oltage drop in AB = 203.15 × 0.02 = 4.063 V

" " " BC = 53.15 × 0.018 = 0.960 V

" " " AD = 244.45 × 0.02 = 4.9 V

∴ potential of B = 250 − 4.063 = 245.93 V

" " C = 245.93 − 0.960 = 244.97 V

" " D = 250 − 4.9 = 245.1 V

It can be seen that with the use of interconnector, the voltage drops in the various sections of the distributor are reduced, leading to the rise of voltages at points B, C, and D.

Electric Supply Systems

An electric supply system consists of three principal components, the power station, the transmission lines and the distribution system.

The electric supply system can be classified into:

1. AC or DC system
2. Overhead or Underground system.

Now adays, 3 phase, 3 wire AC system is universally adopted for generation and transmission of electric power as an economical proposition, However, distribution of electric power is done by three phase four wire AC system.

Typical AC Power System

The large network of conductors between the power station and the consumers can be broadly divided into two parts, transmission system and distribution system.

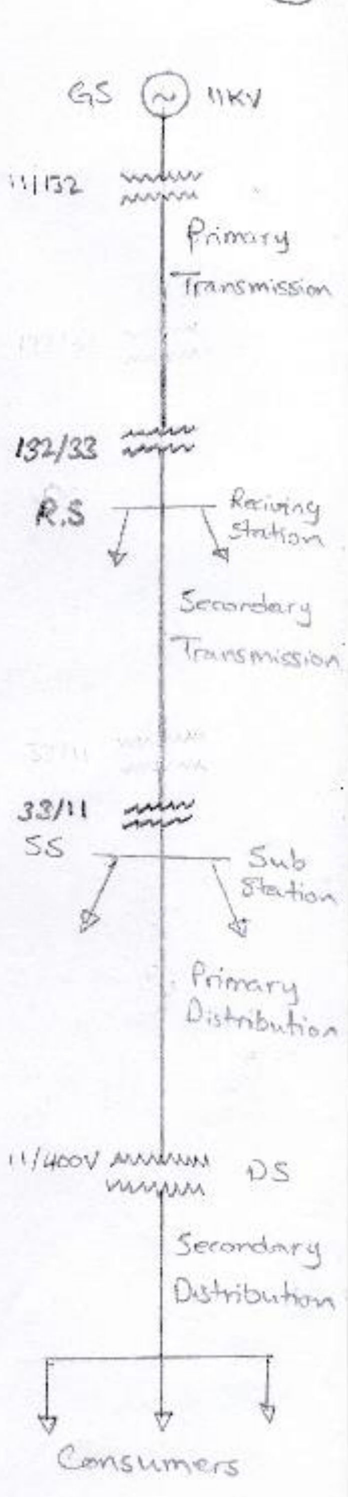
Consider fig(1)

1. Generating Station G.S
where electric power is produced by 3 phose alterrators operating in parallel. The usual generation voltage 11KV is stepped up to 132KV (or more) at the generating station by three phase transformers.

2. Primary Transmission, the electric power at 132 KV is transmitted by 3 phase 3 wire overhead system to the out skirts of the city.

3. Secondary transmission, the primary transmission line terminates at the recieving station (RS) where the voltage is reduced to 33KV. From this station, electric power is transmitted at 33KV by 3 phase 3 wire overhead system to various substations (SS) located at the strategic points in the city.

4. Primary Distribution, where voltage is reduced to 11KV, 3 phase, 3 wire. It may be noted that big consumers having demand more than 50KW are generally supplied at 11KV.



AC Transmission

Nowadays, electrical energy is almost exclusively generated, transmitted and distributed in the form of AC.

Advantages

1. The power can be generated at high voltages.
2. The maintenance of AC substations is easy and cheap.
3. The AC voltage can be stepped up or down by transformers with ease and efficiency. This permits to transmit power at high voltages and distribute it at safe potentials.

Disadvantages

1. An AC line requires more copper than a DC line.
2. The construction of an AC transmission line is more complicated than a DC transmission line.
3. Due to skin effect in AC system, the effective resistance of the line is increased.
4. There is a continuous loss of power due to charging current even when the line is open.

Advantages of High Transmissinon Voltage

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

i. Reduced volume of conductor material.

Consider the transmission by a three phase line.

P : Power transmitted in watts

W : Power loss

V : line voltage

$\cos\varphi$: power factor of the load.

l : length of the line in meters.

R : resistance per conductor in ohms.

ρ : resistivity of conductor material,

a : area of X-section of conductor,

$$P = \sqrt{3}\, V I \cos\varphi$$

$$\therefore \text{load current } I = \frac{P}{\sqrt{3}\, V\cos\varphi}$$

$$\text{Total power loss } W = 3I^2R$$

$$\text{resistance per conductor } R = \rho\frac{l}{a}$$

$$\therefore W = 3\left(\frac{P}{\sqrt{3}\, V\cos\varphi}\right)^2 \rho\frac{l}{a}$$

$$W = \frac{P^2\rho l}{V^2\cos^2\varphi\, a}$$

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

Total volume of conductor material $= 3 a l$

$$= \frac{3 P^2 \rho l^2}{\omega V^2 \cos^2\varphi}$$

For given values of P, ρ, l and ω the volume of conductor material required is inversely proportional to the square of transmission voltage and power factor

2. Increased transmission efficiency.

input power $= P +$ Total losses

$$= P + \frac{P^2 \rho l}{V^2 \cos^2\varphi\, a}$$

assuming J to be the current density

Then $\quad J = \frac{I}{a} \Rightarrow a = \frac{I}{J}$

$$\therefore \text{I/P power} = P + \frac{P^2 \rho l J}{V^2 \cos^2\varphi\, I}$$

$$= P + \frac{P^2 \rho l J}{V^2 \cos^2\varphi} \frac{\sqrt{3} V \cos\varphi}{P}$$

$$= P + \frac{\sqrt{3} P \rho l J}{V \cos\varphi}$$

$$= P\left(1 + \frac{\sqrt{3} \rho l J}{V \cos\varphi}\right)$$

$$\text{Transmission efficiency} = \frac{\text{O/P}}{\text{I/P}} = \frac{P}{P\left(1 + \frac{\sqrt{3} \rho l J}{V\cos\varphi}\right)}$$

$$\eta_T = \frac{1}{1 + \frac{\sqrt{3} \rho l J}{V \cos\varphi}} \approx 1 - \frac{\sqrt{3} \rho l J}{V \cos\varphi}$$

3. Decreased percentage line drop.

$$\text{Line drop} = IR$$
$$= I\rho\frac{l}{a}$$
$$= I\rho l\frac{J}{I}$$
$$= \rho l J$$
$$\text{percentage line drop} = \frac{\rho l J}{V} \times 100\%$$

as ρ, l and J are constants, therefore, percentage line drop decreases when the transmission voltage increases

Limitations of high transmission voltage

From the above discussion, it might appear advisable to use the highest possible voltage, however, it must be realised that high transmission voltage results in

1. The increased cost of insulating the conductors.
2. The increased cost of transformers, switchgear, and other terminal apprarates.

Therefore, there is a limit to the higher transmission voltage which can be economically employed in a particular case. Hence, the choice of proper transmission voltage is essentially a question of economics.

Comparison of conductor material in over head systems

Similar conditions will be assumed

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

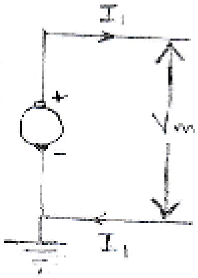
ii. " distance (l meters) over which power is transmitted

iii. " line losses (W watts) in each case

iv. The max. voltage between any conductor and earth (V_m) is the same in each case

i. Two wire DC system with one conductor earthed

The load is connected between the two wires.



Max. voltage between conductors $= V_m$

Power to be transmitted $= P$

$$\therefore I_1 = \frac{P}{V_m}$$

The resistance of each conductor $= R_1$

$$R_1 = \rho \frac{l}{a_1}$$

where a_1 is the cross-sectional area

Line losses $W = 2 I_1^2 R_1$

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

$$\therefore a_1 = \frac{2P^2 \rho l}{W V_m^2}$$

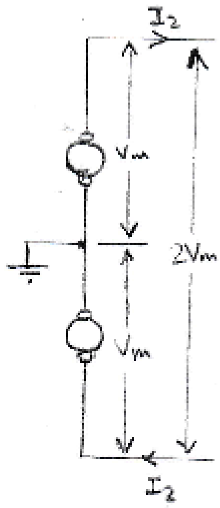
Volume of conductor material $= 2 a_1 l$

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

It is usual practice to make this system as the basis for comparison.

2. Two wire DC system with midpoint earthed

Max. voltage between any conductor and earth is V_m, so that max. voltage between conductors is $2V_m$



$$I_2 = \frac{P}{2V_m}$$

$$W = 2 I_2^2 R_2$$

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

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

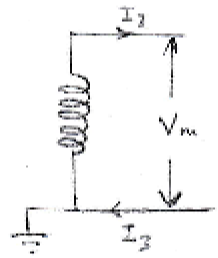
vol. of conductor material $= 2 a_2 l$

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

3. Single phase 2-wire a.c. system with one conductor earthed

Max. voltage between conductors $= V_m$

$\therefore$ r.m.s. voltage $= V_m/\sqrt{2}$



$$P = \frac{V_m}{\sqrt{2}} I_3 \cos\varphi$$

$$I_3 = \frac{P}{\frac{V_m}{\sqrt{2}} \cos\varphi}$$

Line losses $W = 2 I_3^2 R_3 = 2\left(\frac{P}{\frac{V_m}{\sqrt{2}} \cos\varphi}\right)^2 \frac{\rho l}{a_3} = \frac{4 P^2 \rho l}{V_m^2 \cos^2\varphi \, a_3}$

Vol. of conductor material $= 2 a_3 l = 2 \dfrac{4 P^2 \rho l^2}{V_m^2 W \cos^2\varphi}$

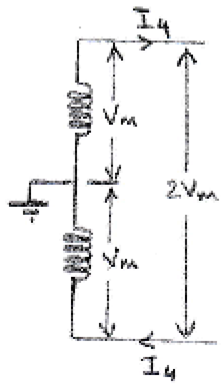
$$= \frac{2K}{\cos^2\varphi}$$

4. Single phase 2-wire a.c. system with midpoint earthed

The two wires possess equal and opposite voltages to earth (V_m). Therefore the max. voltage between the two wires $= 2V_m$

$\therefore$ r.m.s voltage between conductors is :

$$\frac{2V_m}{\sqrt{2}} = \sqrt{2}\,V_m$$



$$I_4 = \frac{P}{\sqrt{2}\,V_m \cos\varphi}$$

Line losses $W = 2 I_4^2 R_4 = 2\left(\frac{P}{\sqrt{2}\,V_m \cos\varphi}\right)^2 R_4$

$$\therefore W = \frac{P^2 \rho l}{V_m^2 \cos^2\varphi \; a_4}$$

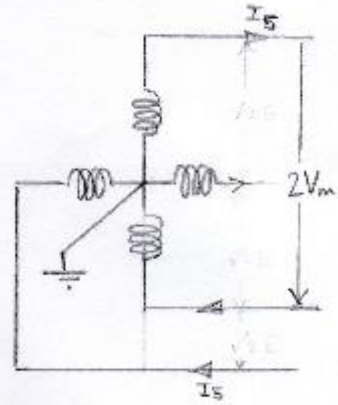
$$\therefore a_4 = \frac{P^2 \rho l}{W V_m^2 \cos^2\varphi}$$

Vol. of conductor material $= 2 a_4 l = \dfrac{2P^2 \rho l^2}{W V_m^2 \cos^2\varphi}$

$$= \frac{K}{2\cos^2\varphi} \qquad \left(K = \frac{4P^2 \rho l^2}{W V_m^2}\right)$$

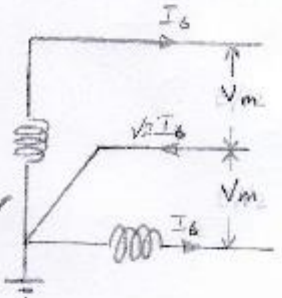
Hence the volume of conductor material required in this system is $\frac{1}{2\cos^2\varphi}$ times that of a two wire D.C. system with one conductor earthed.

5. Two phase 4 wire a.c. system



This system can be considered as two independent single phase 2wire systems each carrying half the total power so that conductor size need be only half that calculated in (4) but the number of conductors being double.
The total volume of conductors remains the same.

6. Two phase 3 wire



The two phase winding voltages are in quadrature with each other.
The r.m.s voltage between outgoing conductors and neutral is $V_m/\sqrt{2}$
each phase transmits half the total power

$$I_6 = \frac{P/2}{V_m/\sqrt{2}\ \cos\varphi} = \frac{P}{\sqrt{2}\ V_m \cos\varphi}$$

current in neutral $= \sqrt{I_6^2 + I_6^2} = \sqrt{2}\, I_6$

For constant current density, the X-section of the neutral wire will be $\sqrt{2}$ times that of either of the outers.

$\therefore$ Resistance of neutral wire $= \dfrac{\rho l}{\sqrt{2}\, a_6} = \dfrac{R_6}{\sqrt{2}}$

$$\text{Line losses} = 2 I_6^2 R_6 + (\sqrt{2}\, I_6)^2 \frac{R_6}{\sqrt{2}}$$

$$W = I_6^2 R_6 (2 + \sqrt{2})$$

$$W = \left(\frac{P}{\sqrt{2}\ V_m \cos\varphi}\right)^2 \frac{\rho l}{a_6} (2 + \sqrt{2})$$

$$\therefore a_6 = \frac{P^2 \rho l}{2 W V_m^2 \cos^2\varphi} (2 + \sqrt{2})$$

volume of conductor material required is

$$= 2 a_6 l + \sqrt{2} a_6 l$$

$$= a_6 l (2 + \sqrt{2})$$

$$= \frac{P^2 \rho l^2}{2 W V_m^2 \cos^2 \varphi} (2+\sqrt{2})^2$$

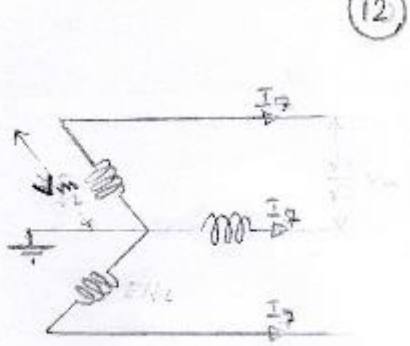
$$= \frac{(2+\sqrt{2})^2}{4 \times 2 \cos^2 \varphi} \frac{4 P^2 \rho l^2}{W V_m^2}$$

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

7. Three phase three wire

The rms voltage to neutral $= \frac{V_m}{\sqrt{2}}$

power transmitted per phase $= \frac{P}{3}$



$$I_7 = \frac{\frac{P}{3}}{\frac{V_m}{\sqrt{2}}\cos\varphi} = \frac{\sqrt{2}\,P}{3\,V_m\cos\varphi}$$

$$W = 3 I_7^2 R_7 = \frac{2P^2\rho l}{3\,a_7 V_m^2\cos^2\varphi}$$

$$\therefore a_7 = \frac{2P^2\rho l}{3W V_m^2\cos^2\varphi}$$

vol. of conductor material required $= 3 a_7 l$

$$= 3\left(\frac{2P^2\rho l}{3W V_m^2\cos^2\varphi}\right) l$$

$$= \frac{2P^2\rho l^2}{W V_m^2\cos^2\varphi} = \frac{1}{2\cos^2\varphi}\,\frac{4P^2\rho l^2}{W V_m^2}$$

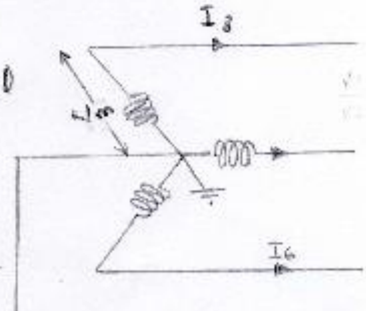
$$= \frac{K}{2\cos^2\varphi}$$

8. Three phase four wire

The x-sectional area of the neutral wire is generally one-half that of the line conductor.

Line losses same as in 7

$$\therefore W = \frac{2P^2\rho l}{3\,a_8 V_m^2\cos^2\varphi}$$



vol. of conductor material $= 3.5 a_8 l$

$$= 3.5\left(\frac{2P^2\rho l}{3W V_m^2\cos^2\varphi}\right) l$$

$$= \frac{7}{12\cos^2\varphi}\,\frac{4P^2\rho l^2}{W V_m^2}$$

$$= \frac{7K}{12\cos^2\varphi}$$

Ex. Estimate the weight of copper required for a 3 phase transmission system supplying 380KV between lines a load of 100MW at a lagging power factor of 0.9. the length of the line is 150 Km. The neutral point is earthed. Efficiency is 92%. The resistance of conductor 1Km long and 1cm² x-section is 0.045 Ω (13)

One cm³ of copper weighs 0.01 Kg.

Find also the weight of copper required for the DC transmission of the same power with equal losses working at a voltage between the lines double that of the peak voltage to earth of the 3 phase supply.

Sol. $$\text{line current} = \frac{100\times10^6}{\sqrt{3}\times380\times10^3\times0.9} = 169\ A$$

$$\eta = 0.92 = \frac{o/p}{o/p + loss} = \frac{10^8}{10^8 + \omega}$$

$$\omega = \frac{10^8}{0.92} - 10^8$$

$$= 8.7\times10^6\ W \text{ is the power loss}$$

$$\therefore I^2R \text{ loss per conductor} = \frac{8.7\times10^6}{3}$$

$$\therefore R = \frac{8.7\times10^6}{3\times(169)^2} = 101.8\ \Omega \text{ per conductor}$$

$$= \frac{101.8}{150} = 0.68\ \Omega \text{ per conductor per Km.}$$

$$\text{given resistance} = 0.045 = \rho\frac{l}{a} = \rho\frac{1Km}{1cm^2}$$

$$R = \rho\frac{l}{a} = 0.68 = 0.045\times\frac{1cm^2}{1Km}\times\frac{1Km}{a}$$

$$\therefore a = \frac{0.045}{0.68} = 0.066\ cm^2$$

volume of copper per meter = $0.066 \times 100 = 6.6\ cm^3$

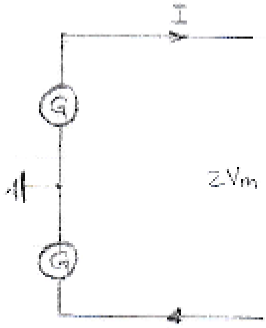
$\therefore$ weight of copper per meter = 6.6×0.01 Kg

$\therefore$ weight for 3 conductors of 150 Km is

$= 3 \times 150 \times 1000 \times 6.6 \times 0.01$

$= 29850$ Kg

(ii) Let V_m = max. ac voltage to neutral
P = power supplied in watts.



$$\text{Losses (DC)} = 2 I^2 R_1$$
$$= 2\left(\frac{P}{2V_m}\right)^2 R_1$$
$$= \frac{P^2}{2V_m^2} R_1$$

For AC losses

rms of phase voltage = $\frac{V_m}{\sqrt{2}}$

rms of line voltage = $\frac{\sqrt{3}}{\sqrt{2}} V_m$

$$P = \sqrt{3}\, V_L I_L \cos\varphi$$

$$\therefore I_L = \frac{P}{\sqrt{3}\,\frac{\sqrt{3}}{\sqrt{2}} V_m \cos\varphi} = \frac{\sqrt{2}\,P}{3 V_m \cos\varphi}$$

$$\text{Losses (AC)} = 3 I_L^2 R_2 = 3\left(\frac{\sqrt{2}\,P}{3V_m\cos\varphi}\right)^2 R_2 = \frac{2P^2}{3V_m^2\cos^2\varphi} R_2$$

since the losses are the same

$$\therefore \frac{P^2}{2V_m^2} R_1 = \frac{2P^2}{3V_m^2\cos^2\varphi} R_2$$

$$\frac{1}{2} R_1 = \frac{2}{3\cos^2\varphi} R_2$$

$$\therefore \frac{R_1}{R_2} = \frac{4}{3\cos^2\varphi}$$

$$\frac{a_1}{a_2} = \frac{3\cos^2\varphi}{4} \quad (\text{as } R \propto \frac{1}{a})$$

$$\therefore \frac{\text{weight of conductors in DC}}{\text{weight of conductors in AC}} = \frac{2}{3} \times \frac{3\cos^2\varphi}{4}$$

[in DC there are 2 wires, in AC there are 3 wires]

$$\therefore \text{weight of conductors in DC} = \frac{\cos^2\varphi}{2} \text{ weight of conductors in AC}$$

$$= \frac{0.9^2}{2} \times 29850$$

$$= 12089 \text{ Kg}$$

peak or max. voltage $= V_{phase} \times \sqrt{2}$

$$= \frac{380\,KV}{\sqrt{3}} \times \sqrt{2}$$

working DC voltage between lines $= 2 \times \frac{380\,KV}{\sqrt{3}} \times \sqrt{2} = 620537.4$ V

$P = 620537.4\, I = 100 \times 10^6$

$\therefore I = 161$ A

power losses $W = 2 I^2 R = 8.7 \times 10^6$

$\therefore R = 167.5\ \Omega$

resistance per KM $= \frac{167.5}{150} = 1.12\ \Omega/KM$

$\therefore 1.12 = \rho \frac{KM}{a}$ and $0.045 = \rho \frac{KM}{cm^2}$

$\therefore a = \frac{0.045}{1.12} = 0.04\ cm^2$

volume for 1m $= 0.04 \times 100 = 4\ cm^3$

weight for 1m $= 4 \times 0.01 = 0.04$ Kg

Total weight $= 2 \times 150 \times 10^3 \times 0.04 = 12089$ Kg

Conductor size and KELVIN'S Law

The cost of conductors is generally a very considerable part of the total cost of a transmission line. Therefore the determination of a proper size of conductor for the line is of vital importance. The most economical area of conductor is that for which the total annual cost of a transmission line is minimum. This is known as Kelvin's law after Lord Kelvin who first stated in 1881, the total annual cost can be divided into:

1. annual charge on capital outlay

This is on account of interest and depreciation on the capital cost of complete installation of transmission line. In case of overhead lines, it will be the annual interest and depreciation on the capital cost of conductors, which is proportional to the area of x-section and the cost of insulators which is constant and the cost of supports and their erection which is partly constant and partly proportional to x-sectional area of the line conductor.

Therefore the annual charge of an overhead line can be expressed as

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

where P_1, P_2 are constants

a is the x-sectional area of the conductor.

