general practice of earthing the neutral point of a power system. Discuss the relative merits of earthing it (1) solidly and (2) through a resistance. [10][May/June’16][U]

The process of connecting neutral point of 3-phase system to earth (i.e. soil) either directly or through some circuit element (e.g. resistance, reactance etc.) is called **neutral grounding.**

Neutral grounding provides protection to personal and equipment. It is because during earth fault, the current path is completed through the earthed neutral and the protective devices (*e.g.* a fuse etc.) operate to isolate the faulty conductor from the rest of the system. This point is illustrated in Fig. 28

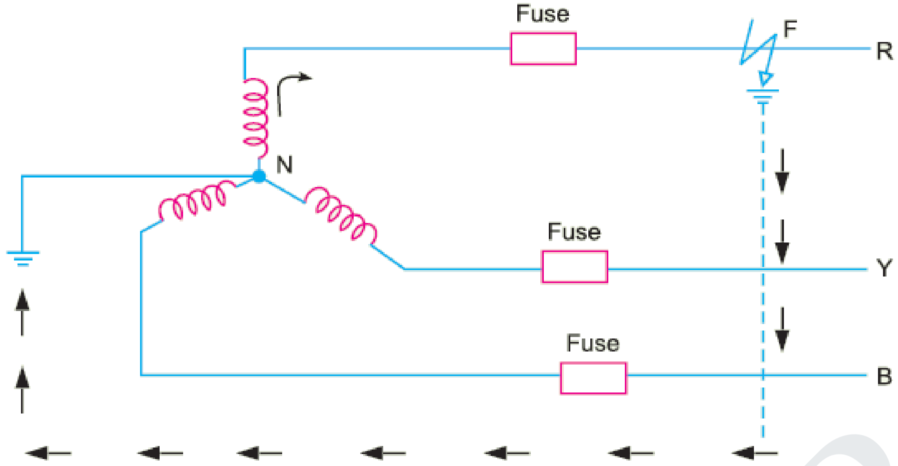


Fig 28

Fig. 28 shows a 3-phase, star-connected system with neutral earthed (*i.e.* neutral point is connected to soil). Suppose a single line to ground fault occurs in line *R* at point *F*.This will cause the current to flow through ground path as shown in Fig. 28 Note that current flows from *R*-phase to earth, then to neutral point *N* and back to *R*-phase. Since the impedance of the current path is low, a large current flows through this path. This large current will blow the fuse in *R*-phase and isolate the faulty line *R*. This will protect the system from the harmful effects (*e.g.* damage to equipment, electric shock to personnel etc.) of the fault. One important feature of grounded neutral is that the potential difference between the live conductor and ground will not exceed the phase voltage of the system *i.e.* it will remain nearly constant.

Advantages of Neutral Grounding

The following are the advantages of neutral grounding:

(*i*) Voltages of the healthy phases do not exceed line to ground voltages *i.e.* they remain nearly constant.

(*ii*) The high voltages due to arcing grounds are eliminated.

(*iii*) The protective relays can be used to provide protection against earth faults. In case earth fault occurs on any line, the protective relay will operate to isolate the faulty line.

(*iv*) Theovervoltage's due to lightning are discharged to earth.

(*v*) It provides greater safety to personnel and equipment.

(*vi*) It provides improved service reliability.

(*vii*) Operating and maintenance expenditures are reduced.

Note: It is interesting to mention here that ungrounded neutral has the following advantages:

(*i*) In case of earth fault on one line, the two healthy phases will continue to supply load for a
Short period.

(*ii*) Interference with communication lines is reduced because of the absence of zero sequence currents.

The advantages of ungrounded neutral system are of negligible importance as compared to the advantages of the grounded neutral system. Therefore, modern 3-phase systems operate with grounded neutral points.

Methods of Neutral Grounding

The methods commonly used for grounding the neutral point of a 3-phase system are:
(*i*) Solid or effective grounding **(*ii*)** Resistance grounding **(*iii*)** Reactance grounding **(*iv*)** Peterson-coil grounding .The choice of the method of grounding depends upon many factors including the size of the system, system voltage and the scheme of protection to be used.