2. Annual cost of energy wasted

This is on account of energy lost in the conductor due to I^2R losses. The energy lost in the conductor is propotional to resistance and resistance is inversely proportional to area of x-section, thus

$$\text{Annual cost of energy wasted} = \frac{P_3}{a}$$

where P_3 is another constant.

$$\therefore \text{Total annual cost } C = P_1 + P_2 a + \frac{P_3}{a}$$

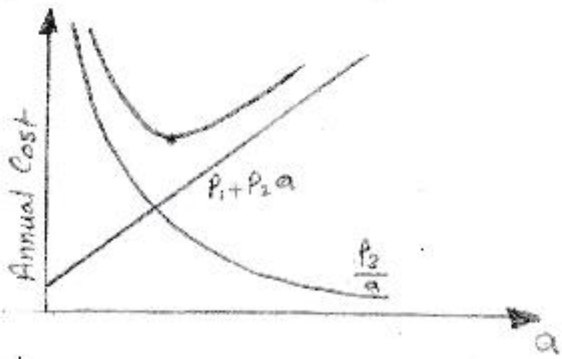
Therefore, the total annual cost will be minimum if differentiation of C w.r.t. a is zero

$$\frac{dC}{da} = P_2 - \frac{P_3}{a^2} = 0$$

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

ie variable part of annual charge = annual cost of energy wasted

which can be illustrated graphically as shown.



Ex. Find the most economical cross-section of a 3-core distributor cable 250 m long supplying a load of 80KW at 400V and 0.8 p.f lagging for 4000 hours per annum and open-circuited for the remainder of the year. The cost of the cable including installation is 15a + 25 per meter, where a is the area of each conductor in cm^2. Interest and depreciation total to 10% and cost of energy wasted is 10 P%.

The resistance per Km of conductor of $1 cm^2$ x-section is 0.173 Ω

sol.

$$I = \frac{80 \times 10^3}{\sqrt{3} \times 400 \times 0.8} = 144.3 \text{ A}$$

$$\text{Energy wasted per annum} = 3 \times (144.3)^2 \times \frac{0.173}{a} \times 10^{-3} \times 250 \times 4000 \times 10^{-3}$$

$$= \frac{10812.5}{a} \text{ Kwh}$$

$$\text{Annual cost of energy wasted} = \frac{10}{100} \times \frac{10812.5}{a} = \frac{1081.25}{a}$$

$$\text{Captital cost of cable} = (15a + 25) \times 250$$

$$\text{Annual cost of cable} = \frac{10}{100} \times (15a + 25) \times 250$$

$$= 375a + 625$$

According to Kelvin's law: $375a = \frac{1081.25}{a}$

$$\therefore a = 1.7 \text{ cm}^2$$

Choice of transmission voltage

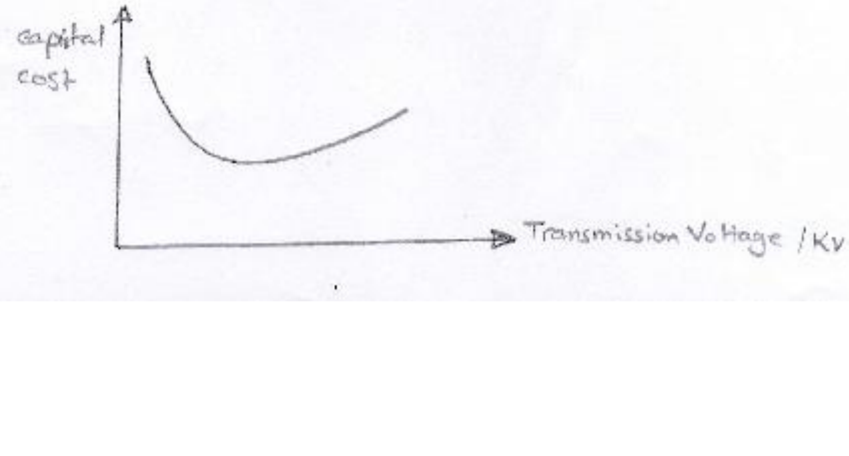
Raising the voltage n times means reducing the conductor size to $1/n^2$ that of the original (assuming constant efficiency of transmission). On the other hand a higher voltage involves higher cost of the system by way of increased insulation, switchgear and terminal apparatus. Thus there is an optimum voltage of transmission for a particular system.

If the power to be transmitted, voltage of generation and the length of transmission are assumed to be known. We then choose a standard voltage of transmission and work out the following costs:

① transformers at generating and receiving ends. ② switch gear and lightning arresters ③ insulators ④ supports ⑤ conductor cost.

All of these items when added give the cost of transmission for the voltage assumed.

Similar calculations should be made for other voltages, a curve can be plotted for cost against the transmission voltage. A typical curve of this type is shown



The lowest point on the curve represents the optimum voltage to be chosen. When in doubt about two voltages for which costs do not differ appreciably then it is better to choose the higher one as larger voltages are easier to control than larger currents, and the ease with which an increased demand of the load can be met.

According to modern American practice (based on empirical formula), the economical line voltage in KV is

$$V_L = 5.5 \sqrt{0.62L + \frac{3P}{150}}$$

where L is the distance of transmission in Km

P is the maximum KW per phase

V_L is the line voltage in KV

another empirical formula used is

$$V_L = 5.5 \sqrt{0.62L + \frac{KVA}{150}}$$

where KVA is the total power

Neutral Grounding

Grounding or earthing means connecting frame of electrical equipment (non-current carrying part) or some electrical part of the system (neutral point in a star connected system) to earth. This connection to earth may be through a conductor or some other circuit element (resistor, circuit breaker..)

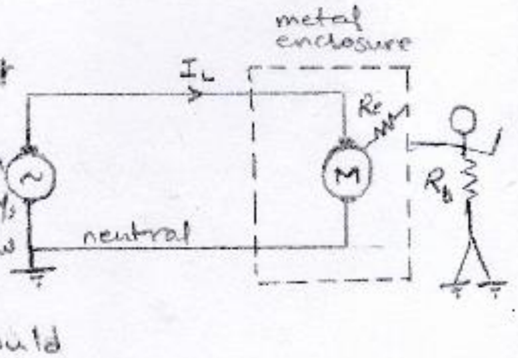
Grounding may be classified as:

1. Equipment Grounding

The process of connecting non-current carrying metal parts (metallic enclosure) of the electrical equipment to earth. The enclosure effectively remains at earth potential.

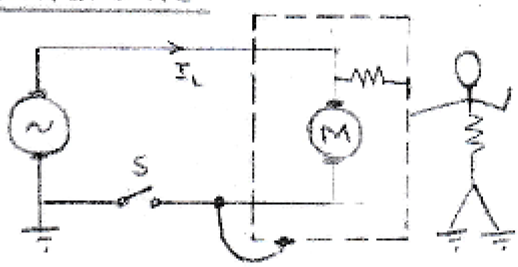
(i) Ungrounded Enclosure

If a person touches the metal enclousure, nothing will happen if the equipment is functioning correctly. But if the winding insulation of the motor becomes faulty, resistance Re drops to a low value. A person having a body resistance R_b would complete the current path.



The leakage current I_L through the person's body could be dangerously high.
Therefore this system is unsafe.

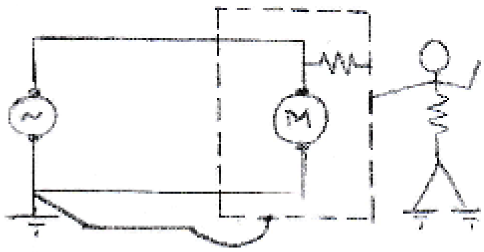
(ii) Enclousure connected to neutral wire



The problem could be solved by connecting the enclosure to the grounded neutral. Now I_L flows from the motor, through the enclosure and back to the neutral wire.

Therefore the enclosure remains at earth potential.
If the switch is in series with the neutral rather than the live wire, the motor can still be turned ON and OFF.
If some one touched the enclosure while the motor is OFF, he would recieve an electric shock, because when the motor is OFF, the potential of the enclosure rises to that of the live conductor.

(iii) Ground wire connected to enclosure

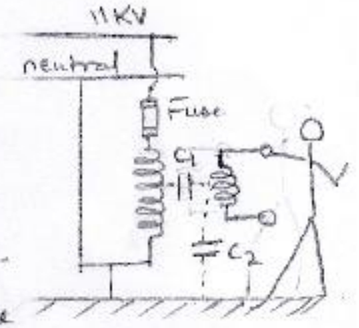


To get rid of this problem, we install a third wire, called ground wire between the enclosure and the system ground.

The ground wire may be bare or insulated.
If it is insulated it is coloured green.
Electrical outlets have three contacts - one for live wire, one for neutral, and one for ground wire.

System Grounding

It is the process of connecting some electrical part of the power system (e.g neutral point of a star connected system, one conductor of the secondary of a transformer) to earth



* Fig. shows a distribution transformer the primary of which is across 11KV line. There is a capacitance C_1 between primary and secondary, C_2 between secondary and ground.

This capacitance coupling can produce high voltage between secondary lines and ground. If a person touches either secondary contacts, I_c will flow through the body. But if one of the secondary contacts is grounded, the capacitive coupling almost reduces to zero and so is I_c.

* Suppose that the high voltage (11KV) touches the 230V conductor (because of an internal fault in the transformer or by a tree falling across the 11KV and 230V).

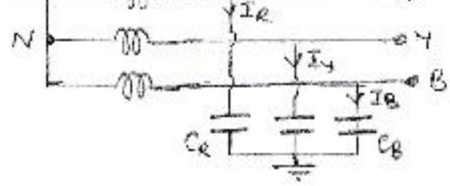
This high voltage imposed between the secondary conductors and ground, which would puncture the 230V insulation, causing massive flashover

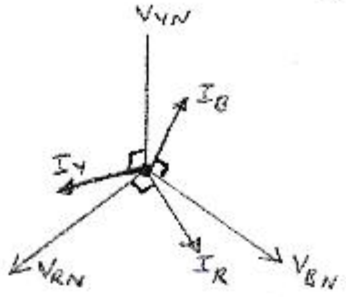
Therefore ungrounded secondary is a potential fire hazard

If one of the secondary conductors is grounded, the contact between 11KV and 230V produces a dead short. The large short circuit current (fault current) will blow the fuse disconnecting the transformer from the 11KV

This explains the importance of system grounding

Ungrounded Neutral System





In an underground system, the neutral is not connected to ground ie the neutral is isolated from the ground.

* circuit behaviour under normal conditions

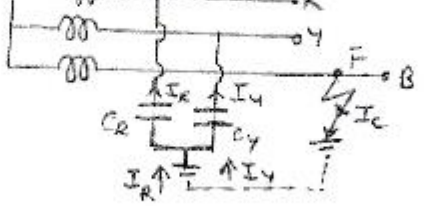
Each conductor has the same capacitance to ground

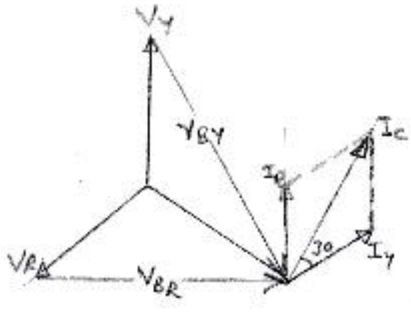
$C_R = C_Y = C_B = C$

$I_R = I_Y = I_B = \frac{V_{ph}}{Z_c}$

The capacitive currents are equal in magnitude and are displaced 120° from each other, therefore their phasor sum is zero. As aresult no current flows to ground and the potential of the neutral is the same as the ground potential

* circuit behaviour under singl line to ground fault





The voltages driving I_R and I_Y are V_{BR} and V_{BY} respectively

Note that V_{BR}, V_{BY} are line voltages

The paths of I_R and I_Y are capacitive. Therefore I_R leads V_{BR} by 90° and I_Y leads V_{BY} by 90°

I_c is the phasor sum of I_R and I_Y

$$\vec{I}_c = \vec{I}_R + \vec{I}_Y$$

$$I_R = \frac{V_{BR}}{x_c} = \frac{\sqrt{3}\,V_{ph}}{x_c} =$$

$$I_Y = \frac{V_{BY}}{x_c} = \frac{\sqrt{3}\,V_{ph}}{x_c}$$

$\therefore I_R = I_Y = \sqrt{3}$ per phase capacitive current under normal conditions

$$I_c = I_R \cos 30 + I_Y \cos 30 = 2 I_R \cos 30 = \sqrt{3}\, I_R$$

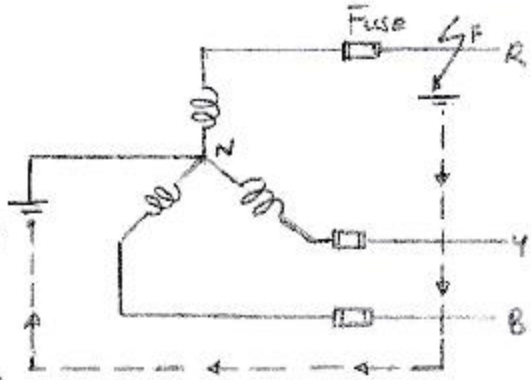
$$= \sqrt{3}\ \frac{\sqrt{3}\,V_{ph}}{x_c} = 3$$ per phase capacitive current under normal conditions.

Therefore when a single line to ground fault occurs on an ungrounded neutral system, the following effects are produced:

1. The potential of the faulty phase becomes equal to ground potential
2. The potential of the healthy phases rise from their normal phase voltages to line voltage.
3. The capacitive current in healthy phases increases to $\sqrt{3}$ times the normal value.
4. The capacitive fault current I_c becomes 3 times the normal per phase capacitive current.
5. This system can not provide adequate protection against earth faults.
6. The capacitive fault current I_F flows into earth, Experience shows that I_c in excess of 4A is sufficient to maintain an arc in the ionized path of the fault.

Due to the above disadvantages, ungrounded neutral system is not used these days.

Neutral Grounding



is the process of connecting neutral point of 3 phase system to earth either directly or through some circuit element (eg resistance)

Suppose a single line to ground fault occurs in line R at point F. This will cause the current to flow from R phase to earth, then to neutral point N and back to R phase. Since the impedance of this current path is low, a large current will flow which will blow the fuse in R phase and isolate the faulty line R

— One important feature of grounded neutral is that the potential difference between the live conductors and ground will not exceed the phase voltage.

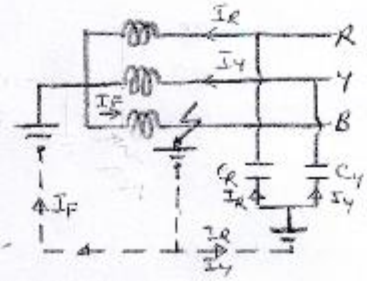
Advantages of neutral grounding

1. Voltages of healthy phases remain nearly constant.
2. The high voltages due to arcing grounds are eleminated.
3. Protective relays can be used.
4. The overvoltages due to lightning are discharged to earth
5. It provides improved service reliability.
6. Operating and maintenance expenditures are reduced.

Methods of neutral grounding

1. Solid grounding

When the neutral point of a 3phase system is directly connected to earth through a wire of negligible resistance and reactance, it is called solid grounding or effective grounding.



The neutral point is held at earth potential under all conditions, therefore under fault conditions, the voltage any conductor to earth will not exceed the normal phase voltage of the system.

Advantages

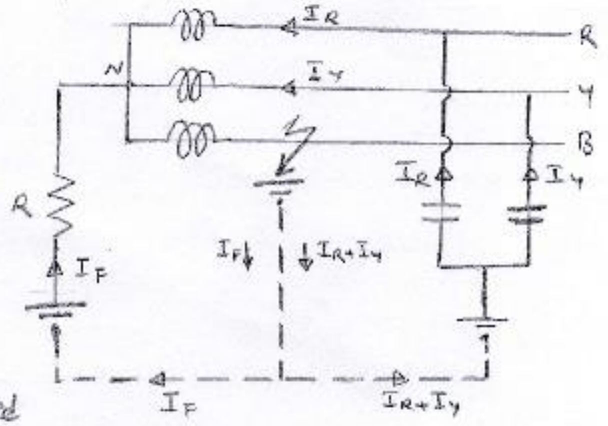
1. The neutral is held at earth potential.
2. When earth fault occurs on any phase, the resultant capacitive current I_c is in opposition to the fault current I_F, the two currents will cancel each other [$\vec{I_c} = \vec{I_R} + \vec{I_Y}$ is capacitive. The power source supplies the fault current I_F which is inductive]
   Therefore no arcing ground or over voltage can occur.
3. When there is an earth fault, the phase to earth voltage of the faulty phase becomes zero. The phase to earth voltage of the remaining healthy phases remain at normal phase voltage, because the potential of the neutral is fixed at earth potential.
4. Large fault current flows between the fault point and the grounded neutral. This permits the easy operation of earth fault relay.

Resistance Grounding

In order to limit the magnitude of earth fault current, the neutral point is connected to earth through a resistor.

If the value of R is very low, the earth fault current will be large and the system becomes similar to solid grounding

If R is very high the system becomes similar to ungrounded neutral system.



In practice, the value of R is selected to limit the earth fault current to 2 times the normal full load current.

Advantages

1. By adjusting the value of R, the arcing grounds can be minimized

[I_F lags behind the phase voltage of the faulted phase by a certain angle depending upon the earting resistance R and the reactance of the system up to the point of fault. I_F can be resolved into two components

a: I_{F1} in phase with the faulty phase voltage

b: I_{F2} lagging behind the faulty phase voltage by 90°

I_{F2} is in phase opposition to capacitive current I_c

- If R is selected so that $I_{F2} = I_c$, arcing grounds is completely eleminated]

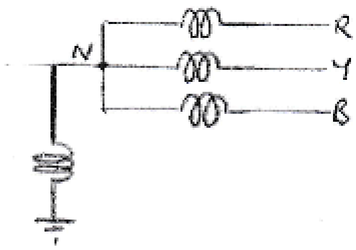
2. The earth fault current is small, therefore, interference with communication circuits is reduced
3. It improves the stability of the system.

Disadvantages

1. Since the neutral is displaced during earth faults, the equipment has to be insulated for higher voltages.
2. This system is costlier than the solidly grounded system
3. Large amount of energy is produced R during earth faults, sometimes it is difficult to dissipate this energy to atmosphere.

Reactance Grounding

A reactance is inserted between the neutral and ground. By changing the earting reactance, the earth fault current can be changed to obtain the conditions similar to that of solid grounding.



This method is not used these days because of the following disadvantages.

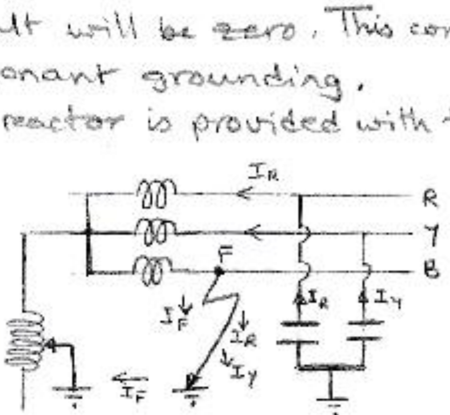
1. The fault current required to operate the protective device is higher than that of resistance grounding for the same fault conditions.
2. High transient voltages appear under fault.

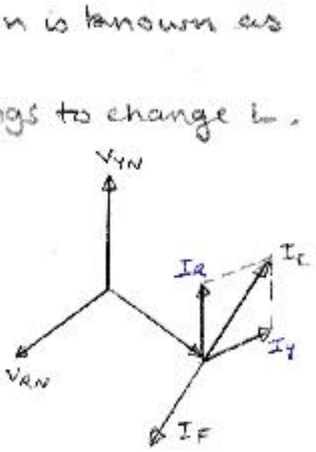
Arc Suppression Coil Grounding (Peterson coil)

Capacitive currents are responsible for producing arcing grounds. These capacitive currents flow because capacitince exists between each line and earth,

If inductance L of appropiate 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 I_c, then the resultant current in the fault will be zero. This condition is known as resonant grounding.

The reactor is provided with tappings to change L.





The voltage of the faulty phase is applied across the arc suppression coil, therefore fault current I_F lags the faulty phase voltage by 90°

current I_F is in phase opposition to capacitive current I_c

By adjusting the tappings, the resultant current in the fault can be reduced, and if $I_L = I_c$ the resultant current in the fault will be zero.

For resonant grounding, the system behaves as an ungrounded neutral system, therefore full line voltage appears across capacitors C_R and C_Y.

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

$$I_c = \sqrt{3}\, I_R = \sqrt{3}\, \frac{\sqrt{3}\, V_{ph}}{x_c} = \frac{3 V_{ph}}{x_c}$$

$$\text{Fault current } I_F = \frac{V_{ph}}{X_L}$$

x_L : is the inductive reactance of peterson coil.

For resonant grounding, $I_L = I_c$

$$\frac{V_{ph}}{x_L} = \frac{3 V_{ph}}{x_c}$$

$$x_L = \frac{x_c}{3}$$

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

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

Advantages

1. The peterson coil is completely effective.
2. " " " has the advantages of ungrounded neutral system.

Disadvantage

Capacitance of the network changes from time to time, therefore, inductance L of Peterson coil requires readjustment.

Ex. 1 Calculate the reactance of Peterson coil suitable for 33 KV, 3 phase transmission line having a capacitance to earth of each conductor as 4.5 μF

$$x_L = \frac{x_c}{3} = \frac{1}{3\omega C}$$

$$= \frac{1}{3 \times 2\pi \times 50 \times 4.5 \times 10^{-6}}$$

$$= 235.8\ \Omega$$

Ex.2 230 KV, 3 phase, 50Hz, 200 Km transmission line has a capacitance to earth of 0.02 MF/Km per phase. Calculate the inductance and KVA rating of the Peterson coil used for earthing.

sol.

$$C = 200 \times 0.02 = 4 \times 10^{-6}\ F$$

$$L = \frac{1}{3\omega^2 C} = \frac{1}{3(2\pi f)^2 C}$$

$$= \frac{1}{3(2\pi \times 50)^2 \times 4 \times 10^{-6}} = 0.84\ H$$

current through Peterson coil is I_F

$$I_F = \frac{V_{ph}}{X_L} = \frac{230 \times 10^3 / \sqrt{3}}{2\pi \times 50 \times 0.85} = 500\ A$$

voltage across Peterson coil is V_{ph}

$$V_{ph} = \frac{V_L}{\sqrt{3}} = \frac{230 \times 10^3}{\sqrt{3}} = 132.8\ KV$$

Rating of Peterson coil $= V_{ph} \times I_F$

$$= 132.8 \times 10^3 \times 500$$

$$= 66.4\ MVA$$

$$V_{ph}\, I_F = \frac{V_L}{\sqrt{3}}\ \frac{V_L/\sqrt{3}}{2\pi f L} = \frac{V_L^2}{3}\ \frac{1}{2\pi f L}$$

Performance of Transmission Lines

A transmission line has three constants R, L and C distributed uniformly along the whole length. R and L form the series impedance. The capacitance between conductors for a single phase line or from a conductor to neutral for a three phase line, forms a shunt path throughout the length of the line.

1. Short line: The length of the line is less than 80Km.
2. Medium line: The length is between 80Km and 240Km.
3. Long line: The length of the line is more than 240Km.

Voltage Regulation: It is the percentage increase in voltage at the recieving end when full load is thrown off, the sending end voltage being kept unchanged.

$$\text{voltage regulation} = \frac{V_s - V_r}{V_r} \times 100\%$$

where V_s: voltage at the sending end
V_r: " " " recieving end.

Transmission efficiency η

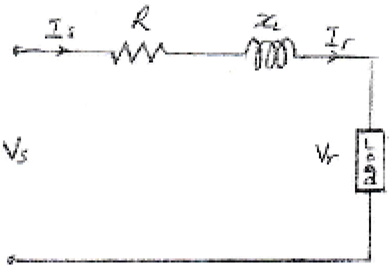
It is the ratio of recieving end power to the sending end power

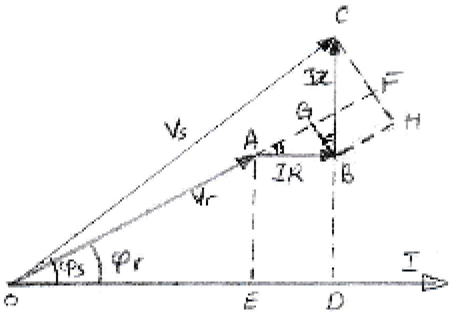
$$\eta = \frac{\text{Recieving end power}}{\text{Sending end power}} = \frac{V_r I_r \cos\varphi_r}{V_s I_s \cos\varphi_s} \times 100\%$$

$\cos\varphi_r$: recieving end power factor
$\cos\varphi_s$: sending " " "

Short transmission line

The effect of the line capacitance is neglected.





an approximate expression for the sending end voltage V_s

$$V_s = OC \approx OF$$
$$\cong OA + AG + GF$$
$$\cong OA + AG + BH$$
$$V_s \cong V_r + IR\cos\varphi_r + Ix\sin\varphi_r$$

$$\therefore V.R. = \frac{IR\cos\varphi_r + Ix\sin\varphi_r}{V_r}$$

N.B.

+ for lagging power factor
- for leading " "

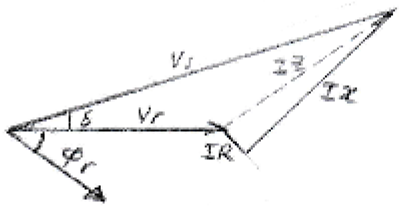
Solution in complex notation

Taking V_r as a referrence.

$\vec{V_r} = V_r \angle 0 = V_r + j0$

$\vec{I} = I \angle -\varphi_r = I(\cos\varphi_r - j\sin\varphi_r)$

$Z = R + jx$



$$\vec{V_s} = \vec{V_r} + \vec{I}\,\vec{Z}$$
$$= V_r + I(\cos\varphi_r - j\sin\varphi_r)(R + jx)$$
$$= V_r + IR\cos\varphi_r + Ix\sin\varphi_r + j(Ix\cos\varphi_r - IR\sin\varphi_r)$$
$$V_s = \sqrt{(V_r + IR\cos\varphi_r + Ix\sin\varphi_r)^2 + (Ix\cos\varphi_r - IR\sin\varphi_r)^2}$$

Now $(Ix\cos\varphi_r - IR\sin\varphi_r)^2$ is quite small and can be neglected.

$$\therefore V_s = V_r + IR\cos\varphi_r + Ix\sin\varphi_r$$

3

Ex. The following data refers to a 50Hz, 3 phase transmission line length 10Km, recieving end voltage 11Kv, load delivered at the recieving end is 1MW at 0.8 lag, resistance of each conductor 0.5 Ω/Km and reactance is 0.56 Ω/Km. Calculate (a) line current (b) sending end voltage (c) efficiency of transmission line.

(a) $P = \sqrt{3}\, V_L I_L \cos\varphi_r$

$$\therefore I_L = \frac{1\times10^6}{\sqrt{3}\times 11\times10^3\times 0.8} = 65.6\text{ A}$$

(b) $V_s = V_r + IR\cos\varphi_r + IX\sin\varphi_r$

$R = 0.5\times10 = 5\,\Omega$

$X = 0.56\times10 = 5.6\,\Omega$

$$V_{r\,phase} = \frac{V_{r\,line}}{\sqrt{3}} = \frac{11\times10^3}{\sqrt{3}} = 6.35\text{ KV}$$

$\therefore V_s = 6.35\times10^3 + 65.6\times5\times0.8 + 65.6\times5.6\times0.6$

$= 6.83\text{ KV}$ to neutral

$\therefore$ line to line $V_s = \sqrt{3}\times6.83 = 11.84\text{ KV}$

(c) I^2R loss $= 3\times I^2\times R$ (3 phase transmission line)

$= 3\times 65.6^2\times5$

$= 64.56\text{ KW}$

$$\eta = \frac{P_r}{P_s} = \frac{P_r}{P_r + loss} = \frac{10^6}{10^6 + 64.56\times10^3}\times100\%$$

$= 93.96\%$

Three-phase Short Transmission Lines

As a matter of convenience we generally analyse 3-phase system by considering one phase only, thus V_s and V_r are phase voltages whereas R and X_L are the resistance and inductive reactance per phase.
power delivered to the load P.

$P = V_r I \cos\varphi_r$ For 1-phase line

$P = 3 V_r I \cos\varphi_r$ For 3-phase line

Medium Transmission Lines.

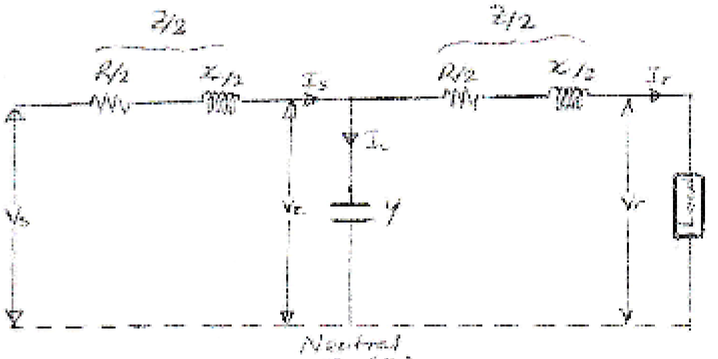
The effect of shunt capacitance becomes more and more pronounced with the increase in the length of a line.
For medium length T.L., the shunt capacitance can be considered as lumped, and there are two main types of equivalent circuits

a: Nominal π circuit

b: " T "

Nominal T Method.

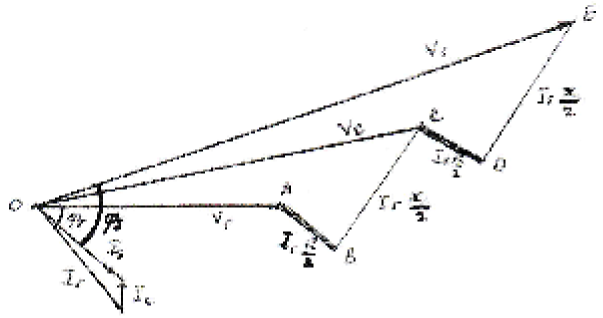
In this method, the whole line capacitance is assumed to be concentrated at the middle point of the line.



Fig(2)

Y: shunt admittance
G: conductance
B: capacitive susceptance
$Z = R + jX$
$Y = G + jB$

In this figuir one phase of a 3-phase transmission line is shown. Taking the receiving end voltage $\vec{V_r}$ as the reference vector.



In complex notation.

$$\vec{V_r} = V_r + j0$$

$$\vec{I_r} = I_r(\cos\varphi_r - j\sin\varphi_r)$$

$$\vec{V_c} = \vec{V_r} + \vec{I_r}\,\vec{Z}/2$$

$$\therefore \vec{V_c} = V_r + I_r(\cos\varphi_r - j\sin\varphi_r)\left(\frac{R}{2} + j\frac{X}{2}\right)$$

$$\vec{I_s} = \vec{I_r} + \vec{I_c} \quad ---- (1)$$

$$\vec{I_c} = j\omega C\vec{V_c} = j\,2\pi f C\,\vec{V_c}$$

$$\vec{V_s} = \vec{V_c} + \vec{I_s}\,\vec{Z}/2$$

$$\vec{V_s} = \vec{V_c} + \vec{I_s}\left(\frac{R}{2} + j\frac{X}{2}\right) \quad ----- (2)$$

Referring to Fig (2)

$V_c = V_r + I_r \frac{Z}{2}$

$I_c = Y V_c$

$= Y (V_r + I_r \frac{Z}{2})$

$I_S = I_r + I_c$

$= I_r + Y (V_r + I_r \frac{Z}{2})$

$= I_r + Y V_r + I_r \frac{YZ}{2}$

$\therefore I_S = Y V_r + (1 + \frac{YZ}{2}) I_r$ ...... (3)

$V_S = V_c + I_S \frac{Z}{2}$

$= V_r + I_r \frac{Z}{2} + [Y V_r + (1 + \frac{YZ}{2}) I_r] \frac{Z}{2}$

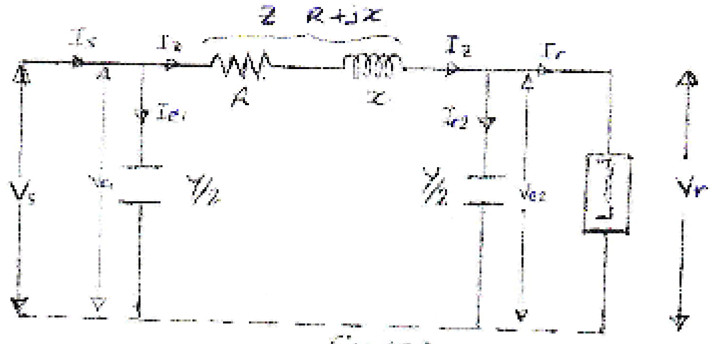
$= V_r + \frac{YZ}{2} V_r + I_r \frac{Z}{2} + I_r \frac{Z}{2} + I_r \frac{YZ}{2} \frac{Z}{2}$

$= V_r + \frac{YZ}{2} V_r + I_r Z + I_r \frac{YZ^2}{4}$

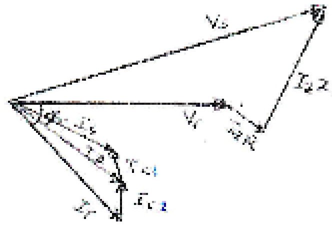
$\therefore V_S = (1 + \frac{YZ}{2}) V_r + Z (1 + \frac{YZ}{4}) I_r$ ..... (4)

Nominal π Method

In this method, capacitance of each conductor (i.e. line to neutral) is divided into two halves, one half being lumped at the sending end and the other at the receiving end as shown in fig. 3



Fig(3)



$$I_{c2} = \frac{Y}{2} V_r$$

$$I_Z = I_r + I_{c2} = I_r + \frac{Y}{2} V_r$$

$$V_s = V_r + I_Z Z$$

$$= V_r + (I_r + \frac{Y}{2} V_r) Z$$

$$\therefore V_s = (1 + \frac{YZ}{2}) V_r + Z I_r \quad \ldots\ldots (5)$$

$$I_{c1} = \frac{Y}{2} V_s$$

$$I_{c1} = \frac{Y}{2} [(1 + \frac{YZ}{2}) V_r + Z I_r]$$

$$I_s = I_Z + I_{c1}$$

$$= I_r + \frac{Y}{2} V_r + \frac{Y}{2} [(1 + \frac{YZ}{2}) V_r + Z I_r]$$

$$= \frac{Y}{2} V_r + \frac{Y}{2} V_r + \frac{Y^2 Z}{4} V_r + I_r + \frac{YZ}{2} I_r$$

$$\therefore I_s = Y (1 + \frac{YZ}{4}) V_r + (1 + \frac{YZ}{2}) I_r \quad \ldots\ldots (6)$$

Generalised circuit constants of a transmission line.

In any four terminal network the input voltage and input current can be expressed in terms of output voltage and output current. A transmission line is a four terminal network, two input terminals where power enters the network, and two terminals where the power leaves the network.
Therefore the input voltage V_s and input current I_s of a 3-phase transmission line can be expressed as:

$$V_s = A V_r + B I_r \quad \ldots\ldots (7)$$
$$I_s = C V_r + D I_r \quad \ldots\ldots (8)$$

For a given transmission line $A = D$ and $AD - BC = 1$
In matrix form

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Short lines

referring to fig.(1)

$$V_s = V_r + Z I_r$$
$$I_s = I_r$$

Comparing with equations (7) and (8)

$A = 1 \qquad B = Z \qquad C = 0 \qquad D = 1$

In matrix form

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 & Z \\ 0 & 1 \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Medium lines - Nominal T Method

referring to fig.(2)
and equations (3) and (4)

$$V_s = (1 + \frac{YZ}{2}) V_r + Z(1 + \frac{YZ}{4}) I_r \quad \cdots \quad (4)$$

$$I_s = Y V_r + (1 + \frac{YZ}{2}) I_r \quad \cdots \quad (3)$$

$$\therefore A = D = 1 + \frac{YZ}{2}, \quad B = Z(1 + \frac{YZ}{4}), \quad C = Y$$

In matrix form

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z(1 + \frac{YZ}{4}) \\ Y & 1 + \frac{YZ}{2} \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Medium lines - Nominal π Method

referring to fig (3)
and equations (5) and (6)

$$V_s = (1 + \frac{YZ}{2}) V_r + Z I_r \quad \cdots \quad (5)$$

$$I_s = Y(1 + \frac{YZ}{4}) V_r + (1 + \frac{YZ}{2}) I_r \quad \cdots \quad (6)$$

$$A = D = 1 + \frac{YZ}{2}$$

$$B = Z$$

$$C = Y(1 + \frac{YZ}{4})$$

In matrix form

$$\begin{bmatrix} V_s \\ I_s \end{bmatrix} = \begin{bmatrix} 1 + \frac{YZ}{2} & Z \\ Y(1 + \frac{YZ}{4}) & 1 + \frac{YZ}{2} \end{bmatrix} \begin{bmatrix} V_r \\ I_r \end{bmatrix}$$

Ex: 3-phase 50Hz overhead transmission line has the following data
$R = 28\,\Omega$, $X_L = 63\,\Omega$, capacitive susceptance $= 4\times10^{-4}$ mho.
If the load at the receiving end is 75 MVA at 0.8 pf lagging with 132 Kv between lines, calculate

(a) voltage (b) current (c) power factor at the sending end

(d) regulation (e) efficiency of transmission, use nominal T.

Sol.

$Z = 28 + j63$

$Z/2 = 14 + j31.5$

voltage at the receiving end V_r

$V_r = \dfrac{132}{\sqrt{3}} = 76.23$ Kv (Taking V_r as a reference)

$I_r = \dfrac{75\times10^6}{\sqrt{3}\times132\times10^3} \angle -\cos^{-1}0.8$

$I_r = 328.1(0.8 - j0.6) = 262.5 - j196.9$ amp

Now $V_c = V_r + I_r \frac{Z}{2}$

$= (76.23 + j0) + (262.5 - j196.9)(14 + j31.5)\times10^{-3}$

$\therefore V_c = 86.1 + j5.5$ KV

$I_c = YV_c = j4\times10^{-4}(86.1 + j5.5)\times10^3$

$\therefore I_c = j34.44 - 2.2$ amp

$I_s = I_r + I_c = (262.5 - j196.9) + (j34.44 - 2.2)$

$\therefore I_s = 260.3 - j162.46 = 306.5 \angle -31^\circ 58'$

voltage drop $I_s \frac{Z}{2}$

$= (260.3 - j162.46)(14 + j31.5)\times10^{-3}$

$= (8.8 + j6)$ Kv

$V_s = V_c + I_s Z/2$

$= (86.1 + j5.5) + (8.8 + j6)$

$\therefore V_s = 94.9 + j11.5$

$V_s = 95.59 \angle 6^\circ 57'$ kV (phase voltage)

$V_s = 165.5$ kV (line to line)

$\phi_s = 6^\circ 51' + 31^\circ 58'$

$= 38^\circ 49'$ with I_s lagging V_s

$\therefore$ Sending end powerfactor $\cos\phi_s = \cos 38^\circ 49' = 0.7791$ lag

percentage regulation $VR = \frac{V_s - V_r}{V_r} \times 100$

$= \frac{165.5 - 132}{132} \times 100$

$= 25.37\%$

power at the sending end is P_s

$P_s = \sqrt{3}\, V_s I_s \cos\phi_s$

$= \sqrt{3} \times 165.5 \times 306.5 \times 0.7791$

$= 68.44$ MW

power at the receiving end $P_r = 75 \times 0.8 = 60$ MW

$\therefore$ Transmission efficiency η_T

$\eta_T = \frac{P_r}{P_s} \times 100$

$= \frac{60}{68.44} \times 100$

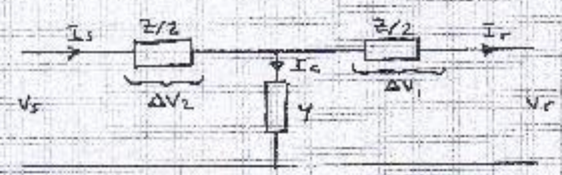
$= 87.66\%$

Ex. A 200 MW, 132 KV, 0.8 lag power factor load is fed by a 150 Km transmission line with impedance $(0.1+j0.2)\ \Omega/Km$ and admittance 0.2×10^{-4} ℧

Taking I_r as reference find $V_s, I_s, \varphi_s, \eta$ and δ. Use T.

Sol.

$Z = (0.1+j0.2)\times150 = 15+j30 = 33.5\angle 63.4$



$I_r = \dfrac{200\times10^6}{\sqrt{3}\times132\times10^3\times0.8} = 1093.5A$ at angle zero (reference vector)

$V_r = \dfrac{132}{\sqrt{3}}\angle \cos^{-1}0.8 = 76.2\angle 36.9$ KV

Draw the phasor diagram

Use a scale of 10KV = 1cm
100 A = 1 cm

$\Delta V_1 = I_r\dfrac{Z}{2} = 1093.5\angle 0\times\dfrac{33.5}{2}\angle 63.4 = 18.32\ KV\angle 63.4 = 1.8$ cm at angle $\angle 63.4$

Draw ΔV_1 and measure V_c

$V_c = 9.3$ cm $= 93\angle 43$ KV

$I_c = YV_c = 0.2\times10^{-4}\angle 90\times93\angle 43 = 1.86\angle 133$ A $= 0.0186$ cm at angle $\angle 133$

Draw I_c and measure I_s

$I_s = 10.8$ cm $= 1080$ A at an angle $\angle 1$ ie $1080\angle 1$

$\Delta V_2 = I_s\dfrac{Z}{2} = 1080\angle 1\times\dfrac{33.5}{2}\angle 63.4 = 17.82\angle 64.4$ KV $\simeq 1.8$ cm

Draw ΔV_2 and measure V_s

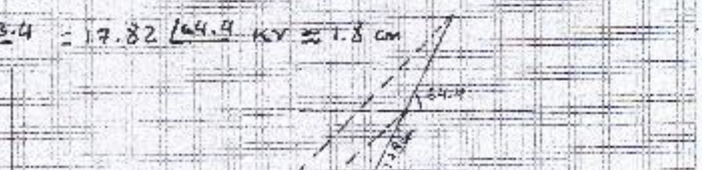
$V_s = 11$cm $= 110\angle 46$ KV

$\therefore \delta = 46 - 36.9 = 9.1$

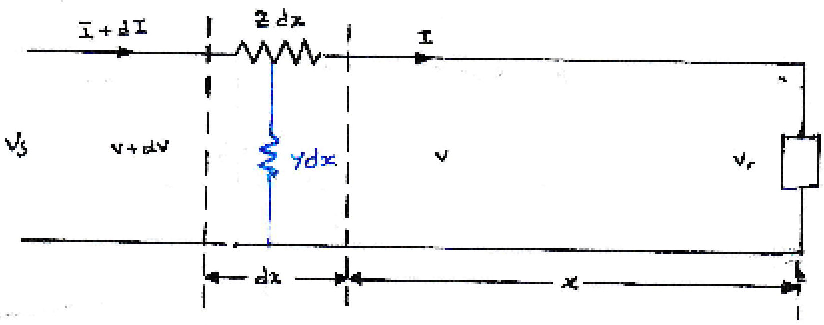
$\eta = \dfrac{V_r I_r\cos\varphi_r}{V_s I_s\cos\varphi_s}\times100\%$

$= \dfrac{\frac{132}{\sqrt{3}}\times1093.5\times\cos36.9}{110\times1080\times\cos46}\times100$

$= 80.8\ \%$



Long Transmission Lines



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

z : series impedance of the line per unit length

y : shunt admittance 〃 〃 〃

V : voltage at the end of element towards recieving end

$V+dV$: 〃 〃 〃 towards sending end.

$I+dI$: current entering the element dx

I : 〃 leaving 〃

For the small element dx

$z\,dx$ is the series impedance

$y\,dx$ is the shunt admittance.