Solid Grounding

When the neutral point of a 3-phase system (e.g. 3- phase generator, 3-phase transformer etc.) is directly connected to earth (i.e. soil) through a wire of negligible resistance and reactance, it is called **solid grounding** *or* **effective grounding**. Fig. 29shows the solid grounding of the neutral point. Since the neutral point is directly connected to earth through a wire, the neutral point is held at earth potential under all conditions. Therefore, under fault conditions, the voltage of any conductor to earth will not exceed the normal phase voltage of the system.

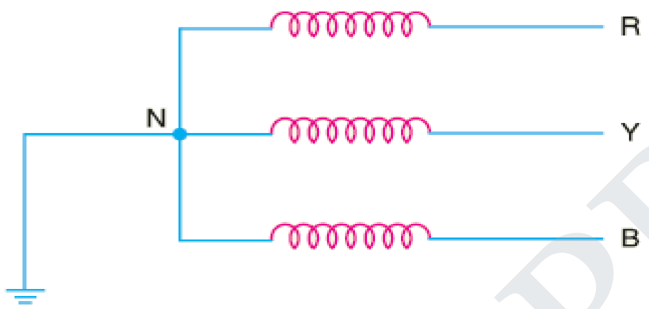


Fig 29

Advantages. The solid grounding of neutral point has the following advantages:
(*i*) The neutral is effectively held at earth potential.

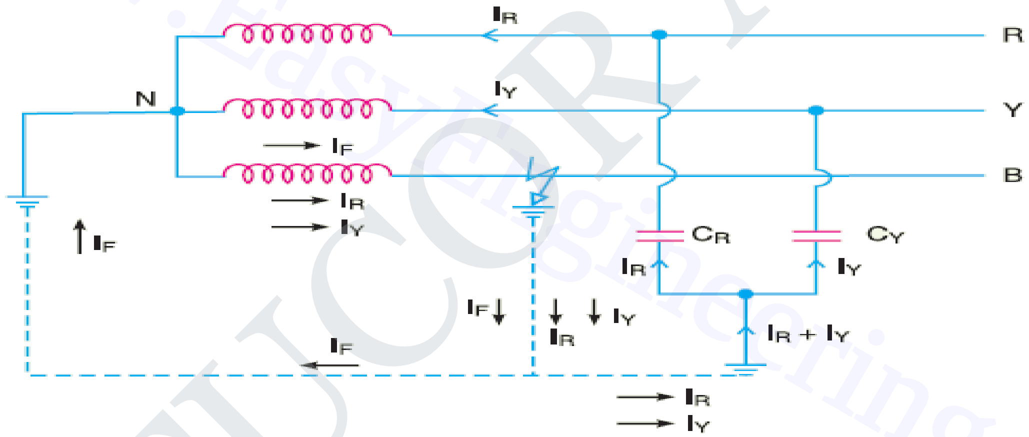


Fig. 30

(ii) When earth fault occurs on any phase, the resultant capacitive current $I_C$is in phase opposition to the fault current I_F. The two currents completely cancel each other. Therefore, no arcing ground or over-voltage conditions can occur. Consider a line to ground fault in line *B* as shown in Fig. 30. The capacitive currents flowing in the healthy phases *R* and *Y* are $I_R$and$I_Y$respectively. The resultant capacitive current $I_C$is the phasor sum of $I_R$andI_Y. In addition to these capacitive currents, the power source also supplies the fault current I_F. This fault current will go from fault point to earth, then to neutral point *N* and back to the fault point through the faulty phase. The path of $I_C$is capacitive and that of $I_F$is inductive. The two currents are in phase opposition and completely cancel each other. Therefore, no arcing ground phenomenon or over-voltage conditions can occur.
(iii) When there is an earth fault on any phase of the system, the phase to earth voltage of the Faulty phase becomes zero. However, the phase to earth voltages of the remaining two healthy phases remains at normal phase voltage because the potential of the neutral is fixed at earth potential. This permits to insulate the equipment for phase voltage. Therefore, there is a saving in the cost of equipment.

(*iv*) It becomes easier to protect the system from earth faults which frequently occur on the system. When there is an earth fault on any phase of the system, large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earthfaultrelay.

Disadvantages. The following are the disadvantages of solid grounding:

(*i*) Since most of the faults on an overhead system are phase to earth faults, the system has to bear a large number of severe shocks. This causes the system to become unstable.

(*ii*) The solid grounding results in heavy earth fault currents. Since the fault has to be cleared by the circuit breakers, the heavy earth fault currents may cause the burning of circuit breaker contacts.

(*iii*) The increased earth fault current results in greater interference in the neighboring communication lines.

Applications. Solid grounding is usually employed where the circuit impedance is sufficiently high so as to keep the earth fault current within safe limits. This system of grounding is used for voltages up to 33 kV with total power capacity not exceeding 5000 kVA.

Explain the following: (i) Neutralgrounding (ii) Resistance grounding. [16][April/May'15][A]

Resistance Grounding

In order to limit the magnitude of earth fault current, it is a common practice to connect the neutral point of a 3-phase system to earth through a resistor. This is called *resistance grounding. When the neutral point of a 3-phase system (e.g. 3-phase generator, 3-phase transformer etc.)is connected to earth (i.e. soil) through a resistor, it is called* **resistance grounding.**

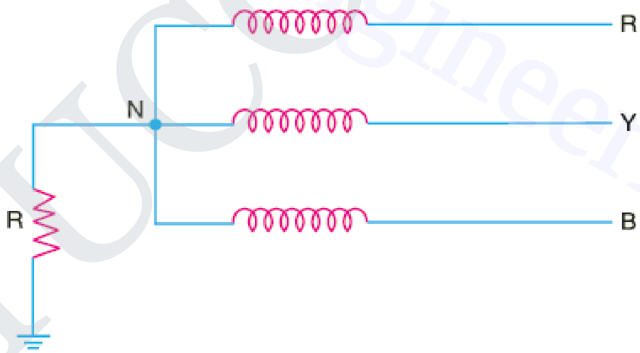


Fig 31

Fig. 31 shows the grounding of neutral point through a resistor *R*. The value of *R* should neither be very low nor very high. If the value of earthing resistance *R* is very low, the earth fault current will be large and the system becomes similar to the solid grounding system. On the other hand, if the earthing resistance *R* is very high, the system conditions become similar to ungrounded neutral system. The value of *R* is so chosen such that the earth fault current is limited to safe value but still sufficient to permit the operation of earth fault protection system. In practice, that value of *R* is selected that limits the earth fault current to 2 times the normal full load current of the earthed generator or transformer.

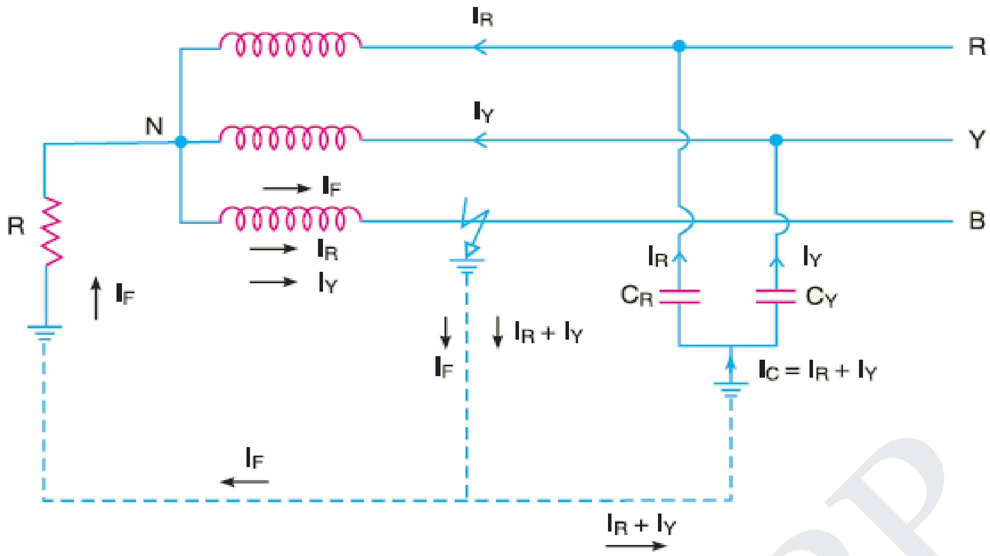


Fig 32

Advantages. The following are the advantages of resistance earthing:

(i) By adjusting the value of *R*, the arcing grounds can be minimized. Suppose earth fault occurs in phase *B* as shown in Fig. 32The capacitive currents $I_R$and$I_Y$flow in the healthy phases *R* and *Y* respectively. The fault current $I_F$lags behind the phase voltage of the faulted phase by a certain angle depending upon the earthing resistance *R*and the reactance of the system up to the point of fault. The fault current $I_F$can be resolved into two components *viz.*

(a) I_{F1} in phase with the faulty phase voltage.