Now :

$$dV = I z\,dx \quad \Rightarrow \quad \frac{dV}{dx} = Iz$$

$$dI = Vy\,dx \quad \Rightarrow \quad \frac{dI}{dx} = Vy$$

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

OR $\frac{d^2V}{dx^2} = ZYV$

This is a differential equation which has the solution of:

$$V = A_1 e^{\sqrt{ZY}\,x} + A_2 e^{-\sqrt{ZY}\,x} \quad \text{------- (1)}$$

$$\frac{dV}{dx} = \sqrt{ZY}\,A_1 e^{\sqrt{ZY}\,x} - \sqrt{ZY}\,A_2 e^{-\sqrt{ZY}\,x} = IZ$$

$$\therefore I = \sqrt{\frac{Y}{Z}}\,A_1 e^{\sqrt{ZY}\,x} - \sqrt{\frac{Y}{Z}}\,A_2 e^{-\sqrt{ZY}\,x} \quad \text{------ (2)}$$

at $x = 0$ $V = V_r$ and $I = I_r$

$$\therefore V_r = A_1 + A_2$$

$$I_r = \sqrt{\frac{Y}{Z}}\,A_1 - \sqrt{\frac{Y}{Z}}\,A_2$$

$$\therefore A_1 = \frac{1}{2}\left(V_r + \sqrt{\frac{Z}{Y}}\,I_r\right) = \frac{1}{2}\left(V_r + Z_c I_r\right)$$

$$A_2 = \frac{1}{2}\left(V_r - \sqrt{\frac{Z}{Y}}\,I_r\right) = \frac{1}{2}\left(V_r - Z_c I_r\right)$$

Z_c : characteristic impedance $= \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R+j\omega L}{G+j\omega C}}$

γ : propagation constant $= \sqrt{ZY} = \sqrt{(R+j\omega L)(G+j\omega C)}$

in (1) ~~&~~ (2)

$$\therefore V = \frac{1}{2}\left(V_r + Z_c I_r\right) e^{\gamma x} + \frac{1}{2}\left(V_r - Z_c I_r\right) e^{-\gamma x}$$

$$I = \frac{1}{2}\left(\frac{V_r}{Z_c} + I_r\right) e^{\gamma x} - \frac{1}{2}\left(\frac{V_r}{Z_c} - I_r\right) e^{-\gamma x}$$

$$V = \frac{V_r}{2} e^{\gamma x} + \frac{Z_c I_r}{2} e^{\gamma x} + \frac{V_r}{2} e^{-\gamma x} - \frac{Z_c I_r}{2} e^{-\gamma x}$$

$$= V_r \frac{e^{\gamma x} + e^{-\gamma x}}{2} + Z_c I_r \frac{e^{\gamma x} - e^{-\gamma x}}{2}$$

$$\therefore V = V_r \cosh \gamma x + Z_c I_r \sinh \gamma x \quad \text{------} (3)$$

$$I = \frac{V_r}{2Z_c} e^{\gamma x} + \frac{I_r}{2} e^{\gamma x} - \frac{V_r}{2Z_c} e^{-\gamma x} + \frac{I_r}{2} e^{-\gamma x}$$

$$= \frac{V_r}{Z_c} \frac{e^{\gamma x} - e^{-\gamma x}}{2} + I_r \frac{e^{\gamma x} + e^{-\gamma x}}{2}$$

$$\therefore I = \frac{V_r}{Z_c} \sinh \gamma x + I_r \cosh \gamma x \quad \text{------} (4)$$

To find V_s & I_s substitute $x = l$ in (3) & (4)

$$\therefore V_s = V_r \cosh \gamma l + Z_c I_r \sinh \gamma l$$

$$I_s = \frac{V_r}{Z_c} \sinh \gamma l + I_r \cosh \gamma l$$

$$\therefore A = D = \cosh \gamma l$$

$$B = Z_c \sinh \gamma l$$

$$C = \frac{1}{Z_c} \sinh \gamma l$$

$$AD - BC = 1$$

where l is the length of the transmission line.

Ex. A 3ϕ transmission line 200 Km long has the following constants:

Resistance / phase / km $= 0.16\,\Omega$
Reactance / phase / km $= 0.25\,\Omega$
shunt admittance / phase / km $= 1.5 \times 10^{-6}$ ℧

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

sol.

Total resistance / phase $= 0.16 \times 200 = 32\,\Omega$
" reactance / phase $= 0.25 \times 200 = 50\,\Omega$
" shunt admittance / phase $= Y$

$$Y = j\,1.5 \times 10^{-6} \times 200 = 0.0003\angle 90$$

$$Z = 32 + j50 = 59.4\,\angle 58$$

$$V_s = V_r \cosh \gamma l + I_r Z_c \sinh \gamma l$$
$$= V_r \cosh \sqrt{ZY} + I_r Z_c \sinh \sqrt{ZY}$$

$$I_s = \frac{V_r}{Z_c} \sinh \gamma l + I_r \cosh \gamma l$$
$$= \frac{V_r}{\sqrt{Z/Y}} \sinh \sqrt{ZY} + I_r \cosh \sqrt{ZY}$$

$$\sinh \gamma l = \gamma l + \frac{\gamma^3 l^3}{3!} + \cdots$$
$$= \sqrt{ZY}\left(1 + \frac{ZY}{3!} + \cdots\right.$$

$$\cosh \gamma l = 1 + \frac{\gamma^2 l^2}{2!} + \frac{\gamma^4 l^4}{4!} + \cdots$$
$$= 1 + \frac{ZY}{2!} + \frac{Z^2 Y^2}{4!} + \cdots$$

$\sqrt{ZY} = \sqrt{59.4\angle 58 \times 0.0003\angle 90} = 0.133\angle 74$ (16)

$ZY = 0.0178\angle 148$

$Z^2Y^2 = 0.00032\angle 296$

$$\sqrt{\frac{Z}{Y}} = \sqrt{\frac{59.4\angle 58}{0.0003\angle 90}} = 445\angle -16$$

$$\therefore \cosh\sqrt{ZY} = 1 + \frac{0.0178}{2}\angle 148 + \frac{0.00032}{24}\angle 296$$

$$= 0.992 + j0.00469$$

$$= 0.992\angle 0.26$$

$$\sinh\sqrt{ZY} = 0.133\angle 74 + \frac{0.0024\angle 222}{6}$$

$$= 0.0362 + j0.1275$$

$$= 0.1325\angle 74.6$$

$$V_r = 110\times 10^3/\sqrt{3} = 63508\ V$$

$$I_r = \frac{20\times 10^6}{\sqrt{3}\times 110\times 10^3\times 0.8} = 131\ A$$

$$V_s = 63508\times 0.992\angle 0.26 + 131\times 445\angle -16\times 1325\angle 74.6$$

$$= 67018 + j6840$$

$$= 67,366\angle 5.5$$

line to line sending end voltage

$$= 67366\times\sqrt{3} = 116.67\times 10^3\ V$$

$$I_s = \frac{63508}{445\angle -16}\times 0.1325\angle 74.6 + 131\times 0.992\angle 0.26$$

$$= 129.83 + j18.24$$

$$= 131.1\angle 8$$

Power Formulae For Transmission Lines

Fig. shows the singl line diagram of a three phase transmission line. The ends of the transmission line are designated as busses.

S_s is the complex power at the sending end, and S_r is the complex power at recieving end of the line.

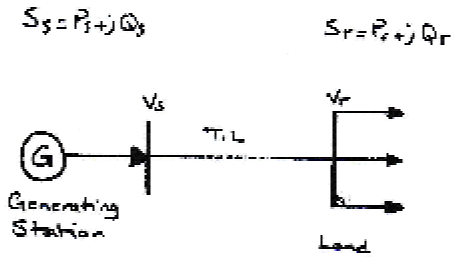


Fig. Two bus power system

$$V_s = A V_r + B I_r \quad ---(1) \qquad V_r = D V_s - B I_s \quad ----(3)$$

$$I_s = C V_r + D I_r \quad ---(2) \qquad I_r = -C V_s + A I_s \quad ---(4)$$

From (1) $$I_r = \frac{V_s}{B} - \frac{A V_r}{B}$$

From (3) $$I_s = \frac{D V_s}{B} - \frac{V_r}{B}$$

Let $V_r = V_r \angle 0$, $V_s = V_s \angle \delta$, $D = A = A \angle \alpha$, $B = B \angle \beta$

$$\therefore I_r = \frac{V_s}{B} \angle \delta - \beta - \frac{A V_r}{B} \angle \alpha - \beta$$

$$I_s = \frac{A V_s}{B} \angle \alpha + \delta - \beta - \frac{V_r}{B} \angle -\beta$$

$$\therefore I_r^* = \frac{V_s}{B} \angle \beta - \delta - \frac{A V_r}{B} \angle \beta - \alpha$$

$$I_s^* = \frac{A V_s}{B} \angle \beta - \alpha - \delta - \frac{V_r}{B} \angle \beta$$

The complex power per phase

$$S_r = P_r + jQ_r = V_r I_r^*$$

$$= V_r \angle 0 \left[\frac{V_s}{B} \angle \beta-\delta - \frac{AV_r}{B} \angle \beta-\alpha \right]$$

$$S_r = \frac{V_s V_r}{B} \angle \beta-\delta - \frac{AV_r^2}{B} \angle \beta-\alpha \quad \text{------} (5)$$

$$S_s = P_s + jQ_s = V_s I_s^*$$

$$= V_s \angle \delta \left[\frac{AV_s}{B} \angle \beta-\alpha-\delta - \frac{V_r}{B} \angle \beta \right]$$

$$S_s = \frac{AV_s^2}{B} \angle \beta-\alpha - \frac{V_s V_r}{B} \angle \beta+\delta \quad \text{------} (6)$$

$$\therefore P_r = \frac{V_s V_r}{B} \cos(\beta-\delta) - \frac{AV_r^2}{B} \cos(\beta-\alpha)$$

$$Q_r = \frac{V_s V_r}{B} \sin(\beta-\delta) - \frac{AV_r^2}{B} \sin(\beta-\alpha)$$

$$P_s = \frac{AV_s^2}{B} \cos(\beta-\alpha) - \frac{V_s V_r}{B} \cos(\beta+\delta)$$

$$Q_s = \frac{AV_s^2}{B} \sin(\beta-\alpha) - \frac{V_s V_r}{B} \sin(\beta+\delta)$$

For fixed values of V_s, V_r, the recieving end real power is maximum when $\beta = \delta$

$$\therefore P_{r\,max} = \frac{V_s V_r}{B} - \frac{AV_r^2}{B} \cos(\beta-\alpha)$$

The corresponding value of Q_r at this power limit

$$Q_{r\,max} = -\frac{AV_r^2}{B} \sin(\beta-\alpha)$$

∴ The load must draw the leading vars given by $Q_{r\,max}$ to achieve the condition of max. real power.

Now: For a short line $A = D = 1\angle 0$, $B = Z = Z\angle\theta$

$$\therefore P_r = \frac{V_s V_r}{Z}\cos(\theta - \delta) - \frac{V_r^2}{Z}\cos\theta$$

$$Q_r = \frac{V_s V_r}{Z}\sin(\theta - \delta) - \frac{V_r^2}{Z}\sin\theta$$

$$P_s = \frac{V_s^2}{Z}\cos\theta - \frac{V_s V_r}{Z}\cos(\theta + \delta)$$

$$Q_s = \frac{V_s^2}{Z}\sin\theta - \frac{V_s V_r}{Z}\sin(\theta + \delta)$$

The resistance of a transmission line is usually very small as compared to inductive reactance.

Therefore $Z \simeq x$ and $\theta \approx 90^\circ$

$$\therefore P_r = \frac{V_s V_r}{x}\cos(90 - \delta) = \frac{V_s V_r}{x}\sin\delta$$

Equations above are for short transmission lines. However a long line can be represented by an equivalent π circuit. The shunt admittance at the recieving end can be combined with the load and the shunt admittance at the sending end can be combined with the generator. Thus the above equations can also be applied to long lines.

Important Conclusions.

1. For fixed values of V_s, V_r and x the real power depends on angle δ which is the phase angle between V_s and V_r, which is why it is called the power angle.

2. Power can be transferred over a line even when $V_s = V_r$, the phase difference between them causes the flow of current in the line.

3. an increase of 10% in V_s and V_r increases the power transfer by 21%.

   This is another reason for adopting high and extra high transmission voltage.

4. $$Q_r = \frac{V_s V_r}{x}\cos\delta - \frac{V_r^2}{x}$$

   The power or load angle δ is generally small from considerations of stability.

   $$\therefore Q_r = \frac{V_s V_r}{x} - \frac{V_r^2}{x}$$

   $$= \frac{V_r}{x}\left[V_s - V_r\right]$$

   $\therefore$ Reactive power transferred is directly proportional to $[V_s - V_r]$ ie to voltage drop along the line. This means the major cause of voltage drop is the transfer of reactive power.

Power Circle Diagrams

The complex power at the recieving and sending ends of a line are given by (5) & (6) which can be rewritten as:

$$S_r = \frac{-AV_r^2}{B} \angle \beta-\alpha + \frac{V_s V_r}{B} \angle \beta-\delta$$

$$S_s = \frac{AV_s^2}{B} \angle \beta-\alpha - \frac{V_s V_r}{B} \angle \beta+\delta$$

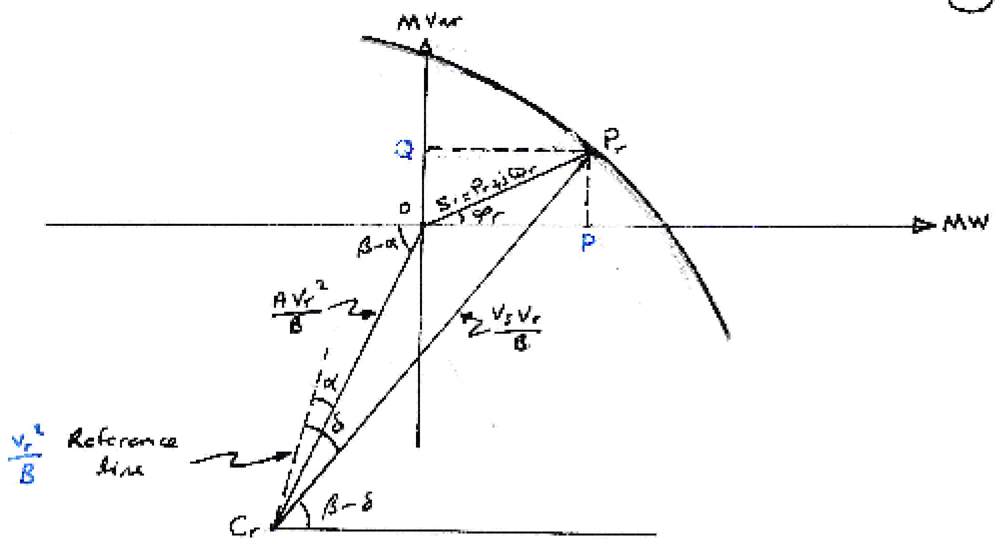
Each of the powers is the sum of two phasors.

Since the real parts of these phasors represent real power P and the imaginary part represents reactive power Q, it is possible to plot S_r and S_s in the x-y plane whose horizontal and vertical coordinates represent the real and reactive powers respectively.

The loci of S_r and S_s are circles drawn from the tip of constant phasors as centers.

The center of the recieving end circle is located at the tip of the phasor $-\frac{AV_r^2}{B} \angle \beta-\alpha$

The radius of the recieving end circle is $\frac{V_s V_r}{B}$



C_r is located by drawing OC_r equal to $\frac{AV_r^2}{B}$ inclined at $\angle\beta-\alpha$ in the positive (anticlockwise) direction from the negative x-axis. From center C_r the recieving end circle is drawn with radius $\frac{V_sV_r}{B}$. The operating point P_r on the circle is located by the amount of real power delivered to the load ie P_r, the corresponding value of Q can be read from the diagram. The power angle is the angle between the reference line (inclined by angle α from oC_r) and phasor C_rP_r (radius).

The recieving end power circles for constant V_r but varying V_s are concentric circles with C_r as the center and $\frac{V_sV_r}{B}$ as radii.

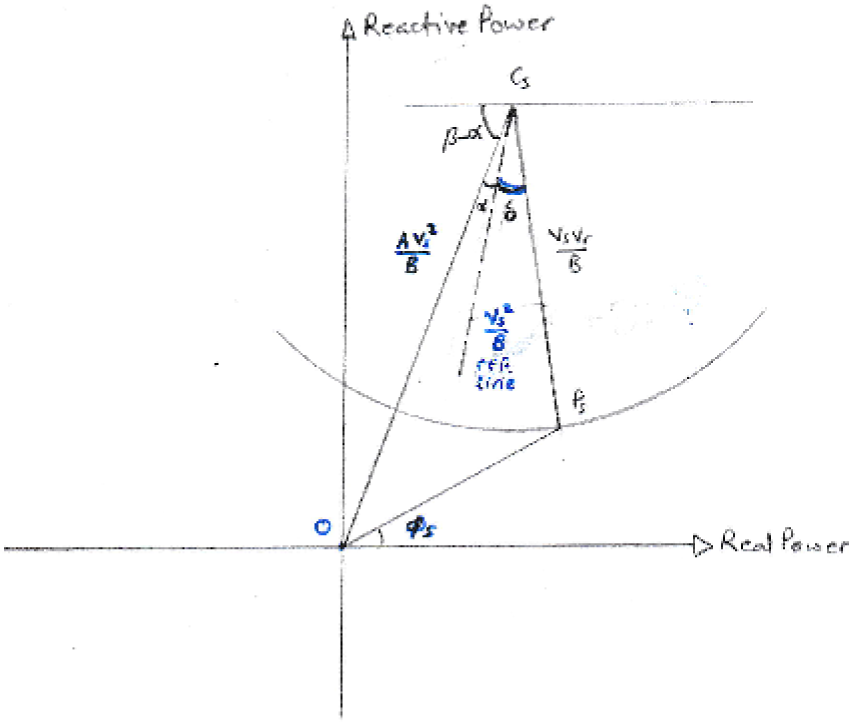
For constant V_s and varying V_r the centers of the power circles move along OC_r.

Sending end Power Circle Diagram

The center of the sending end circle is located at the tip of the phasor $\frac{AV_s^2}{B}$ which would be inclined at an angle of $\angle\beta-\alpha$ in the positive direction.

The radius of the sending end circle is of magnitud $-\frac{V_sV_r}{B}$ inclined at an angle $\angle\beta+\delta$ in the positive direction

The operating point P_s on the circle is located by the amount of real power delivered by the generating station ie P. The power angle is the angle between the reference line and phasor C_sP_s (radius).



Ex. A three phase transmission line, transmits a load of 90 MW at 0.8 p.f. lagging. The line voltage at the recieving end is 230 KV, the constants of the line are as follows:-

$A = D = 0.9785\angle 0.3 \qquad B = 85.2\angle 77.47$

Construct the recieving end and sending end circle diagrams for the transmission line and calculate.

1. V_s, I_s, $\cos\varphi_s$, regulation and efficiency of the T.L.
2. load in KW that could be carried at 8% regulation.
3. voltage drop if the load is 120 MW and the MVAR leading required for 120 MW load at 8% regulation
4. rating of the SPM (synchronous phase modifier) connected in parallel with the load so that the $V_s = 230$ KV (the same as the recieving voltage)
5. what will be the maximum power that can be transmitted in case 4 and the corresponding p.f.

Sol.

$$I_r = \frac{P_r}{\sqrt{3}\, V_r \cos\varphi_r} = \frac{90\times10^6}{\sqrt{3}\times 230\times10^3\times0.8} = 282.4\ A$$

$$\beta - \alpha = 77.47 - 0.3 = 77.17$$

For C_r (recieving end center)

$$\text{Horizontal component} = -\frac{AV_r^2}{B}\cos(\beta-\alpha)$$

$$= -\frac{0.9785}{85.2}\left(\frac{230}{\sqrt{3}}\times10^3\right)^2\cos 77.17 = -45\ MW$$

$$\text{vertical component} = -\frac{AV_r^2}{B}\sin(\beta-\alpha)$$

$$= -\frac{0.9785}{85.2}\left(\frac{230}{\sqrt{3}}\times10^3\right)^2\sin 77.17 = -197.5\ MVAR$$

scale choosen

1cm = 20 MW
1cm = 20 MVAR

locate center C_r

draw load line $OP_r = V_r I_r = \frac{230}{\sqrt{3}} \times 10^3 \times 282.4 = 37.5$ MW
$= 1.9$ cm

at an angle $\cos^{-1} 0.8 = 36.9$

From the graph $C_r P_r = 11.7$ cm $= 234$ MVA $= \frac{V_s V_r}{B}$

$\therefore V_s = \frac{234 \times 10^6 \times 85.2}{230 \times 10^3 / \sqrt{3}} = 150$ KV

line to line $V_s = 150 \times \sqrt{3} = 260$ KV

From graph $\angle \beta - \delta = 71°$ $\Rightarrow \delta = \beta - 71 = 77.47 - 71 = 6.47$

For C_s (sending end center)

Horizontal component $= \frac{A V_s^2}{B} \cos(\beta - \alpha)$
$= \frac{0.9785}{85.2} \left(\frac{260}{\sqrt{3}} \times 10^3\right)^2 \cos 77.17 = 57.5$ MW
$= 2.9$ cm

Vertical component $= \frac{A V_s^2}{B} \sin(\beta - \alpha)$
$= \frac{0.9785}{85.2} \left(\frac{260 \times 10^3}{\sqrt{3}}\right)^2 \sin 77.17 = 252$ MVAR
$= 12.6$ cm

locate C_s at (2.9, 12.6) on graph

radius $= \frac{V_s V_r}{B} = 11.7$ cm (from recieving circle)

radius inclined by angle $\angle \beta + \delta = 77.47 + 6.47 = 83.94$

draw $C_s P_s$ of length 11.7 cm with angle 83.94 in the positive direction.

join $OP_s = V_s I_s = 1.9$ cm (from graph)

$= 38$ MVA

$\therefore I_s = \frac{38 \times 10^6}{150 \times 10^3} = 253$ A

From graph $\phi_s = 30$

$\therefore$ power factor of sending end $\cos\phi_s = 0.87$

Voltage Regulation $VR = \frac{V_s - V_r}{V_r} = \frac{260 - 230}{230} \times 100\% = 13\%$

(2) $0.08 = \frac{V_s - V_r}{V_r} = \frac{V_s}{V_r} - 1 \Rightarrow \frac{V_s}{V_r} = 1.08 \Rightarrow V_s = 1.08\, V_r$

new radius of recieving circle $= \frac{1.08 \frac{230}{\sqrt{3}} \times \frac{230}{\sqrt{3}}}{85.2} = 223.5$ MVA

$= 11.2$ cm

draw new recieving end circle and locate point of intersection with load line and measure new horizontal component $OP_{r2} = 1.1$ cm $= 22$ MW

$\therefore$ Total load $= 3 \times 22 = 66$ MW

(3) load per phase $= \frac{120}{3} = 40$ MW

$\therefore$ load MVA per phase $= \frac{40}{0.8} = 50$ MVA $= 2.5$ cm

$= OP_{r3}$ on graph

From graph $C_r P_{r3} = 12.2$ cm $= 244$ MVA $= \frac{V_s V_r}{B}$

$\therefore V_s = \frac{244 \times 85.2}{\frac{230}{\sqrt{3}}} = 156.6$ KV

$\therefore$ voltage drop per phase $= 156.6 - \frac{230}{\sqrt{3}} = 23.8$ KV

For increased load (120 MW) at $VR = 0.08$ then P_{r3} must be moved downwards to circle (2) by a distance $= 1.1$ cm $= 22$ MVAR leading

4 For $V_s = 230KV$ then

$$\text{radius} = \frac{V_s V_r}{B} = \frac{\frac{230}{\sqrt{3}} \cdot \frac{230}{\sqrt{3}}}{85.2} = 207 \text{ MVA} = 10.35 \text{ cm}$$

draw new circle 3 ~~for~~ for the recieving end

with a radius equal to 10.35 cm

measure the vertical distance from P_r to circle 3

∴ P_r must be moved vertically downwords by 1.5 cm

∴ Rating of SPM = 1.5 x 20 = 30 MVAR leading

5 on graph point P_{max} represent the maximum power transmitted, Measure it's distance