(b) I_{F2} lagging behind the faulty phase voltage by 90°.

The lagging component I_{F2} is in phase opposition to the total capacitive current I_C. If the value ofearthing resistance *R* is so adjusted that $I_{F2} = I_C$, the arcing ground is completely eliminated and the operation of the system becomes that of solidly grounded system. However, if *R* is so adjusted that $I_{F2}<I_C$, the operation of the system becomes that of ungrounded neutral system.

(ii) The earth fault current is small due to the presence of earthing resistance. Therefore, interference with communication circuits is reduced.

(iii) It improves the stability of the system.

Disadvantages. The following are the disadvantages of resistance grounding:

(i) Since the system neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.

(ii) This system is costlier than the solidly grounded system.

(iii) A large amount of energy is produced in the earthing resistance during earth faults. Sometimes it becomes difficult to dissipate this energy to atmosphere.

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

Reactance Grounding

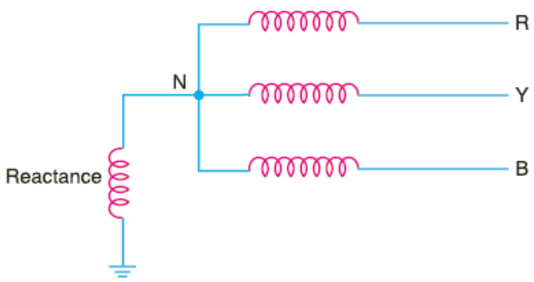


Fig 33

In this system, a reactance is inserted betweenthe neutral and ground as shown in Fig. 33. The purpose of reactance is to limit the earth fault current. By changing the earthing reactance, the earth fault current can to change to obtain the conditions similar to that of solid grounding. This method is not used these days because of the following disadvantages:
(i) In this system, the fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.
(ii) High transient voltages appear under fault conditions.
Arc Suppression Coil Grounding (or Resonant Grounding)

We have seen that capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitance exists between each line and earth. If inductance L of appropriate value is connected in parallel with the capacitance of the system, the fault current $I_F$flowing through L will be in phase opposition to the capacitive current $I_C$of the system. If L is so adjusted that $I_L= I_C$, then resultant current in the fault will be zero. This condition is known as *resonantgrounding. When the value of L of arc suppression coil is such that the fault current* I_F *exactly balances thecapacitive current* I_C, *it is called* **resonant grounding**.

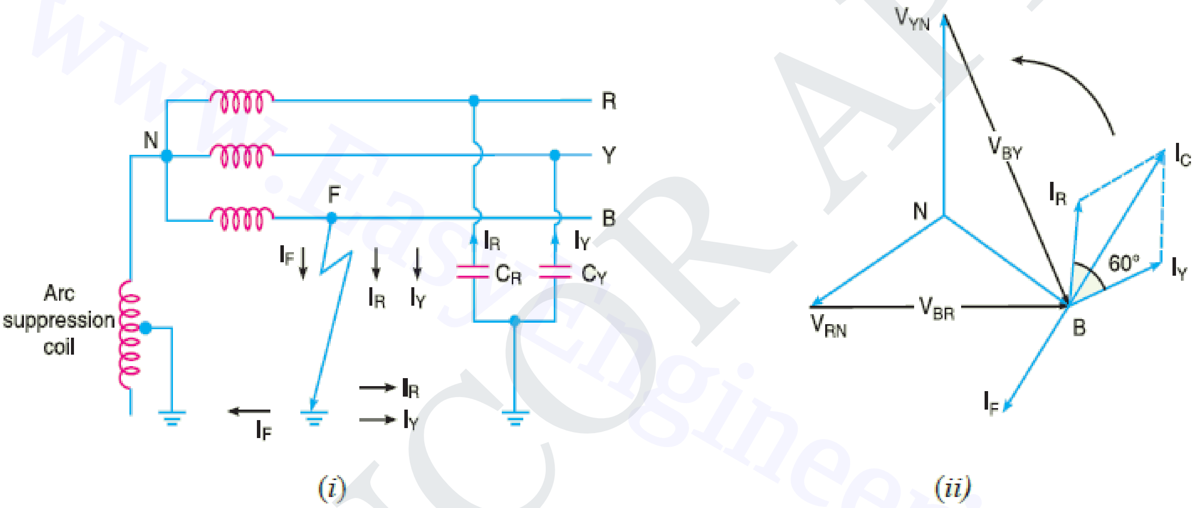


Fig 34

Circuit details. An arc suppression coil (also called Peterson coil) is an iron-cored coil connected between the neutral and earth as shown in Fig. 34(*i*). The reactor is provided with tapping to change the inductance of the coil. By adjusting the tapings on the coil, the coil can be tuned with the capacitance of the system i.e. resonant grounding can be achieved.
Operation. Fig. 34(*i*) shows the 3-phase system employing Peterson coil grounding. Suppose line to ground fault occurs in the line *B* at point *F*. The fault current $I_F$and capacitive currents$I_R$and $I_Y$will flow as shown in Fig. 34(*i*). Note that $I_F$flows through the Peterson coil (or Arc suppression coil) to neutral and back through the fault. The total capacitive current $I_C$is the Phasor sum of $I_R$and$I_Y$as shown in phasor diagram in Fig. 34(*ii*). The voltage of the faulty phase is applied across the arc suppression coil. Therefore, fault current *IF* lags the faulty phase voltage by 90°. The current $I_F$is in phase opposition to capacitive current I_C[See Fig. 34(*ii*)]. By adjusting the tapings on the Peterson coil, the resultant current in the fault can be reduced. If inductance of the coil is so adjusted that $I_L= I_C$, then resultant current in the fault will be zero.
Value of L for resonant grounding. For resonant grounding, the system behaves as an ungrounded neutral system. Therefore, full line voltage appears across capacitors $C_R$and C_Y.

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

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

Here, $X_C$is the line to ground capacitive reactance.

Fault current, $I_F = \frac{V_{Ph}}{X_L}$

Here, $X_L$is the inductive reactance of the arc suppression coil.
For resonant grounding, $I_L = I_C$.

Or $\frac{V_{ph}}{X_L} = \frac{3V_{ph}}{X_C}$ *or* $X_L = \frac{X_C}{3}$ *or* $\omega L = \frac{1}{3\omega C}$

$$\therefore L = \frac{1}{3\omega^2 C} \quad \text{.......................... (i)}$$

Exp. (*i*) gives the value of inductance *L* of the arc suppression coil for resonant grounding.
Advantages. The Peterson coil grounding has the following advantages:
(*i*) The Peterson coil is completely effective in preventing any damage by an arcing ground.
(*ii*) The Peterson coil has the advantages of ungrounded neutral system.
Disadvantages. The Peterson coil grounding has the following disadvantages:
(*i*) Due to varying operational conditions, the capacitance of the network changes from time to time. Therefore, inductance *L* of Peterson coil requires readjustment.
(*ii*) The lines should be transposed.

Voltage Transformer Earthing

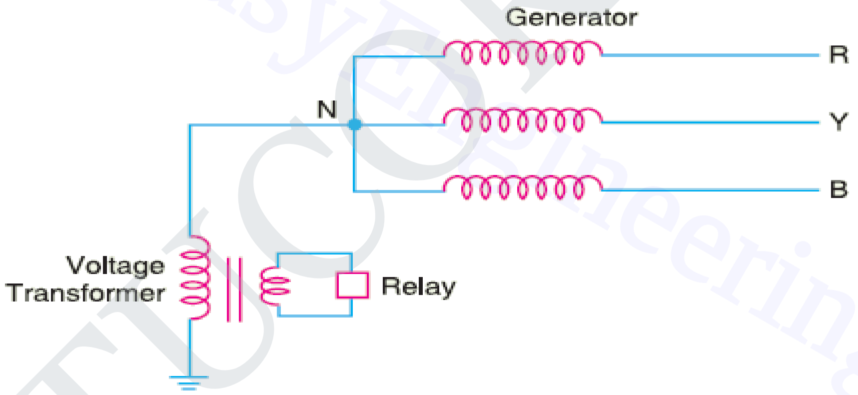


Fig 35

In this method of neutral earthing, the primary of a single-phase voltage transformer is connected between the neutral and the earth as shown in Fig. 26.17. A low resistor in series with a relay is connected across the secondary of the voltage transformer. The voltage transformer provides a high reactance in the neutral earthing circuit and operates virtually as an ungrounded neutral system. Anearth fault on any phase produces a voltage across the relay. This causes the operation of the protective device.