P_{max} = 8 cm = 160 MW for one phase

Total maximum power = 3 x 160 = 480 MW

The new ϕ_r is represented by the angle

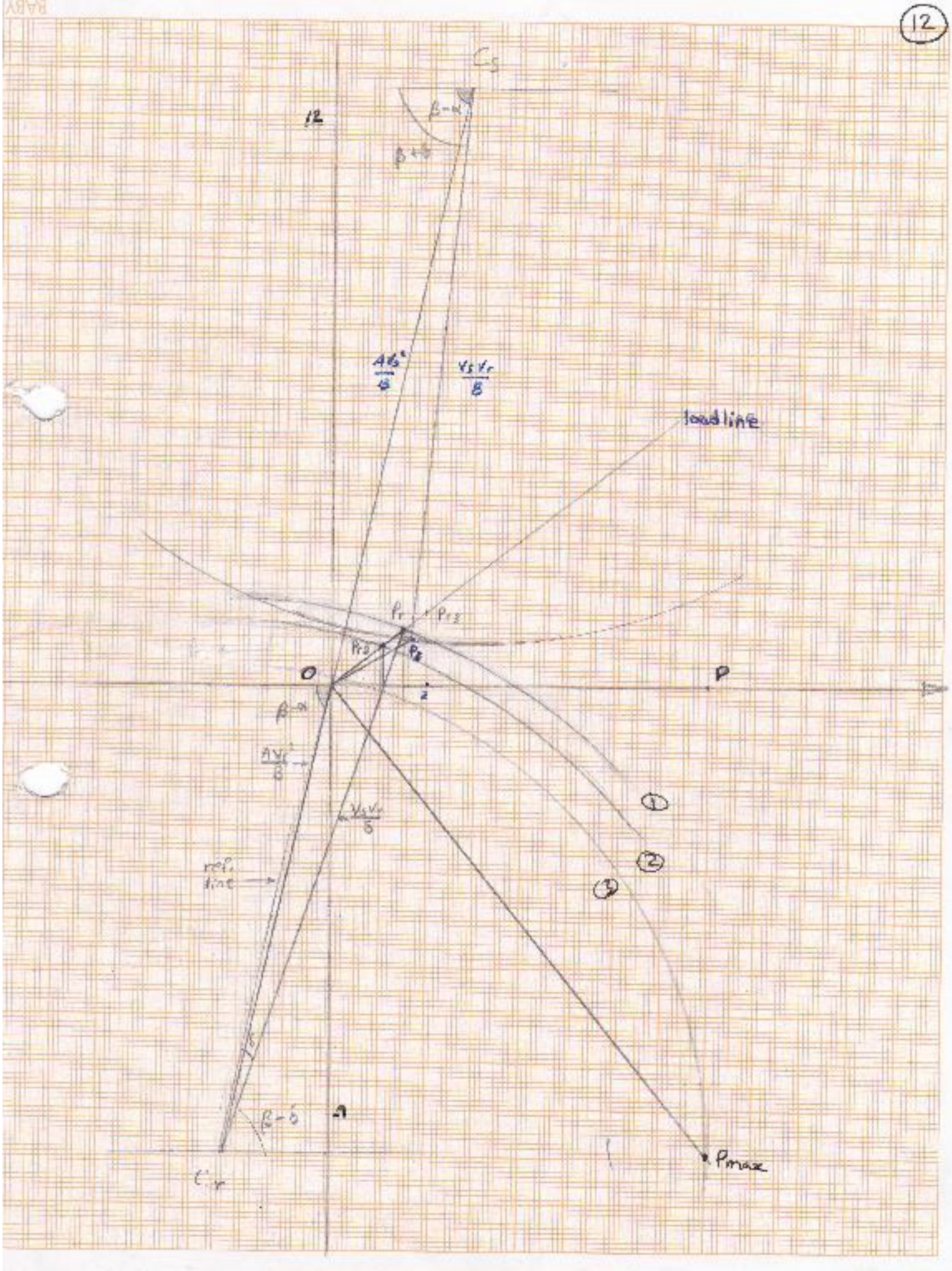
$\measuredangle P\, O\, P_{max}$

measure it from graph

$\measuredangle P\, O\, P_{max} = 51^\circ$

∴ corresponding power factor = cos 51

= 0.63 lead

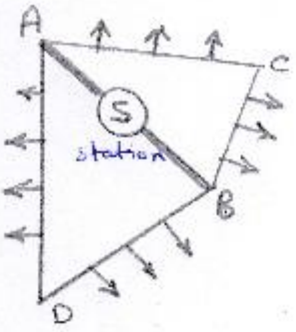


C_s
12
$\beta-\alpha$
$\beta+\delta$
$\frac{AV_s^2}{B}$
$\frac{V_sV_r}{B}$
load line
P_r
P_{rs}
P_{rs}
P_s
O
P
$\beta-\alpha$
$\frac{AV_r^2}{B}$
$\frac{V_sV_r}{B}$
ref. line
①
②
③
$\beta-\delta$
C_r
P_{max}

Power Distribution Systems

D.C. Distribution

A distribution system can be subdivided into feeders (SA, SB) distributors (ACB, ADB) and service mains.

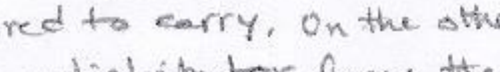


Feeders are conductors of large current carrying capacity

It is imprtant to note that:
The size of the feeder is determined by the current it is required to carry. On the other hand, voltage drop along a distributor forms the main basis of design in the case of a distributor.

Radial and Ring main systems

If the distributor is connected to the supply on one end only, the system is called a radial system

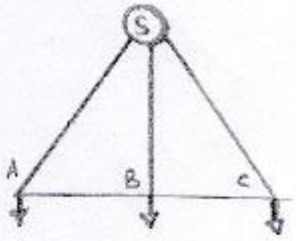


It is clear that the end of the distributor nearest to the generating station would be heavily loaded, and the consumer at the distant end of the distributor would be subjected to serious voltage variation as the load on the distributor varies.

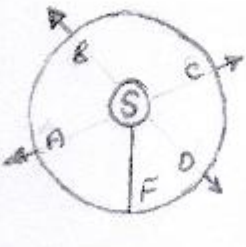
The voltage across the loads away from the feeding point goes on decreasing, thus the minimum voltage occurs at load point C.

In addition, the consumer is dependent upon a single feeder, so that a fault on the feeder or distributor cuts off the supply on the side of the fault away from the station.

This can be remedied to some extent if the distributor is fed at a number of points as shown; Three feeders SA, SB and SC from the generating station are feeding the distributor AC.



Another system of distribution employs a feeder which covers the whole area of supply and finally returning to the generating station, the feeder is closed on itself.

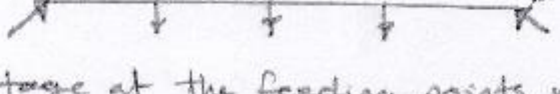


ABCDA forms the complete ring.

This arrangement is similar to two feeders in parallel on different routes.

The advantage of such an arrangement is that, it offers a greater reliability of supply.

It equivalent to a distributor fed at both ends



The voltage at the feeding points may or may not be equal. The load voltage goes on decreasing as we move away from one feeding point, and reaches minimum value and then again starts rising and reaches maximum value at the other feeding point.

DC Distribution Calculations

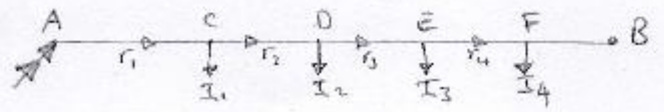
A distributor may have
1. concentrated loading
2. uniform "
3. both concentrated and uniform loading

One important point is the determination of point of minimum potential. The distributor is so designed that the min. potential on it is not less than 6% of rated voltage at the consumers terminal.

Concentrated Loading

1. DC distributor fed at one end

Fig. shows the single line diagram of a 2-wire DC distributor AB fed at one end A.



r_1, r_2, r_3, r_4 : The resistance of both go and return

current fed from point $A = I_1 + I_2 + I_3 + I_4$

" in section $AC = I_1 + I_2 + I_3 + I_4$

" " " $CD = I_2 + I_3 + I_4$

" " " $DE = I_3 + I_4$

" " " $EF = I_4$

Voltage drop in section $AC = r_1 (I_1 + I_2 + I_3 + I_4)$

" " " " $CD = r_2 (I_2 + I_3 + I_4)$

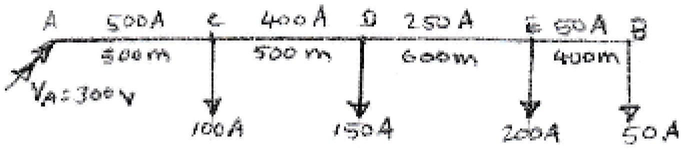
" " " " $DE = r_3 (I_3 + I_4)$

" " " " $EF = r_4 (I_4)$

$$\text{Total voltage drop} = r_1 (I_1 + I_2 + I_3 + I_4) + r_2 (I_2 + I_3 + I_4) + r_3 (I_3 + I_4) + r_4 I_4$$

The min. potential is at point F which is furthest from the feeding point A.

Ex: A 2-wire DC distributor cable AB is 2 Km long and supplies loads as shown. Each conductor has a resistance of 0.01 Ω /Km. Calculate the p.d. at each load point if a p.d of 300V is maintained at A



Sol.

Resistance per Km of distributor $= 2 \times 0.01 = 0.02\,\Omega/Km$

Resistance of section AC $= \frac{0.02}{1000} \times 500 = 0.01\,\Omega$

" " CD $= \frac{0.02}{1000} \times 500 = 0.01\,\Omega$

" " DE $= \frac{0.02}{1000} \times 600 = 0.012\,\Omega$

" " EF $= \frac{0.02}{1000} \times 400 = 0.008\,\Omega$

p.d at load point C : $V_C = V_A -$ Voltage drop in AC

$= V_A - I_{AC} R_{AC}$

$= 300 - 500 \times 0.01 = 295\,V$

p.d at load point D: $V_D = V_C - I_{CD} R_{CD}$

$= 295 - 400 \times 0.01 = 291\,V$

p.d at load point E: $V_E = V_D - I_{DE} R_{DE}$

$= 291 - 250 \times 0.012 = 288\,V$

p.d at load point B: $V_B = V_E - I_{EB} R_{EB}$

$= 288 - 50 \times 0.008 = 287.6\,V$

2. Distributor fed at both ends

Total voltage drop can be considerably reduced without increasing the cross-section when fed at both ends.

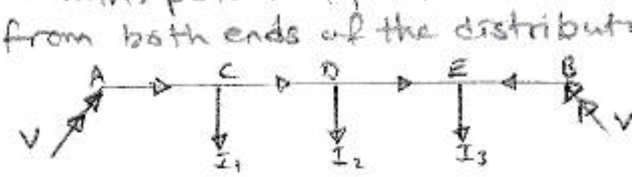
(i) Two ends fed with equal voltages

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, then it starts rising and becomes V volts at point B.
points between A and E will be supplied from A while those between E and B " " " " B
E will be partly supplied from A and partly supplied from B

If these currents are x and y respectively then

$$I_3 = I_x + I_y$$

i.e at min. potential point current comes from both ends of the distributor.



$I_{AC} = I_A$
$I_{CD} = I_A - I_1$
$I_{DE} = I_A - I_1 - I_2$
$I_{EB} = I_A - I_1 - I_2 - I_3$

voltage drop over AB is

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

(ii) Two ends fed with unequal voltages

The point of min. potential can be found by the same procedure as above

voltage drop between A & B = voltage over AB

$V_A - V_B =$ " " "

Ex.2 A two wire DC distributor AB is fed from both ends. At feeding point A, the voltage is maintained at 230V and at B 235V. The total length of the feeder is 200 m and loads are tapped off as:

25 A at 50m from A; 50 A at 75m from A.
30 A at 100 m " A; 40A at 150m " A.

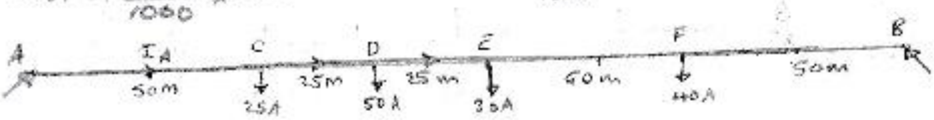
The resistance per Km of one conductor is 0.3 Ω

Calculate:

1. currents in various sections of the distributor
2. min. voltage at point at which it occurs.

Sol. $R_{AC} = \frac{2\times0.3}{1000}\times 50 = 0.03\,\Omega$; $R_{CD} = \frac{2\times0.3}{1000}\times 25 = 0.015\,\Omega = R_{DE}$

$R_{EF} = \frac{2\times0.3}{1000}\times 50 = 0.03\,\Omega$; $R_{FB} = \frac{2\times0.3}{1000}\times 50 = 0.03\,\Omega$



$$V_A - V_B = I_A R_{AC} + (I_A - 25)R_{CD} + (I_A - 75)R_{DE} + (I_A - 105)R_{EF} + (I_A - 145)R_{FB}$$

$$230 - 235 = 0.03\,I_A + 0.015(I_A - 25) + 0.015(I_A - 75) + 0.03(I_A - 105) + 0.03(I_A - 145)$$

$$-5 = 0.12\,I_A - 9$$

$$I_A = 33.33\,A$$

$\therefore I_{AC} = I_A = 33.33A$

$I_{CD} = I_A - 25 = 8.34A$

$I_{DE} = I_A - 75 = -41.66A$ from D to E
$= 41.66A$ from E to D

$I_{EF} = I_A - 105 = 71.66A$ from F to E

$I_{FB} = I_A - 145 = 111.66A$ from B to F

The currents are coming to point D from both sides of the distributor.

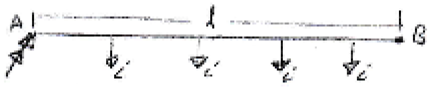
Therefore, load point D is the point of min. potential

$$V_D = V_A - (I_{AC}R_{AC} + I_{CD}R_{CD})$$
$$= 230 - (33.33\times0.03 + 8.33\times0.015)$$
$$= 230 - 1.125$$
$$= 228.875$$

Uniform Loading

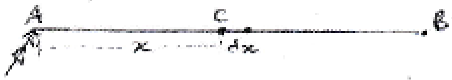
1. Uniformly loaded distributor fed at one end

Fig. shows the single line diagram of a 2-wire D.C. distributor AB fed at one end A and loaded uniformly with i amperes per meter length



Let l be the length of the distributor
r be the resistance per meter.

Consider a point C at distance x meters from point A.



Then current at point C $= il - ix$
$= i(l-x)$

Now consider a small length dx near point C.
It's resistance is $r\,dx$ and the voltage drop is

$$dV = i(l-x)\,r\,dx$$
$$= ir(l-x)\,dx$$

Total voltage drop up to point C is

$$V = \int_0^x ir(l-x)\,dx$$
$$= ir\left(lx - \frac{x^2}{2}\right)$$

Voltage drop up to point B can be obtained by putting $x = l$

$$= ir\left(l.l - \frac{l^2}{2}\right)$$
$$= \frac{1}{2} ir\,l^2$$
$$= \frac{1}{2} il\,rl$$
$$= \frac{1}{2} I R$$

I : Total current entering point A
R : " resistance of the distributor.

Ex. 3 A two-wire DC distributor 200m long is uniformly loaded with 2A/m. Resistance of single wire is 0.3 Ω/Km. If the distributor is fed at one end Calculate:

1. The voltage drop up to a distance of 150m from the feeding point.
2. The maximum voltage drop.

Sol.

$$\text{Resitance/m} = 2 \times \frac{0.3}{1000} = 0.0006\ \Omega/m$$

$$\text{voltage drop up to point } x = ir\left(lx - \frac{x^2}{2}\right)$$

$$\therefore \text{voltage drop} = 2 \times 0.0006\left(200 \times 150 - \frac{150^2}{2}\right)$$
$$= 22.5\ V$$

$$\text{Total resistance } R = rl = 0.0006 \times 200$$
$$= 0.12\ \Omega$$

$$\text{Total current } I = il = 2 \times 200$$
$$= 400\ A$$

$$\therefore \text{Total drop} = \frac{1}{2} IR$$
$$= \frac{1}{2} \times 400 \times 0.12$$
$$= 24\ V$$

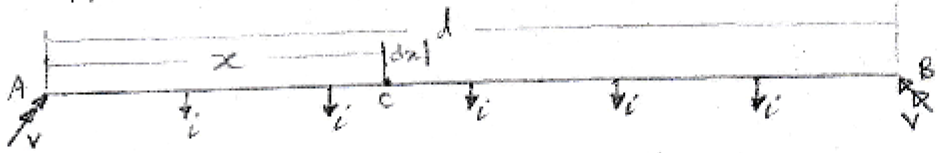
2. Uniformly loaded distributor fed at both ends

(i) Two ends fed with equal voltages

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 il.

As the two end voltages are equal, therefore, current supplied from each feeding point is $il/2$



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

Resistance of small length $dx = r\,dx$

Voltage drop over length dx is dv

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

Voltage drop up to point C is:

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

$$= \frac{ir}{2}\left(lx - x^2\right)$$

Obviously the point of min. potential will be the mid-point. Therefore, max. voltage drop will occur at $x = l/2$

$$\therefore \text{max voltage drop} = \frac{ir}{2}\left(l \times \frac{l}{2} - \frac{l^2}{4}\right)$$

$$= \frac{1}{8} irl^2$$

$$= \frac{1}{8} il\, rl$$

$$= \frac{1}{8} IR$$

$$\text{min. voltage} = V - \frac{IR}{8}$$

(ii) Two ends fed with unequal voltages

Let the distributor be fed at points A & B with voltages V_A & V_B respectively.

Suppose that the point of min. potential C is situated at a distance x meters from A. Then current supplied by feeding point A will be ix

(as C is at min. potential, therefore, there is no current at this point, consequently, current in section AC is supplied by feeding point A)

$\therefore$ voltage drop in section AC $= ir\dfrac{x^2}{2}$ volts.

As the distance of C from feeding point B is $(l-x)$ and current from B is $i(l-x)$

$\therefore$ voltage drop in section BC $= ir\dfrac{(l-x)^2}{2}$

voltage at point C, $V_C = V_A$ - drop over AC

also $V_C = V_B$ - drop over BC

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

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

$$= irlx - \frac{irl^2}{2}$$

$$V_A - V_B + \frac{irl^2}{2} = irlx$$

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

Ex.4 A two wire DC distributor 500m long is fed from both ends and is loaded uniformly at the rate of 1 A/m. At feeding point A the voltage is maintained at 255 V and at B 250 V. If the resistance of each conductor is 0.1 Ω/Km, determine

1. The min. voltage and the point where it occurs.
2. The currents supplied from points A and B.

Sol.

1/ Resistance /m $= r = 2 \times \frac{0.1}{1000} = 0.0002\,\Omega$

Let the min. potential occur at point C distant x from point A

$$x = \frac{V_A - V_B}{i r l} + \frac{l}{2} = \frac{255-250}{1 \times 0.0002 \times 500} + \frac{500}{2} = 300\,m$$

min. voltage $V_C = V_A - \frac{i r x^2}{2}$

$$= 255 - \frac{1 \times 0.0002 \times 300^2}{2}$$

$$= 246\,V$$

2/ current supplied from A $= i x$

$$= 1 \times 300$$

$$= 300\,A$$

current supplied from B $= i(l - x)$

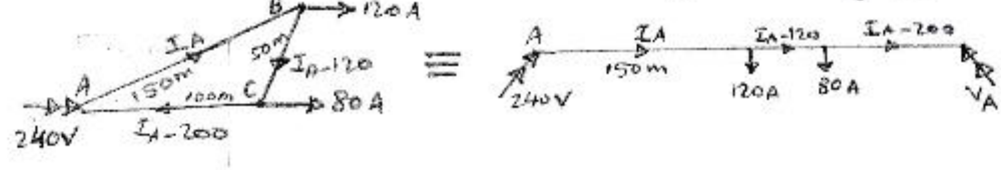
$$= 1(500 - 300)$$

$$= 200\,A$$

Ring Distributor

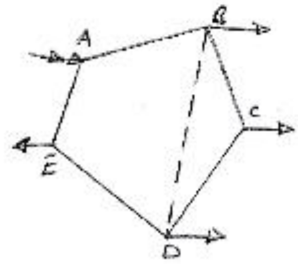
A distributer arranged to form a closed loop and fed at one or more points is called a ring distributor.

The distributor can be considered as a series of open distributors fed at both ends with equal voltages.



Ring Distributor with interconnector

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



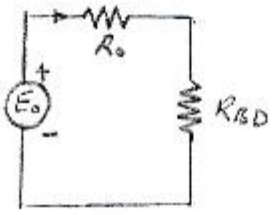
B and D are joined through the interconnector BD

The solution of such a network can be obtained by applying Thevenin's theorem

The steps are :-

1. Consider interconnector BD to be disconnected, and find the potential difference between B & D
   This gives Thevenin's equivalent voltage E_o
2. Calculate the resistance viewed from points B & D
   this gives Thevenin's equivalent series resistance R_o
3. If R_{BD} is the resistance of interconnector BD then current in interconnector BD is

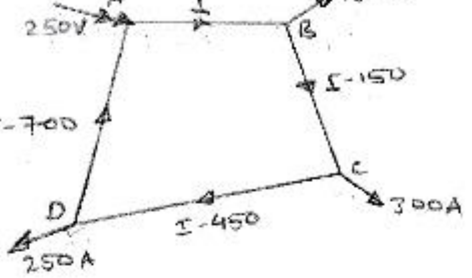
$$I_{BD} = \frac{E_o}{R_o + R_{BD}}$$



Ex.5 A DC ring main ABCDA is fed from point A from a 250 V supply and the resistances (both lead and return) are as follows: $AB = 0.02\,\Omega$, $BC = 0.018\,\Omega$, $CD = 0.025\,\Omega$ and $DA = 0.02\,\Omega$. The main supplies loads of 150 A at B, 300 A at C and 250 A at D.

- Determine the voltage at each load point.
- If the points A & C are linked through an interconnector of resistance $0.02\,\Omega$. Determine the new voltage at each load point.

Sol.