Advantages. The following are the advantages of voltage transformer earthing:
(*i*) The transient overvoltage's on the system due to switching and arcing grounds are reduced.
It is because voltage transformer provides high reactance to the earth path.
(*ii*) This type of earthing has all the advantages of ungrounded neutral system.
(*iii*) Arcing grounds are eliminated.
Disadvantages. The following are the disadvantages of voltage transformer earthing:

(i) When earth fault occurs on any phase, the line voltage appears across line to earth capacitances. The system insulation will be overstressed.
(ii) The earthed neutral acts as a reflection point for the travelling waves through the machine winding. This may result in high voltage build up.
Applications. The use of this system of neutral earthing is normally confined to generator Equipment's which are directly connected to step-up power transformers.
Grounding Transformer
We sometimes have to create a neutral point on a 3-phase, 3-wire system (e.g. delta connection etc.)to change it into 3-phase, 4-wire system. This can be done by means of a *grounding transformer*. It is a core type transformer having three limbs built in the same fashion as that of the power transformer. Each limb of the transformer has two identical windings wound differentially (i.e. directions of current in the two windings on each limb are opposite to each other) as shown in Fig. 36 Under normal operating conditions, the total flux in each limb is negligibly small. Therefore, the transformer draws very small magnetizing current.

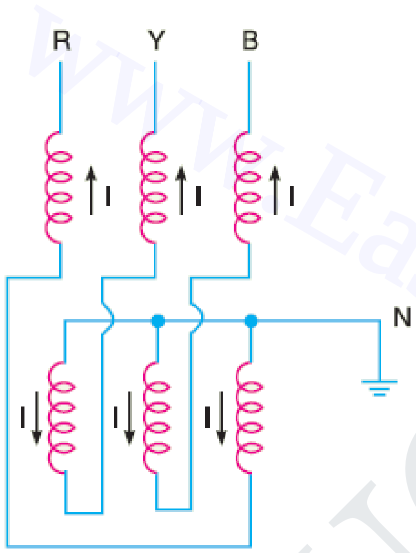


Fig 36

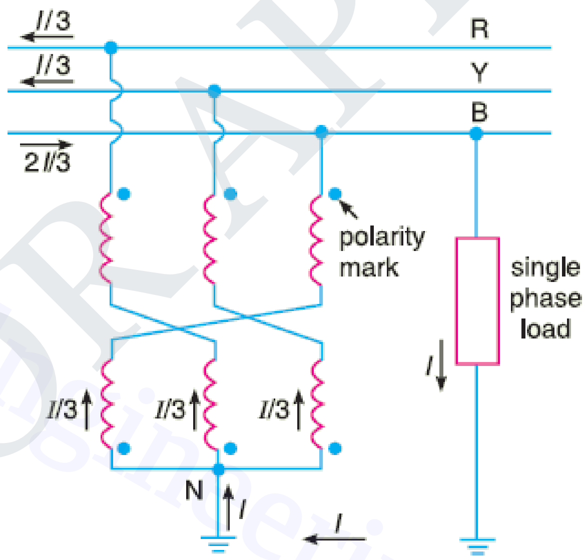


Fig 37

Fig. 37 shows the use of grounding transformer to create neutral point *N*. If we connect a single-phase load between one line and neutral, the load current *I* divide into three equal currents in each winding. Because the currents are equal, the neutral point stays fixed and the line to neutral voltages remain balanced as they would be on a regular 4-wire system. In practice, the single-phase loads are distributed as evenly as possible between the three phases and neutral so that unbalanced load current *I* is relatively small. The impedance of grounding transformer is quite low. Therefore, when line to earth fault occurs, the fault current will be quite high. The magnitude of fault current is limited by inserting a resistance (not shown in the figure) in the neutral circuit. Under normal conditions, only iron losses will be continuously occurring in the grounding transformer. However, in case of fault, the high fault Current will also produce copper losses in the transformer. Since the duration of the fault current is generally between 30-60 seconds, the copper losses will occur only for a short interval.

PART-A

1. **What is Ring main distributor?[Nov/Dec 12][R]**
In this system, various power stations or sub-stations are interconnected alternate routes, thus forming a closed ring. In case of damage to any section of the ring, that section may be disconnected for repairs and power will be supplied from both ends of the ring. A radial system has a single simultaneous path of power.
2. **List the types of substations[Nov/Dec 12][Nov/Dec'10][R]**
    - Indoor sub-station
    - Outdoor sub-station
    - Underground sub-station
    - Pole-mounted sub-station
3. **Mention any 4 bus schemes in the substation. [May/June'13][R]**
    - Single bus single breaker scheme
    - Double bus double breaker scheme
    - Main transfer bus scheme
    - Ring main arrangement scheme
    - One and half breaker scheme
4. **What is the function of isolators? [Nov/Dec'13][R]**
The function of isolators is to disconnect a part of power system for repair and maintenance and operated after switching off the load by means of a circuit breaker.
5. **What is the need of an earthing system?[Nov/Dec'13][R]**
In order to provide safety of personnel or human beings against electrical shocks (include animals and plants), to reduce the possibility of getting electrical shocks and avoiding accidents, to protect the equipment's, buildings, machinery/appliances against lightning and voltage surges, to reduce stress on the lines along with that on the equipment with respect to earth under abnormal conditions earthing is required.
6. **State the advantages of outdoor substation over indoor substation.[April/May'11][R]**
Following are the disadvantages of outdoor substation over indoor substation:
i. Time required for erection is less
ii. Future expansion is easier
iii. The capital cost required is less
iv. All equipment's are within view and the fault location is easier
v. The cost of switchgear installation is less and amount of building material required is small.
7. **What are the objectives of earthing?[April/May'11][R]**
i. It should provide adequate safety of operating personnel/human being (including animals and plants) against electrical shocks/hazards and avoid accidents
ii. It should provide an alternative path for the fault current to flow so as to reduce danger of the user

iii. It should ensure that all the exposed conductive parts do not reach a dangerously high potential and should reduce the stress on the lines along with that on the equipment with respect to earth under abnormal conditions.
iv. It should be able to maintain the voltage at any part of an electrical system at a known value so as to avoid excessive voltage on the appliances or equipment or over current situation.

8. **What are the various methods of earthing in substations?[Nov/Dec'11][U]**
The earthing in substations is carried out with the help of equipment's such as electrodes, driven rods, risers and grounding grid or mat consisting of number of meshes and connected to several earth electrodes driven at intervals. The various methods adopted for earthing are
i. Solid or effective grounding
ii. Resistance grounding
iii. Reactance grounding
iv. Resonant grounding

9. **What are the materials mainly used in bus bars?[April/May'15][U]**
The bus bars are either rigid type of strain type. For rigid type bus bars, copper or aluminum bars are used. Such bus bars are used for low and medium voltage levels. For strain type bus bars mainly stranded aluminum (ACSR) conductors are used which are supported by strain insulators. The strain type bus bars are used for high voltage levels.

10. **What are the classifications of substation according to service?[April/May'15][U]**
According to service, the substations are classified as:
i. Transformer substations: In these substations, power is transformed from one voltage level to other.
These are further classified as, transmission or primary substation, sub transmission or secondary substation and step down or distribution substation.
ii. Industrial substations: For industries demanding huge power, a separate substation is installed.
iii. Switching substations: These are used for switching operations of power lines
iv. Synchronous substations: These are used for synchronous phase modifiers used for the improvement of power factor.
v. Frequency change substations: These are used for converting normal frequency to other useful frequency.
vi. Converting substations: These are used for converting a.c to d.c required for electric welding, battery charging etc.

11. **Define sag.[May/June'16][Nov/Dec'13][U]**
When a conductor is suspended between two points then it takes the shape of parabola or catenary and sags down. The difference in levels between the point of support and the lowest point on the conductor is called sag.

12. **What is meant by tower spotting?[Nov/Dec'15][R]**
A celluloid template, shaped to the form of the suspended conductor, is used to scale the distance from the conductor to the ground and to adjust structure locations

and heights to (1) provide proper clearance to the ground; (2) equalize spans; and (3) grade the line.