Let current I flows in section AB

According to Kirchhoff's voltage law,
The voltage drop in the closed loop ABCDA is zero

$$I_{AB}R_{AB} + I_{BC}R_{BC} + I_{CD}R_{CD} + I_{DA}R_{DA} = 0$$

$$0.02I + 0.018(I-150) + 0.025(I-450) + 0.02(I-700) = 0$$

$$0.083I = 27.95$$

$$I = 336.75\ \text{A}$$

$\therefore$ voltage drop in $AB = 336.75 \times 0.02 = 6.735\ \text{V}$

" " $BC = 186.75 \times 0.018 = 3.361\ \text{V}$

" " $CD = 113.25 \times 0.025 = 2.831\ \text{V}$

" " $DA = 363.25 \times 0.02 = 7.265\ \text{V}$

voltage at point $B = 250 - 6.735 = 243.265\ V = V_B$

" " " $C = 243.265 - 3.361 = 239.904\ V = V_C$

" " " $D = 239.904 + 2.831 = 242.735\ V = V_D$

(ii) with interconnector AC

E_0 = voltage between points A + C $= V_A - V_C$

$= 250 - 239.904 = 10.096$

R_0 = Resistance viewed from points A + C

$= R_{AB} + R_{BC} \parallel R_{CD} + R_{DA}$

$$= \frac{(0.02 + 0.018) \times (0.02 + 0.025)}{(0.02 + 0.018) + (0.02 + 0.025)} = 0.02\,\Omega$$

Resistance of interconnector $R_{AC} = 0.02\,\Omega$

Current in interconnector $I_{AC} = \dfrac{10.096}{0.02 + 0.02}$

$= 252.4\,A$ from A to C

Let the current in AB be I_1

Then current in BC will be $I_1 - 150$

current in CD $= I_1 - 150 + 252.4 - 300$

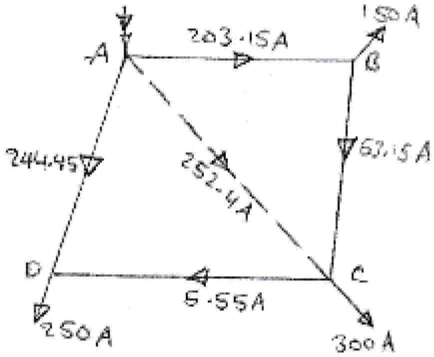
" " DA $= I_1 - 150 + 252.4 - 300 - 250$

The voltage drop round the closed mesh ABCA is zero

$0.02 I_1 + 0.018(I_1 - 150) - 0.02 \times 252.4 = 0$

$\therefore I_1 = 203.15\,A$

The actual distribution of currents in the ring distributor with the interconnector will be as shown :-



A.C. Distribution

AC distribution calculations differ from those of DC distribution in the following:

1. In case of DC system, the voltage drop is due to resistance alone, however, in an AC, the voltage drops are due to the combined effects of resistance, inductance and capacitance.

2. In a DC system additions and subtractions of currents or voltages are done arithmetically but in case of AC system those operations are done vectorially.

3. In the AC system power factor has to be taken into account. Loads tapped off from the distributor are generally at different power factors.

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

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

Power factor referred to receiving end voltage

Consider the distributor shown:

taking V_B as a reference vector

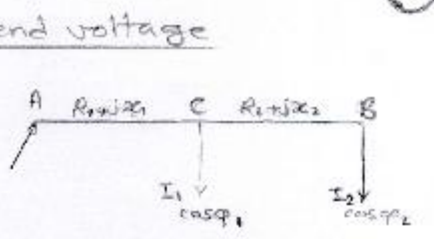


fig (1)

$\vec{I}_1 = I_1(\cos\varphi_1 - j\sin\varphi_1)$

$\vec{I}_2 = I_2(\cos\varphi_2 - j\sin\varphi_2)$

Drop in section CB = $V_2 = I_{CB} Z_{CB}$

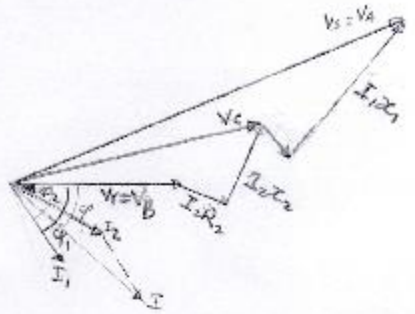
$\vec{V}_2 = I_2(\cos\varphi_2 - j\sin\varphi_2)(R_2 + jx_2)$

$\vec{I} = \vec{I}_1 + \vec{I}_2 = I(\cos\varphi - j\sin\varphi)$

Drop in section AC = V_1

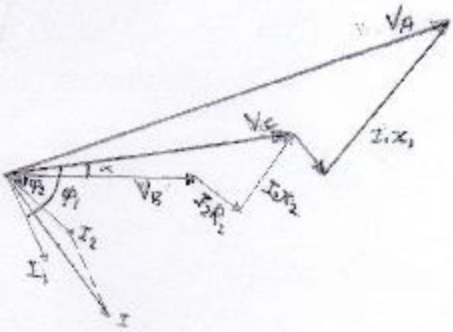
$\vec{V}_1 = (\vec{I}_1 + \vec{I}_2)\vec{Z}_1$

$\vec{V}_1 = I(\cos\varphi - j\sin\varphi)(R_1 + jx_1)$



Power factor referred to respective load voltages

For fig (1) the phasor diagram will be as shown: →



I_2 lags V_B by angle φ_2

I_1 lags V_C by angle φ_1

$\vec{I}_2 = I_2(\cos\varphi_2 - j\sin\varphi_2)$

$\vec{I}_1 = I_1(\cos(\varphi_1 - \alpha) - j\sin(\varphi_1 - \alpha))$

$\vec{I} = \vec{I}_1 + \vec{I}_2$

For both cases

$V_A = V_B +$ drop in section AC + drop in section CB

$= V_B + (I_1 + I_2)Z_1 + I_2 Z_2$

Ex. 6 A single phase AC distributer AB 300 m long is fed from end A and is loaded as under

(i) 100A at 0.707 p.f lagging, 200m from point A.

(ii) 200A at 0.8 p.f lagging, 300m from point A.

The load resistance and reactance is 0.2 Ω and 0.1 Ω per Km, Calculate the total voltage drop in the distributor, the load P.f referred to the voltage at the far end.

Sol.

Impedance / Km = $0.2 + j0.1$

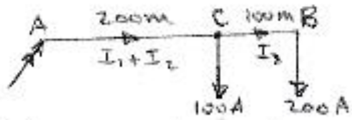
$$Z_{AC} = \frac{0.2+j0.1}{1000} \times 200 = 0.04 + j0.02 \ \Omega$$

$$Z_{CB} = \frac{0.2+j0.1}{1000} \times 100 = 0.02 + j0.01 \ \Omega$$

Taking voltage V_B at far end as the reference vector

$\vec{I}_2 = I_2(\cos\varphi_2 - j\sin\varphi_2)$

$= 200(0.8 - j0.6) = 160 - j120$ A



$\vec{I}_1 = I_1(\cos\varphi_1 - j\sin\varphi_1)$

$= 100(0.707 - j0.707) = 70.7 - j70.7$ A

$\vec{I}_{AC} = \vec{I}_1 + \vec{I}_2 = 230.7 - j190.7$ A

Voltage drop in section CB

$\vec{V}_{CB} = \vec{I}_{CB}\vec{Z}_{CB} = (160 - j120)(0.02 + j0.01) = 4.4 - j0.8$ V

Voltage drop in section AC

$\vec{V}_{AC} = \vec{I}_{AC}\vec{Z}_{AC} = (230.7 - j190.7)(0.04 + j0.2) = 13.04 - j3.01$ V

Voltage drop in the distributor

$\vec{V}_{AB} = \vec{V}_{AC} + \vec{V}_{CB}$

$= 13.04 - j3.01 + 4.4 - j0.8$

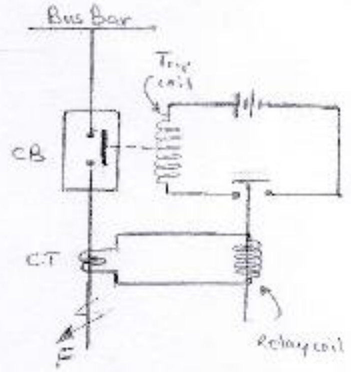
$= 17.44 - j3.81$ V

$= 17.85 \angle 12.3$

∴ magnitude of drop = 17.85 V

Protective Relays

Protective relay: is a device that detects the fault and initiates the operation of a circuit breaker to isolate the defective element from the rest of the system.



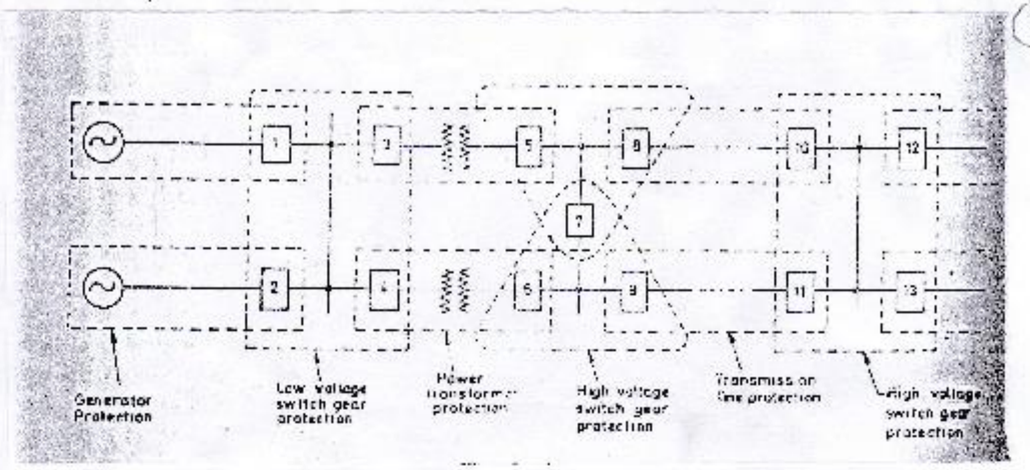
The diagram shows a typical relay of one phase of a 3 phase system.

1. primary winding of a current transformer CT which is connected in series with the line.
2. Secondary winding of the CT and the relay operating coil.
3. Tripping circuit which maybe AC or DC. It consists of a source of supply, the trip coil of the circuit breaker and the relay stationary contacts.

Fundamental Requirements

The principal function of protective relaying is to cause the removal from the service of any element of the power system when it starts to operate in abnormal manner. in order to do that it should have the following qualities:

1. Selectivity: The ability of the protective system to select correctly the faulty part and disconnect it without disturbing the rest of the system.



It is a usual practice to divide the entire system into several zones. If a fault occurs at bus bars on the last zone, then only breakers nearest to the fault (10, 11, 12, 13) should open.

2. Speed; the relay system should disconnect the faulty section as fast as possible.

3. Sensitivity: the ability to operate with low value of actuating quantity.

4. Reliability: the ability of the relay to operate under the predetermined conditions.

5. Simplicity: it should be simple to be easily maintained.

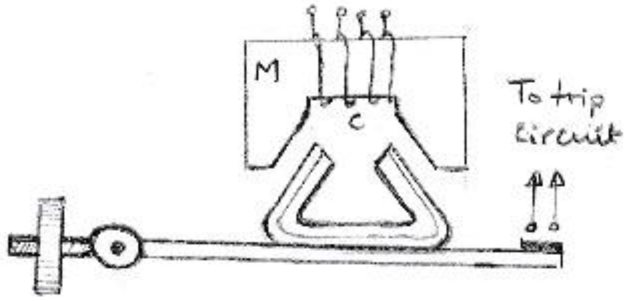
6. Economy: economics plays a major role as with all good engineering designs.

Electromagnetic Attraction Relay

They work on the idea that an armature is attracted to the poles of an electromagnet. Such relays may be actuated by DC or AC quantities.

Attracted Armature Relay

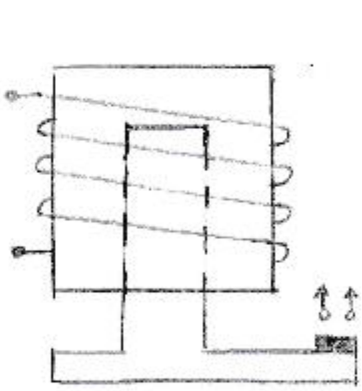
It consists of a laminated electromagnet M carrying a coil C and a pivoted laminated armature.



The armature is balanced by a counter weight and carries a pair of contacts. Under short circuit the current through the relay coil increases and the relay armature is attracted upwards.

Solenoid Relay

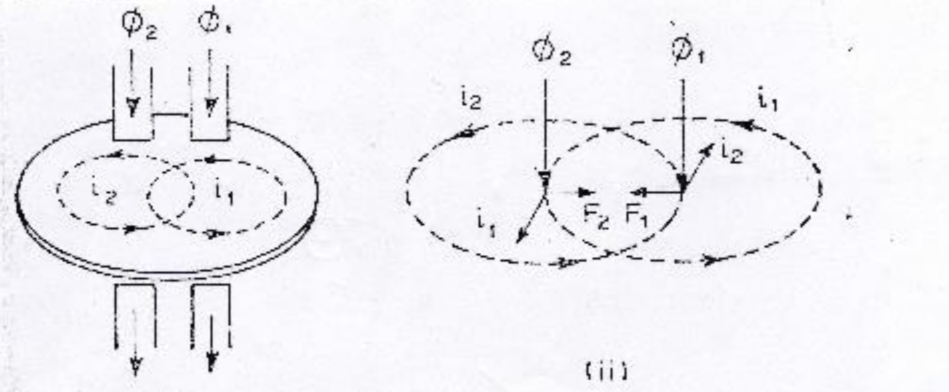
At fault, the current through the relay coil becomes more than the pickup value, causing the plunger to be attracted, this movement closes the trip circuit, thus opening the circuit breaker



Induction Relays.

Electromagnetic induction relays operate on the principle of induction motor. They are not used with DC quantities owing to the principle of operation.

It consists of a pivoted aluminium disc placed in two alternating magnetic fields of the same frequency but displaced in time and space. The torque is produced in the disc by the interaction of one of the magnetic fields with the currents induced in the disc by the other magnetic field



(i)

The two AC fluxes φ_1 and φ_2 differing in phase by an angle α, induce emf's in the disc and cause circulation of eddy currents i_1 and i_2 respectively.

Let $\varphi_1 = \varphi_{1max} \sin \omega t$

$\varphi_2 = \varphi_{2max} \sin(\omega t + \alpha)$

ie φ_2 leads φ_1 by an angle α

Assuming that the paths in which the rotor currents flow have a negligible self inductance, the rotor currents will be in phase with their voltages.

$$i_1 \propto \frac{d\varphi_1}{dt} \propto \frac{d}{dt}\varphi_{1max}\sin\omega t \propto \varphi_{1max}\cos\omega t$$

$$i_2 \propto \frac{d\varphi_2}{dt} \propto \frac{d}{dt}\varphi_{2max}\sin(\omega t+\alpha) \propto \varphi_{2max}\cos(\omega t+\alpha)$$

Now $F_1 \propto \varphi_1 i_2$

$F_2 \propto \varphi_2 i_1$

The two forces F_1, F_2 are in opposition.

$\therefore$ The net force $F \propto F_2 - F_1$

$\therefore F \propto \varphi_{2max}\sin(\omega t+\alpha).\varphi_{1max}\cos\omega t - \varphi_{1max}\sin\omega t\,.\,\varphi_{2max}\cos(\omega t+\alpha)$

$\therefore F \propto \varphi_{1max}\varphi_{2max}[\sin(\omega t+\alpha)\cos\omega t - \sin\omega t\cos(\omega t+\alpha)]$

$\propto \varphi_{1max}\varphi_{2max}\sin\alpha$

$\therefore F \propto \Phi_1 \Phi_2 \sin\alpha$

where Φ_1, Φ_2 are the rms values of the fluxes.

N.B.

① The greater the phase angle (α) between the fluxes, the greater is the net force applied to the disc.

② The direction of the force and hence the direction of motion of the disc depends upon which flux is leading.

The following types of structures are commonly used for obtaining the phase difference and hence the operating torque.

Shaded-Pole structure

It consists of a pivoted aluminium disc free to rotate in the air gap of an electro-magnet. One half of each pole is surrounded by a copper band known as shading ring.

The alternating flux φ_s in the shaded portion will lag behind the flux φ_u in the unshaded portion by an angle α (owing to the reaction of the current induced in the ring)

These two AC fluxes differing in phase will produce the necessary torque to rotate the disc

$$T \propto \varphi_s \varphi_u \sin\alpha$$

Assuming φ_s, φ_u to be proportional to the current I in the relay coil, then $T \propto I^2 \sin\alpha$

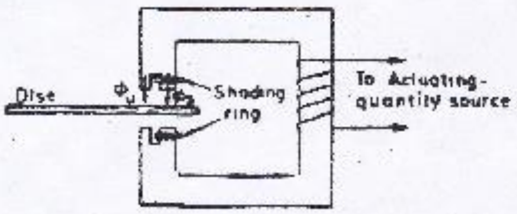


Fig.

Watt hour-meter structure.

It consists of a pivoted aluminium disc arranged to rotate freely between the poles of two electromagnets. The upper electromagnet carries two windings, the primary and the secondary. The primary winding carries the relay current I_1 while the secondary is connected to the windings of the lower magnet. The primary current I_1 induces emf in the secondary and so circulates a current I_2 in it. The flux φ_2 induced in the lower magnet will lag behind φ_1 by an angle α, this will produce the driving torque on the disc proportional to $\varphi_1 \varphi_2 \sin\alpha$.

N.B. This relay can be made inoperative by opening it's secondary winding circuit.

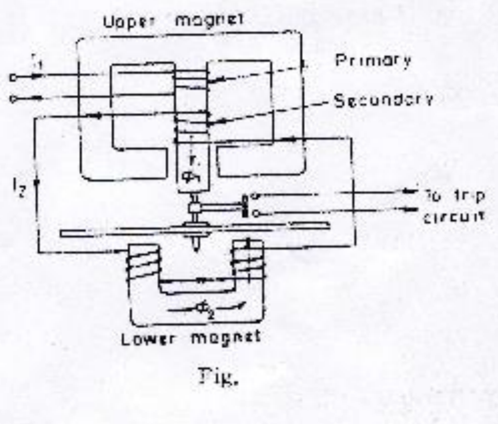


Fig.

Relay Timing (Time of operation)

1. Instantaneous Relay

An instantaneous relay is one in which no intentional time delay is provided. Relay contacts are closed immediately after current in the relay coil exceeds the minimum calibrated value.

2. Inverse-time Relay

An inverse-time relay is one in which the operating time is approximately inversely proportional to the magnitude of the actuating quantity.

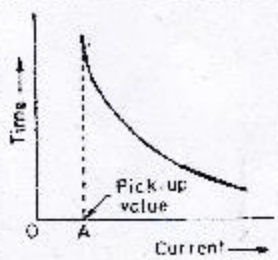


Fig.

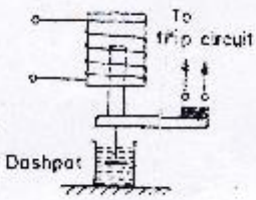


Fig.

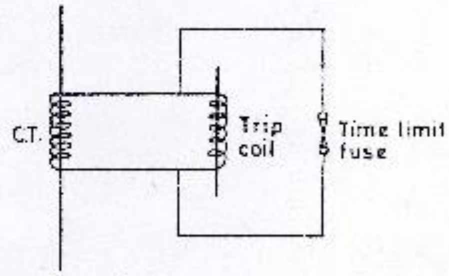


Fig.

3. Definit-time lag Relay.

In this type of relay, there is a definite time elapse between the instant of pickup and the closing of relay contacts. This particular time setting is independent of the amount of current through the relay coil.

pick up current: It is the minimum current in the relay coil at which the relay starts to operate.

Current Setting

It is the adjustment of the pickup current to any required value, and is usually achieved by the use of tappings on the relay operating coil. The taps are brought out to a plug bridge which permits to alter the number of turns on the relay coil. This changes the torque on the disc and hence the time of operation of the relay. The values assigned to each tap are expressed in terms of percentage full-load rating of C.T. (current transformer) and represents the value above which the disc starts to rotate and finally closes the trip circuit.

$$\therefore \text{Current setting} = \frac{\text{Pick up current}}{\text{Rated secondary current}}$$

Plug-Setting Multiplier PSM

It is the ratio of fault current in relay coil to the pick up current.

$$PSM = \frac{\text{Fault current in relay coil}}{\text{pick up current}}$$

suppose that a relay is connected to a 400/5 CT and has a current setting of 150%, with a primary fault current of 2400 A, the PSM can be calculated as under:

$$\text{pick up current} = 1.5 \times 5 = 7.5\ A$$

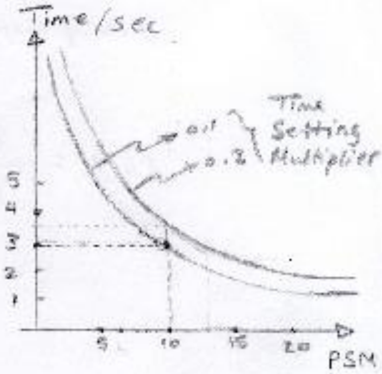
$$\text{Fault current} = 2400 \times \frac{5}{400} = 30\ A$$

$$\therefore PSM = \frac{30}{7.5} = 4$$

Time setting multiplier

A relay is generally provided with control to adjust the time of operation. This adjustment is known as time setting multiplier. The time setting dial 0 to 1 in steps of 0.05, these figures are multipliers to be used to convert the time derived from time / PSM curve into the actual operating time. In an induction relay, the time of operation is controlled by adjusting the amount of travel of the disc from it's reset position to it's pickup position.

Time / PSM curve



fig(A)

The vertical scale is marked in terms of the time required for relay operation. If the PSM is 10 then the time of operation (from the curve) is 3 sec. The actual time of operation is obtained by multiplying this time by the time setting multiplier.

If the time setting multiplier is set at 0.1 then the actual time of operation is $3 \times 0.1 = 0.3$ sec.

From (Time – PSM curve): for lower values of overcurrent, time of operation varies inversely with the current, but as the current approaches 20 times full load value, the operating time of relay tends to become constant. This feature is necessary in order to ensure discrimination on very heavy fault currents.

Ex. An over-current relay has a current setting of 150%
and has a time multiplier setting of 0.5. The relay is connected
in a circuit through a CT having a ratio 500/5.
Calculate the time of operation of the relay if the circuit
carries a fault current of 6000A.
Use the curve in fig (B).

Sol. current setting = $\frac{\text{pickup current}}{\text{Rated secondary current}}$

$\therefore$ pick up current $= 1.5 \times 5 = 7.5$

Fault current $= 6000 \times \frac{5}{500} = 60A$

Plug Setting Multiplier $= \frac{\text{Fault current}}{\text{pick up current}}$

$= \frac{60}{7.5} = 8$

Time from graph = 3.15 sec.

$\therefore$ operating time = Time from graph × Time multiplier

$= 3.15 \times 0.5$

$= 1.575$ sec.