13. **What is meant by sag template?[Nov/Dec'15][U]**
For normal spans and for standard towers, the sag and the nature of the conductor curve are calculated under excepted load conditions and plotted on a thin stiff plastic sheet. Such a graph is called sag template.
14. **What are the advantages of ring main distributors?[May/June'16][R]**
   i. The feeders get equally loaded.
   ii. If fault develops on one of the feeders then consumer gets continuous supply from the other part of the feeder.
   iii. It eliminates the possibility of the voltage fluctuations
   iv. Easy from the maintenance and repair point of view without interrupting the supply to the consumers.
   v. Great saving in copper required.
15. **What is the economic value of span of 400kV transmission line?[April/May'10][R]**
The span must be between 200m to 400m. For river and ravine crossing exceptionally long spans up to 800m or so is sufficient.
16. **Give two factors which affect the sag in transmission line. [Nov/Dec'12][R]**
   i. Ice coating on the conductor which increases weight of the conductor
   ii. Wind pressure due to which the conductor gets subjected to the additional forces.
17. **What is deviation tower?[April/May'13]**[R]
The transmission line goes as per available straight paths as far as possible. Due to unavailability of shortest distance straight corridor, transmission line has to deviate from its straight way then obstruction comes. The towers used in such cases to deviate the route of the transmission lines are called deviation towers or angle towers. The design of such towers is such that they can withstand large mechanical stress.
18. **Define factor of safety.[U]**
The ultimate stress which conductor can sustain without fail is called breaking stress. The normal tension in the conductor is called working stress. The ration of breaking stress to the working stress is called the factor of safety denoted as S_f.
19. **Which are the types of vibrations possible in overhead conductors?[U]**
The two types of vibrations possible in overhead conductors in vertical plane are
   i. Aeoline vibrations having frequency range of 8 to 40 Hz with amplitudes varying from 2 to 5 cm.
   ii. Galloping or dancing of conductors at the low frequency and high amplitude.

PART-B

1. Explain the following: (i) Main and transfer bus (ii) Ringbus (iii) double bus with single breaker (iv) Double bus-bar with bypass isolators. [16] [Nov/Dec 12][U]
2. Explain the following. (i) solid grounding (ii) Reactance grounding (iii) Indoor substations (iv) Outdoor substations.[16] [May/June'13][U]

3. Write a short note on sub—station equipment's.[10][Nov/Dec'13][U]
4. Explain about double bus—bar with bypass isolators scheme[6][Nov/Dec'13][U]
5. Discuss the design of primary distribution system with respect to following: (i) Selection of voltage[6] (ii) Choice of scheme [5] (iii) Size of feeders[5][April/May'11][U]
6. Explain the following substation bus schemes. (i) Main and transfer bus (ii) double bus-bar with bypass isolators.[16]Discuss the design of primary distribution system with respect to following: (i) Selection of voltage[6] (ii) Choice of scheme [5] (iii) Size of feeders[5][April/May'11][U]
7. Draw the circuit arrangement and explain the various elements of the following bus-bar arrangements. (i) Single bus scheme (ii) Double bus-bar scheme (iii) Main transfer bus-bar. (iv) Mesh scheme.[16][Nov/Dec'11][A]
8. Explain briefly the various types of bus bar arrangements in a substation.[16][Nov/Dec'10][A]
9. Write shorts on : (i) sub mains (ii) Stepped and tapered mains (iii) Grounding grids.[16][April/May'15][A]
10. Explain the following: (i) Neutral grounding (ii) Resistance grounding.[16][April/May'15][A]
11. Explain the methods of neutral grounding.[16][May/June'16][Nov/Dec'15][A]
12. A transmission line has a span of 275 m between level supports. The conductor has an effective diameter of 1.96cm and weighs 0.865kg/m. If the conductor has ice coating of radial thickness 1.27cm and is subjected to a wind pressure of 3.9 gm/sq.cm of projected area. The ultimate strength of the conductor is 8060kg. Calculate the sag if the factor of safety is 2 and weight of 1 c.c of ice is 0.91gm.[16][May/June'16][A]
13. Assuming that the shape of an overhead line can be approximated by a parabola, deduce expressions for calculating sag and conductor length. How can the effect of wind and ice loadings be taken into account?[16][Nov/Dec'15][A]
14. Draw and explain the single line diagram, showing the location of substation equipment's for the following bus bar arrangements:
    (iii) Single bus scheme
    (iv) Single bus-bar with sectionalizing scheme
    State the merits and demerits of each scheme. [16][May/June'16][A]
15. Explain the reasons leading to the general practice of earthing the neutral point of a power system. Discuss the relative merits of earthing it (1) solidly and (2) through a resistance.[10][May/June'16][U]
16. Write short notes on 'earthing practices in a substation'.[06][May/June'16][R]
17. What are the different types of bus bar arrangement used in substations? Illustrate your answer with suitable diagrams.[16][Nov/Dec'15][R]