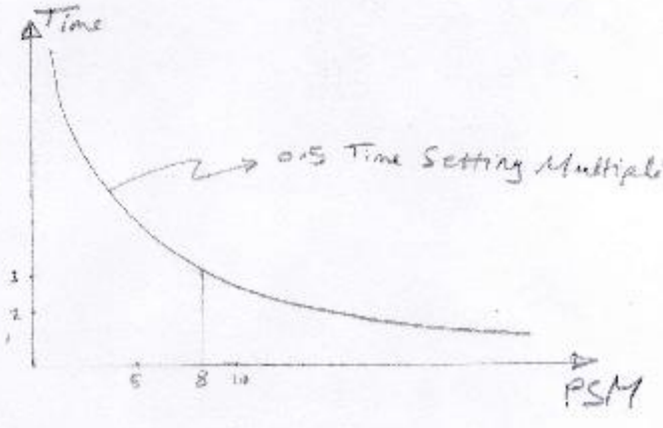


Fig (B)

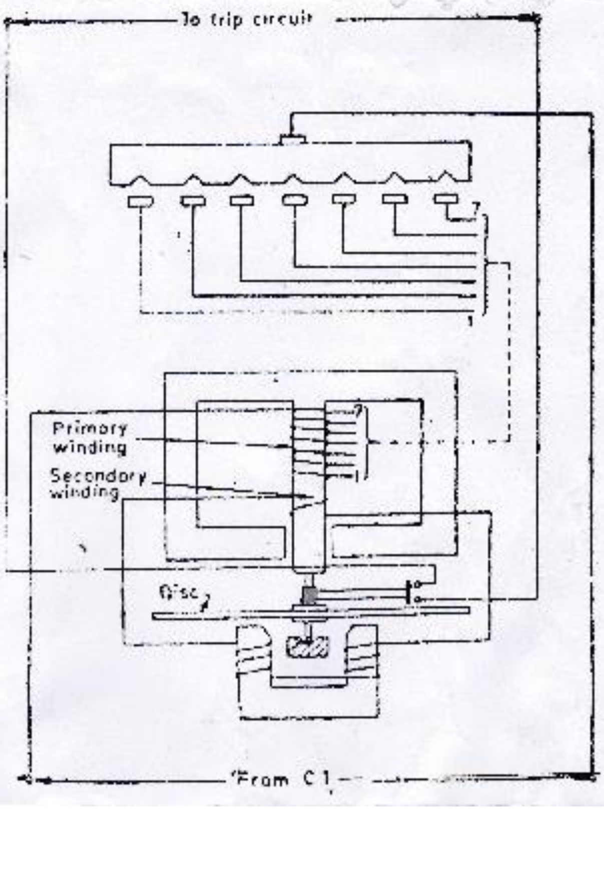
Functional Relay Types

Relays are generally classified according to the function they are called upon to perform in the protection of electric power circuits.

Induction Type Over-current Relay (non-directional)

These relays are used in AC circuits only and can operate for fault flow in either direction.

The upper electromagnet has a primary and a secondary winding. The primary is connected to the secondary of a CT in the line to be protected and is tapped at intervals. The tappings are connected to a plug-setting bridge by which the number of active turns on the relay operating coil can be varied to give the desired current setting. The secondary winding is energised by induction from primary and is connected in series with the winding on the lower magnet.



The control torque is provided by a spiral spring.
The spindle of disc carries a moving contact which bridges two fixed contacts (connected to trip circuit) when the disc rotates through a pre-set angle. This angle can be adjusted to any value (0→360°) and so the travel of the moving contact can be adjusted and hence can be given any desired time setting (Time Setting Multiplier).

Induction Type Directional Power Relay

This type operates when power in the circuit flows in a specific direction. It is designed to obtain it's operating torque by the interaction of magnetic fields derived from both voltage and current sources. The direction of the torque set up in the relay depends upon the direction of the current relative to the voltage.

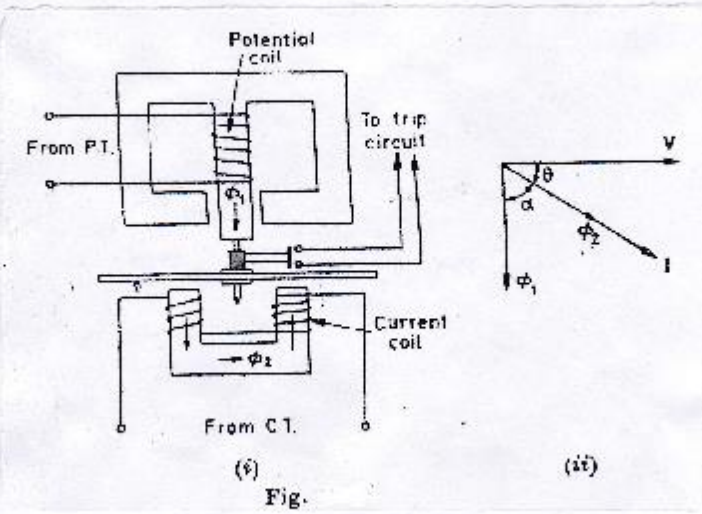


Fig.

The flux ϕ_1 due to current in the potential coil will be nearly 90° lagging behind the applied voltage V. The flux ϕ_2 due to current coil will be nearly in phase with the operating current I.

The interaction of fluxes φ_1 and φ_2 with eddy currents induced in the disc produces the driving torque :

$$T \propto \varphi_1 \varphi_2 \sin \alpha$$

since $\varphi_1 \propto V$, $\varphi_2 \propto I$ and $\alpha = 90 - \theta$

$$\therefore T \propto VI \sin(90 - \theta)$$

$$\propto VI \cos \theta$$

$\propto$ power in the circuit.

It is clear that the direction of the deriving torque on the disc depends upon the direction of power flow. When the power flows in the normal direction, the deriving torque and the restraing torque (due to the spring) help each other to turn away the moving contact from the fixed contacts, consequently the relay remains inoperative.

The reversal of current reverses the direction of the deriving torque. When the reversed deriving torque is large enough, the disc rotates in the reverse direction and the moving contact closes the trip circuit.

Induction Type Directional Overcurrent Relay

When a short-circuit occurs, the system voltage falls to a low value and there maybe insufficient torque developed in the relay to cause it's operation. This difficulty is overcome in the directional overcurrent relay, which is designed to be almost independent of system voltage and power factor.

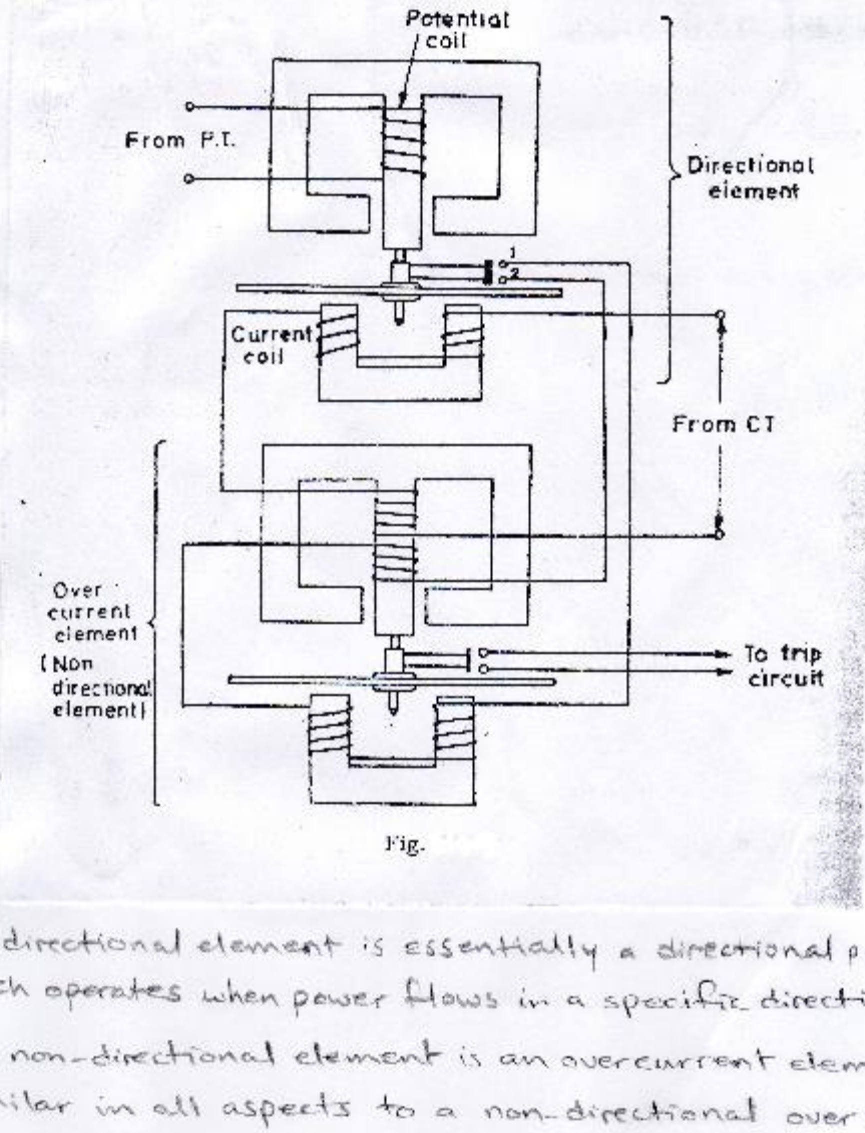


Fig.

The directional element is essentially a directional power relay which operates when power flows in a specific direction.

The non-directional element is an overcurrent element, similar in all aspects to a non-directional over current relay described erlier.

Distance or Impedance Relay

The torque produced by a current element is opposed by the the torque produced by a voltage element. The relay will operate when the ratio V/I is less than a predetermined value.

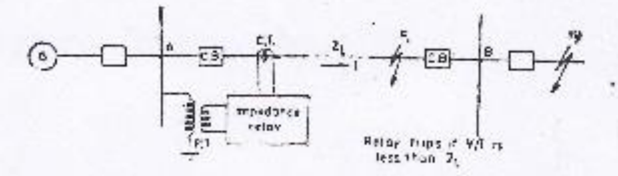


Fig. 21·50

The voltage element of the relay is excited through a potential transformer (PT) from the line to be protected. The current element of the relay is excited from a current transformer (CT). The portion AB of the line is the portected zone. Z_L is the impedance of the line under normal conditions. The relay is so designed that it closes it's contacts when impedance of the protected section falls below the predetermined value ie Z_L

when a fault occurs at point F_1, the impedance $Z = \frac{V}{I}$ between the point where the relay is installed and the point of fault will be less than Z_L and hence the relay operates.

If the fault occurs beyond the protected zone (F_2) the impedance Z will be greater than Z_L and so the relay does not operate.

1. Definit Distance Impedance Relay

It operates instantaneously for faults upto a predetermined distance from the relay.

The armatures of the two electromagnets are mechanically coupled to the beam on the opposite sides of the fulcrum.

The relay is designed that the torques produced by the two electromagnets are in opposite direction.

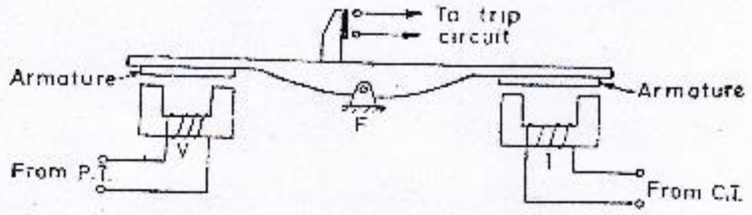


Fig.

Under normal conditions the pull due to the voltage element is greater than that of the current element. Therefore the contacts remain open.

At fault, the applied voltage to the relay decreases whereas the current increases, the ratio V/I (impedance) falls below the predetermined value. The pull of the current element (αI^2) will exceed that of the voltage element (αV^2) which causes the beam to tilt in a direction to close the trip contacts.

The relay will operate when:

$$K_1 V^2 < K_2 I^2$$

$$\left(\frac{V}{I}\right)^2 < \frac{K_2}{K_1}$$

$$Z < \sqrt{\frac{K_2}{K_1}}$$

K_1, K_2 are constants depending upon the ampere-turns of the two electromagnets.

2. Time - Distance Impedance Relay

A time distance relay is one which automatically adjusts it's operating time according to the distance of the relay from the fault point. ie

$$\text{operating time}, T \propto \frac{V}{I}$$
$$\propto Z$$
$$\propto \text{distance}$$

It consists of a current driven induction element similar to the double winding type induction over current relay. The bridge is normally held in the open position by an armature held against the pole face of an electromagnet excited by the voltage of the circuit to be protected.

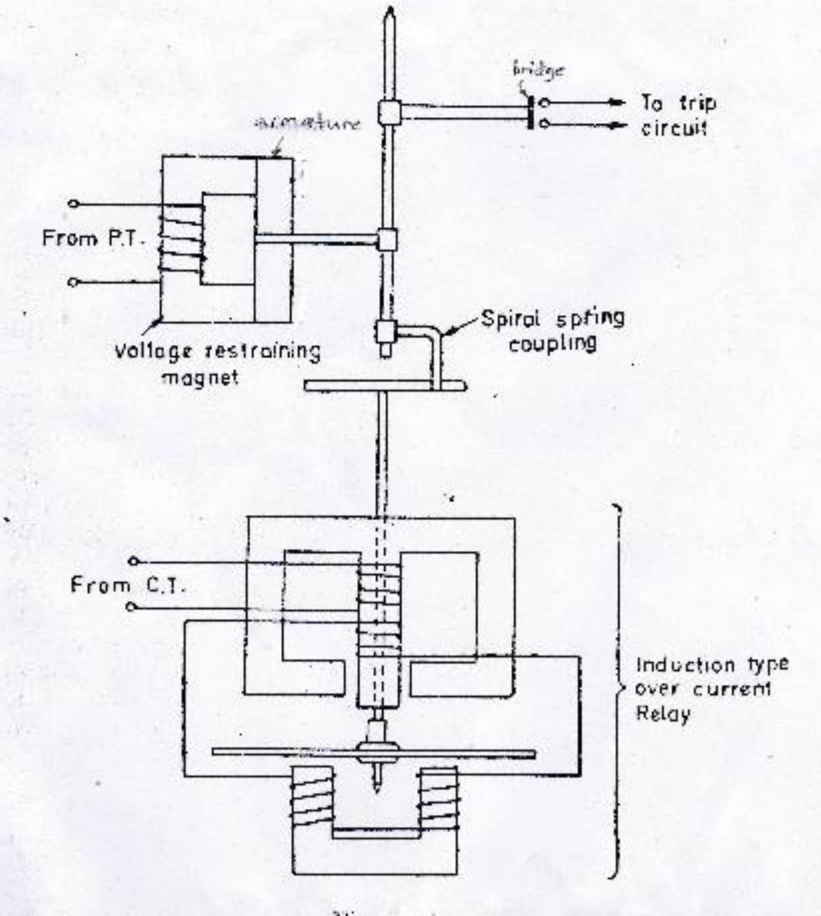


Fig.

Under normal load conditions, the pull of the armature is more than that of the induction element and hence the trip circuit remains open. However, on the occurance of a short circuit, the disc of the induction current element starts to rotate at a speed depending upon the operating current, and so the spiral spring coupling is wound up till the tension of the spring is sufficient to pull the armature away from the pole face of the voltage excited magnet. (The pull of this magnet depends upon the line voltage - the greater the line voltage, the greater the pull and hence the larger will be the travel of the disc ie the operating time is proportional to V).

Then immediately the spindle carrying the armature and the bridging piece moves rapidly in response to the tension of the spring and trip contacts are closed.

(The speed of rotation of the disc is approximately propotional to the operating current, neglecting the effect of control spring)

Therefore, the time of operation would vary as $\frac{V}{I}$ ie as Z or distance.

Differential Relay

is one that operates when the vector difference of two or more electrical quantities exceeds a predetermined value. i.e it compares the current entering a section of the system with the current leaving the section.

The difference between incoming and outgoing currents is arranged to flow through the operating coil of the relay. If this differential current ≥ pick up value, the relay will operate and open the circuit breaker.

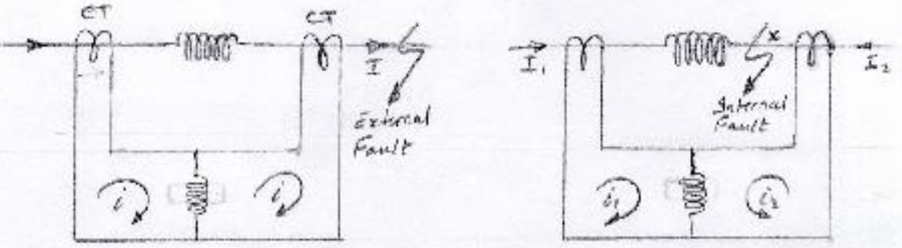
Any type of relay when connected in a particular way can be made to operate as a differential relay

There are two fundamental systems of differential or balanced protection.

1. Current balance protection,
2. Voltage balance protection.

Current Differential Relay

Figure shows an overcurrent relay connected to operate as a differential relay.



A pair of identical current transformers are fitted on either end of the section to be protected. The operating coil of the overcurrent relay is connected across the CT secondary. Suppose that current I flows through the primary circuit to external fault as shown above, then no current will flow through the relay and it will remain inoperative. If an internal fault occurs at x, then the current flowing through the relay will be $i_1 + i_2$. Therefore, The differential relay current is proportional to the phasor difference between the currents entering and leaving the protected circuit, and if the differential current exceeds the pickup value of the relay, the relay will operate.

It may be noted that the fault current does not need to flow from both sides to cause current flow in the relay. A flow of one side only, or even some current flowing out of one side while a large current enters the other side will cause a differential current.

Biased Beam Relay

Also called percentage differential relay is designed to respond to the differential current in terms of it's fractional relation to the current flowing through the protected section.
It is essentially an overcurrent balanced beam relay.
The restraining coil produces a bias force in the opposite direction to the operating force.

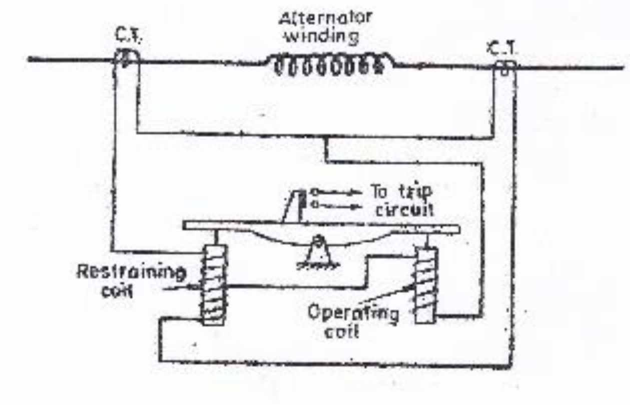


Fig.

Under normal and through load conditions, the bias force due to restraining coil is greater than the operating force.
When an internal fault occurs, the operating force exceeds the bias force, consequently the trip contacts are closed.
The bias force can be adjusted by varying the number of turns of the restraining coil

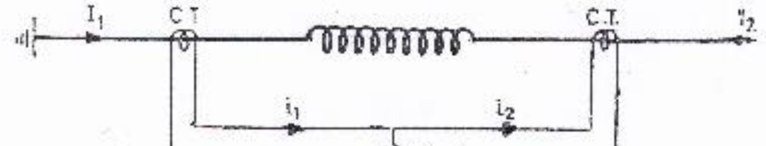
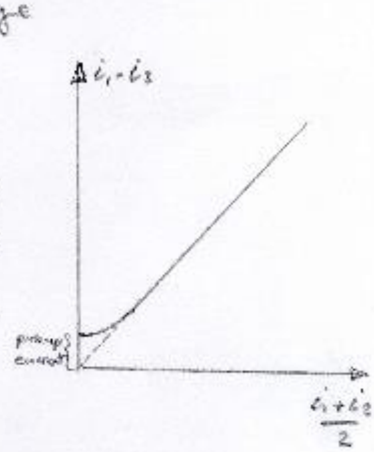


Fig.

The differential current in the operating coil "O" is $i_1 - i_2$ while the current in the restraining coil "R" is $i_1 + i_2/2$, since the ~~the~~ operating coil is connected to the midpoint of the restraining coil.

The ratio of the differential operating current to the average restraining current is a fixed percentage

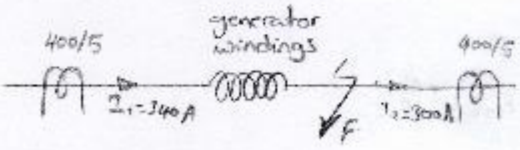
Since this relay has a rising operating characteristics (the pickup value increases as the magnitude of the through current increases) the relay is restrained or biased against operating inaccurately.



The differential relay will operate if

$$|i_1 - i_2| > \frac{i_1 + i_2}{2} \times \text{slope} + \text{pickup current}$$

For the system shown, if the relay characteristics have a slope of 10% and pickup current of 0.18 A



$i_1 = 340 \times \frac{5}{400} = 4.25\ A$

$i_2 = 300 \times \frac{5}{400} = 3.75\ A$

$\therefore |i_1 - i_2| = 0.5\ A$

Now $\frac{i_1 + i_2}{2} \times slope + I_{pickup}$

$$= \frac{4.25 + 3.75}{2} \times 10\,\% + 0.18$$

$$= \frac{8}{2} \times \frac{10}{100} + 0.18$$

$$= 0.58$$

$$\therefore |i_1 - i_2| < \frac{i_1 + i_2}{2} \times slope + I_{pickup}$$

$\therefore$ Relay will not operate the trip circuit

Voltage Balance Differential Relay

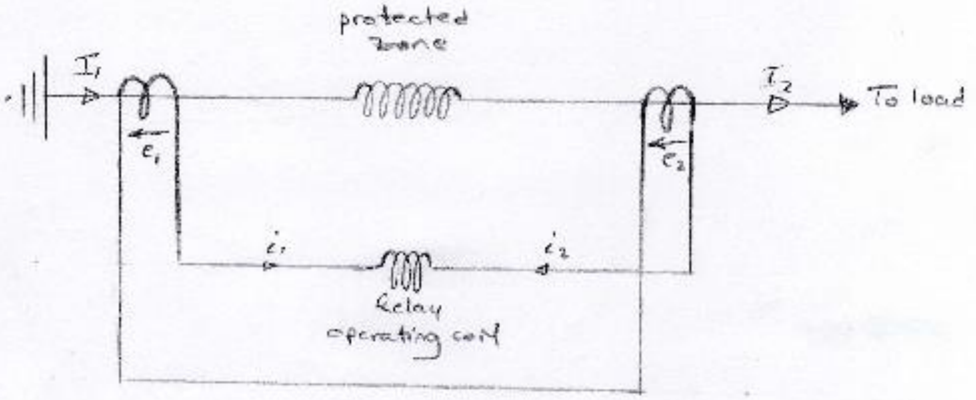
Two similar current transformers are connected at either end of the element to be protected by means of pilot wires.

The CT secondaries are connected in opposition.

Under healthy conditions ($i_1 = i_2$), therefore the secondary voltages are balanced against each other.

When a fault occurs in the protected zone ($i_1 \neq i_2$) and secondary voltages will no longer be in balance.

This voltage difference will cause a current to flow through the operating coil of the relay.



Transley Relay

In this type, the opposition is between voltages induced in the secondary coils of the relay magnets and not between the secondary voltages of CTs.

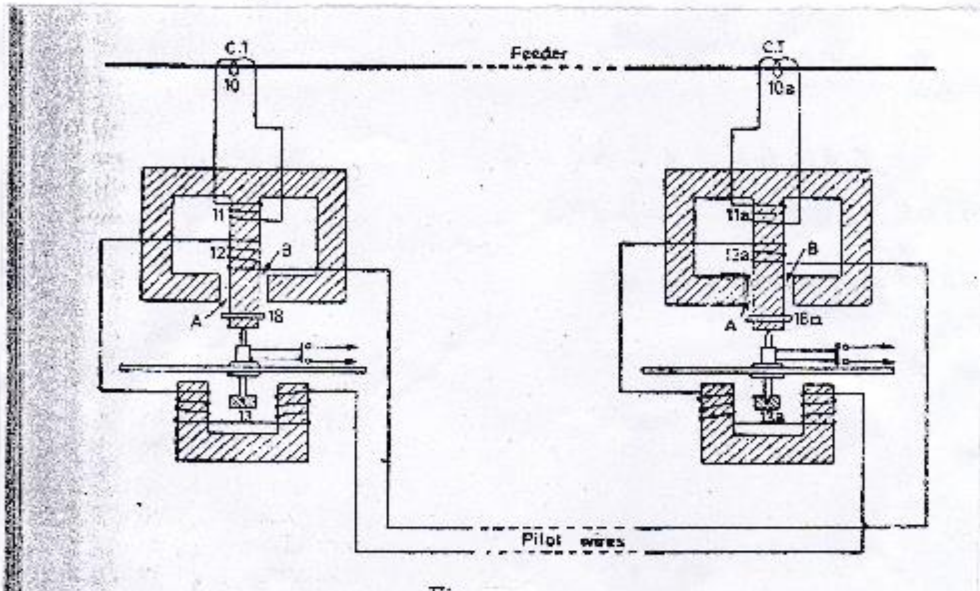


Fig.

The copper rings (18, 18a) neutralise the effect of pilot wire capacitance currents.

Under healthy conditions primary windings (11, 11a) carry the same current and induce equal emf's in the secondary windings (12, 12a, 13, 13a), as these windings are so connected that their induced voltages are in opposition, no current will flow through the pilots or operating coils and hence no torque will be exerted on the disc of either relay.

At fault, current leaving the feeder will differ from that entering the feeder. Consequently unequal voltages will be induced in the secondary windings of the relays and current will circulate between the two windings, causing torque to be exerted on the discs

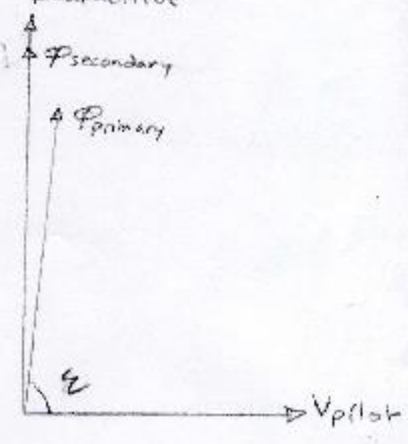
As the direction of secondary current is opposite in the two relays, therefore, torque in one relay will tend to close the trip circuit while in the other relay the torque will hold the movement in the unoperated position (ie depending upon the position of fault in the protected zone, at least one element of either relay will operate.)

pilot capacitive currents lead the voltage across the pilot wires by 90°, and when they flow in the operating windings 13, 13a (which are of low inductance) produce fluxes that also lead the pilot voltage by 90°.

The pilot voltage is that induced in (12, 12a) which lags by an angle (ε) behind the fluxes in the field magnet air gaps (A, B.)

The closed copper rings (18, 18a) are adjusted so that this angle is approximately 90°, in this way fluxes acting on the disc are in phase and hence no torque is exerted on the relay disc.

hence the effects of the capacitive currents in the pilot wires are compensated.



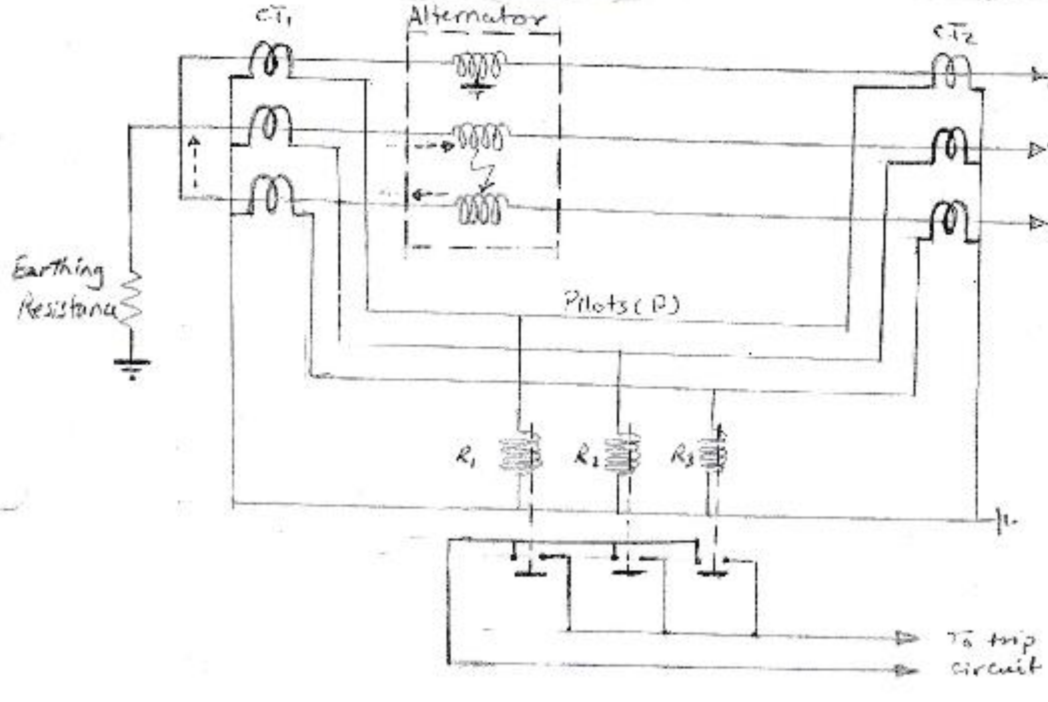
Alternator Protection

Important faults which may occur

1. Failure of prime mover
2. " of field
3. Over current
4. " speed
5. " voltage
6. Unbalanced loading
7. Stator winding faults.

Differential Protection

The most common system for protection of stator winding faults employs circulating-current principle. Currents at the two ends are compared, The difference is arranged to pass through the operating coil of the relay. This form of protection is also known as Merz-Price circulating current scheme.



Operation

The relays are connected in shunt across each circulating path. Suppose an earth fault occurs on phase R, the current will flow to earth, the circuit is completed through the neutral earthing resistance.

The currents in the secondaries of the two CTs in phase R will be unequal, and the difference will flow through the corresponding relay coil (R_1) Consequently, the relay operates to trip the circuit breaker

- If a short circuit occurs between phases Y and B.

The short circuit current circulates via the neutral and through the two windings as shown by the dotted arrows, making the currents in the secondaries unequal and so the relay operates.

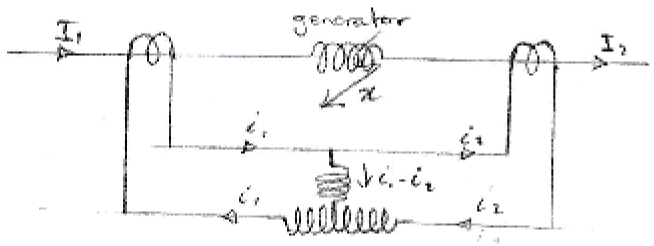
- It is a general practice to use neutral earthing resistance in order to limit the effects of earth fault currents. When an earth fault occurs near the neutral point, there may be insufficient voltage across the short circuited portion to drive the necessary current round the fault circuit to operate the relay.

The magnitude of unprotected zone depends upon the value of earthing resistance and relay setting.

$$\% \text{ of winding unprotected} = \frac{R I_o}{V_{ph}} \times 100$$

I_o = min. operating current in primary of C.T.

Basic Percentage Differential Protection



The current through the operating coil is $i_1 - i_2$, while the current through the restraining coil is $\frac{i_1+i_2}{2}$. This is because the operating coil is connected to the midpoint of the restraining coil

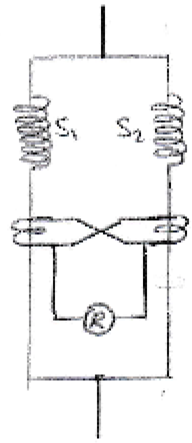
Stator Inter-Turn Protection

Merz-price circulating current system protects against phase to ground and phase to phase. It does not protect against turn to turn fault on the same phase winding.

This type of protection is not necessary for single turn generators (large steam-turbine generators). However it is provided for multiturn generators such as Hydro-electric generators, as they have double winding armatures (ie each phase winding is divided into two halves).

Under normal conditions, the currents in the stator winding S_1, S_2 are equal. The secondary current around the loop is the same at all points and no current flows through the relay R.

If short circuit develops between adjacent turns, then current in the stator windings S_1 and S_2 will no longer be equal, therefore, unequal currents will be induced in the secondaries of CTs and the difference flows through R



Ex.1 A star connected 3-phase, 10 MVA, 6.6KV alternater has a per phase reactance of 10%. It is protected by Merz-price circulating current, which is set to operate for fault currents not less than 175A. Calculate the value of earthing resistance to be provided in order to ensure that only 10% of the alternator winding remains unprotected.

Sol.

$$V_{ph} = \frac{6.6\times10^3}{\sqrt{3}} = 3810\,V$$

$$\text{Full load current} = \frac{10\times10^6}{\sqrt{3}\times6.6\times10^3} = 875\,A$$

$$\text{Reactance } x = \frac{6.6\times10^3/\sqrt{3}}{875}\times\frac{10}{100} = 0.436\,\Omega$$

$$\text{Reactance of 10\% winding} = 0.436\times\frac{10}{100} = 0.0436\,\Omega$$

$$\text{emf induced in 10\% winding} = V_p\times\frac{10}{100} = 3810\times\frac{10}{100} = 381\,V$$

Let r be the earthing resistance

Let Z_f be the impedance offered to fault by 10% winding

$$Z_f = \sqrt{(0.0436)^2 + r^2}$$

Earth fault current due to 10% winding

$$= \frac{381}{\sqrt{(0.0436)^2+r^2}}$$

when this fault current becomes 175A the relay will trip

$$175 = \frac{381}{\sqrt{(0.0436)^2+r^2}}$$

$$\therefore r = 2.171\,\Omega$$

Ex.2 A generator is protected by restricted earth fault protection. The generator ratings are 132KV, 10MVA. The percentage of winding protected against phase to ground fault is 85 %. The relay setting is such that it trips for 20 % out of balance.
Calculate the resistance to be added in the neutral to ground connection.

Sol.
$$I = \frac{10 \times 10^6}{\sqrt{3} \times 13.2 \times 10^3} = 437.39 \text{ A}$$

$$I_o = 437.39 \times \frac{20}{100} = 87.48 \text{ A}$$

= min. operating current.

$$\% \text{ of winding unprotected} = \frac{R\, I_o}{V_{ph}} \times 100$$

$$15 = \frac{R \times 87.48}{13.2 \times 10^3/\sqrt{3}} \times 100$$

$$\therefore R = 13.068\ \Omega$$

Ex.3 An alternator stator winding protected by a percentage differential relay. The relay has 15% slope characteristics of $(i_1 - i_2)$ against $\left(\frac{i_1+i_2}{2}\right)$. The high resistance ground fault has occured near the grounded neutral end of the generator winding. The currents flowing at each end of the generator are $i_1 = 300\,A$, $i_2 = 340\,A$. For C.T ratio to be 500/5 will the relay operate to trip the C.B.

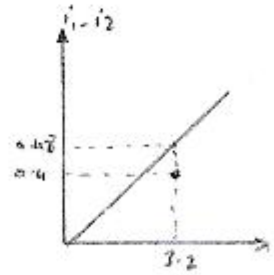
Sol.

$$i_1 = 300 \times \frac{5}{500} = 3A$$

$$i_2 = 340 \times \frac{5}{500} = 3.4A$$

$$i_1 - i_2 = -0.4A$$

$$\frac{i_1 + i_2}{2} = \frac{6.4}{2} = 3.2A$$



From the characteristics of 15% slope,

The out of balance current required, corresponding to $\frac{i_1+i_2}{2}$

$$= \text{slope} \times \frac{i_1+i_2}{2}$$

$$= 0.15 \times 3.2$$

$$= 0.48\,A$$

$$\therefore |i_1 - i_2| = 0.4 < \text{slope} \times \frac{i_1+i_2}{2} = 0.48$$

$\therefore$ relay will not operate.

Protection of Transformers

Power transformers may suffer from:

1. open circuit
2. over heating
3. windage short circuit (e.g earth faults, phase to phase faults and interturn faults.)

Buchholz Relay

It's a gas actuated relay installed in oil immersed transformers. It's used to give an alarm in case of incipient faults in the transformer, and to disconnect the transformer in the event of sever internal faults.

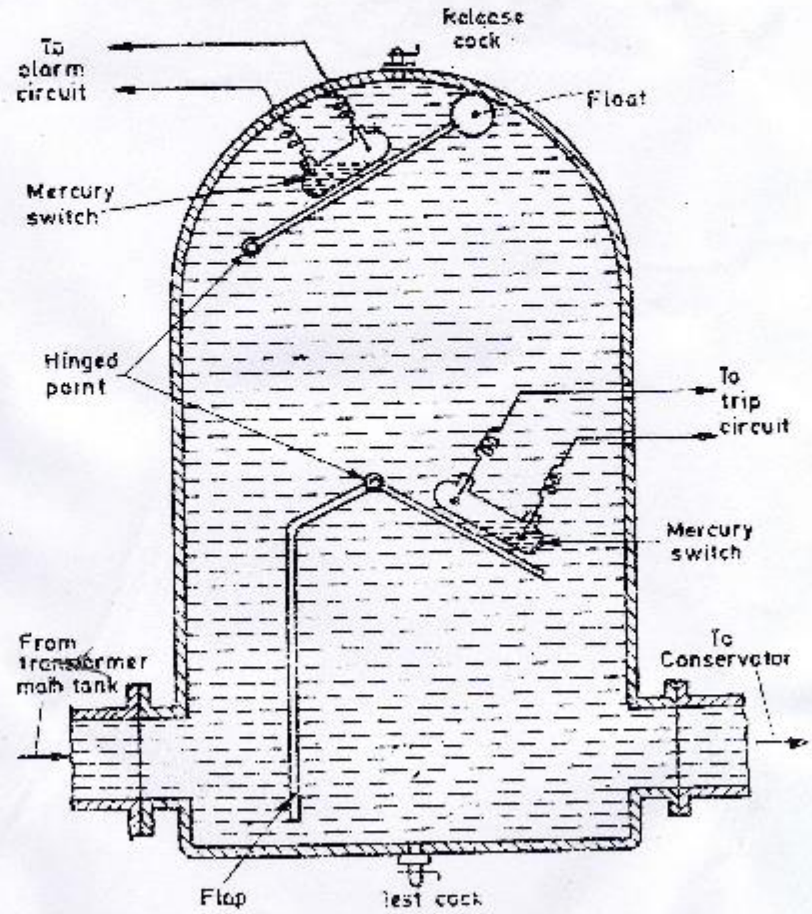


Fig. 22·11

Construction

It is placed in the connecting pipe between the main tank and the conservator. The device has two elements The upper element consists of a mercury type switch attached to a float. The lower element contains a hinged type flap located in the direct path of the flow of oil from the transformer to the conservator.

Operation

1. In case of incipient faults within the transforer, the heat due to faults causes decomposition of some of the transformer oil. The products of decomposition contain more than 70% hydrogen. The light hydrogen gas gets entrapped in the upper part of the relay chamber. When a pre-determined amount of gas gets accumulated, it exerts sufficient pressure on the float to tilt it and close the contacts of the mercury switch to complete the alarm circuit.
2. If a serious fault occurs in the transformer, an enormous amount of gas is generated. The oil in the main tank rushes towards the conservator via the Buchholz relay, and in doing so, tilts the hinged flap to close the contacts of mercury switch to complete the trip circuit to open the circuit breaker.

Applying Circulating Current System to Transformers

Merz-Price circulating current principle as applied to transformers is the same as that for generators, but with certain features not encountered in generator application

1. In a power transformer, currents in the primary and secondary are different, therefore, the use of identical CT's will operate the relay even under no fault; Therefore, the turn ratio of CT on low voltage side is made T times that of CT on high " " .

2. There is usually a phase difference between the primary and secondary currents.
   A differential current may flow through the relay under normal conditions and cause relay operation.
   The correction for phase difference is effected by appropriate connection of CT's, as shown below

power transforme		current transformer	
Primary	Secondary	Primary	Secondary
Star	Star	Delta	Delta
Star	Delta	Delta	Star
Delta	Star	Star	Delta
Delta	Delta	Star	Star

3. Most transformers have means for tap changing. Tap changing will cause differential current to flow even under normal operating conditions.
   This difficulty is overcome by adjusting the turn ratio of CT on the side of power transformer provided with taps.

Circulating Current Scheme

Fig. below shows Merz-Price circulating current scheme for the protection of a 3φ delta / delta power transformer. The CT's on the two sides are connected by pilot wires and one relay is used for each pair of CT's.

If a ground or phase to phase fault occurs, the currents in the secondaries of CT's will no longer be the same and the differential current flowing through the relay circuit will clear the circuit breakers on both sides of the power transformer. The protected zone is limited to the region between CT's on high voltage side and CT's on low voltage side of the power transformer.

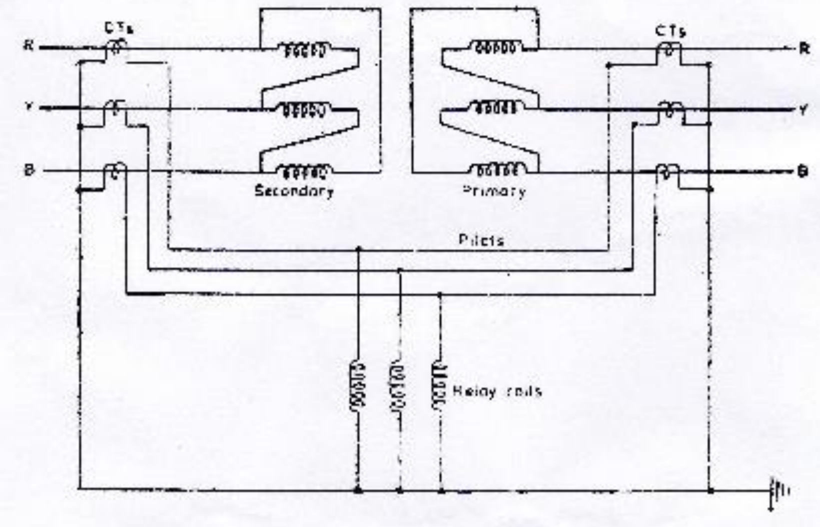


Fig. 22·14

Ex. A 3φ transformer of 220/11000 line volts is connected in star/delta. The protective transformers on 220V side have a current ratio of 600/5. What should be the CT ratio on 11000 V side.

Sol.

The CT's will be connected in delta/star as shown below

suppose the line current on 220 V side is 600 A

∴ Phase current of delta connected CT $= 5$ A

∴ Line " " " " " $= 5\sqrt{3}$ A

This current (ie $5\sqrt{3}$) will flow through the pilot wires. Obviously, this will be the current which flows through the secondary of CT's on the 11000V side

∴ Phase current of star connected CT $= 5\sqrt{3}$ A

Let I be the line current on 11000V side

primary apparent power = secondary apparent power

$\sqrt{3} \times 220 \times 600 = \sqrt{3} \times 11000 \times I$

$\therefore I = 12$ A

∴ Turn ratio of CT on 11000V side $= 12 / 5\sqrt{3}$

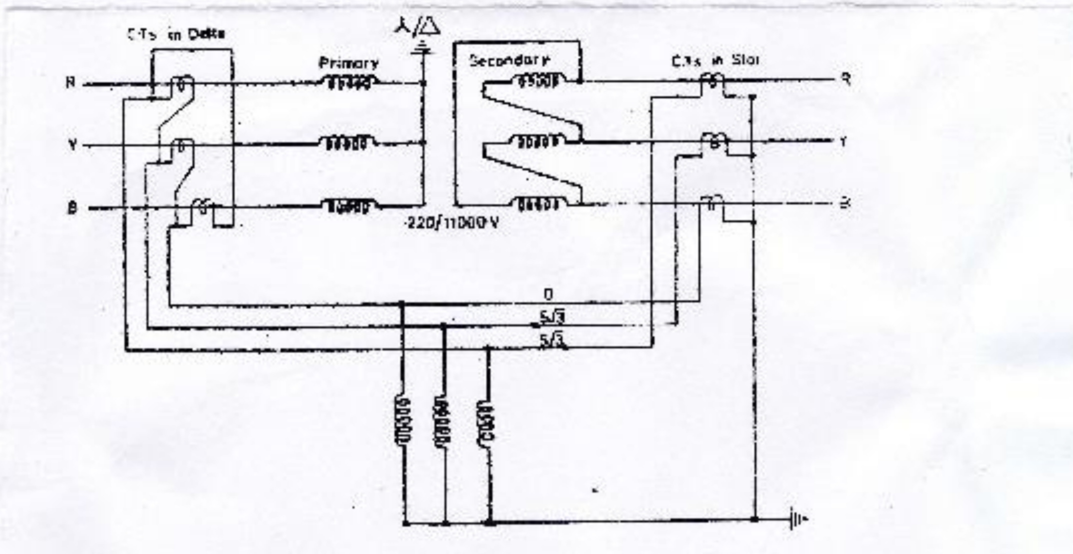


Fig. 22-15