MODULE 4

Unsymmetrical Fault Analysis

Course Objectives

1. To explain the analysis of synchronous machine and simple power systems for different unsymmetrical faults using symmetrical components

4.1 INTRODUCTION

The sequence circuits and the sequence networks developed in the previous chapter will now be used for finding out fault current during unsymmetrical faults. Specifically we are going to discuss the following three types of faults:

- Single-line-to-ground (1LG) fault
- Line-to-line (LL) fault
- Double-line-to-ground (2LG) fault

4.2 Symmetrical Component Analysis of Unsymmetrical Faults

For the calculation of fault currents, we shall make the following assumptions:

- The power system is balanced before the fault occurs such that of the three sequence networks only the positive sequence network is active. Also as the fault occurs, the sequence networks are connected only through the fault location.
- The fault current is negligible such that the pre-fault positive sequence voltages are same at all nodes and at the fault location.
- All the network resistances and line charging capacitances are negligible.

- All loads are passive except the rotating loads which are represented by synchronous machines.

Based on the assumptions stated above, the faulted network will be as shown where the voltage at the faulted point will be denoted by V_f and current in the three faulted phases are I_{fa}, I_{fb} and I_{fc}. We shall now discuss how the three sequence networks are connected when the three types of faults discussed above occur.

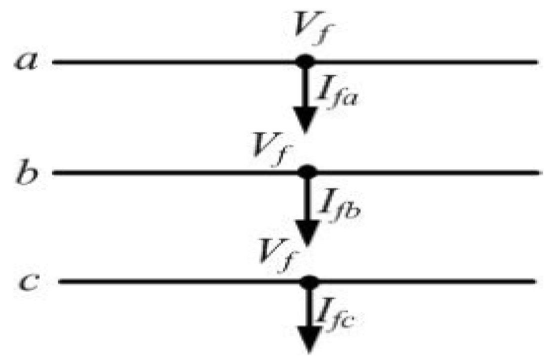


Fig4 .1 Representation of faulted segment

4.3 Single Line-To-Ground (LG) Fault, Line-To-Line (LL) Fault, Double Line-To-Ground (LLG) Fault

Let a 1LG fault has occurred at node *k* of a network. The faulted segment is shown where it is assumed that phase-a has touched the ground through an impedance Z_f. Since the system is unloaded before the occurrence of the fault we have

$$I_{fb} = I_{fc} = 0$$

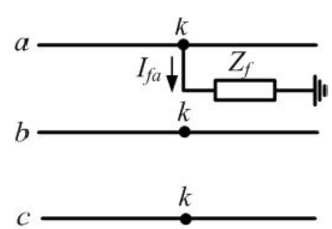


Fig. 4.2: Representation of 1LG fault.

Also the phase-a voltage at the fault point is given by

$$V_{ka} = Z_f I_{fa}$$

$$I_{fa012} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_{fa} \\ 0 \\ 0 \end{bmatrix}$$

$$I_{fa0} = I_{fa1} = I_{fa2} = \frac{I_{fa}}{3}$$

This implies that the three sequence currents are in series for the 1LG fault. Let us denote the zero, positive and negative sequence Thevenin impedance at the faulted point as Z_{kk0}, Z_{kk1} and Z_{kk2} respectively. Also since the Thevenin voltage at the faulted phase is V_f we get three sequence circuits

$$V_{ka0} = -Z_{kk0} I_{fa0}$$
$$V_{ka1} = V_f - Z_{kk1} I_{fa1}$$
$$V_{ka2} = -Z_{kk2} I_{fa2}$$

$$\begin{aligned} V_{ka} &= V_{ka0} + V_{ka1} + V_{ka2} \\ &= V_f - (Z_{kk0} + Z_{kk1} + Z_{kk2}) I_{fa0} \end{aligned}$$

$$V_{ka} = Z_f I_{fa} = Z_f (I_{fa0} + I_{fa1} + I_{fa2}) = 3 Z_f I_{fa0}$$

$$I_{fa0} = \frac{V_f}{Z_{kk0} + Z_{kk1} + Z_{kk2} + 3Z_f}$$

The Thevenin equivalent of the sequence network is shown

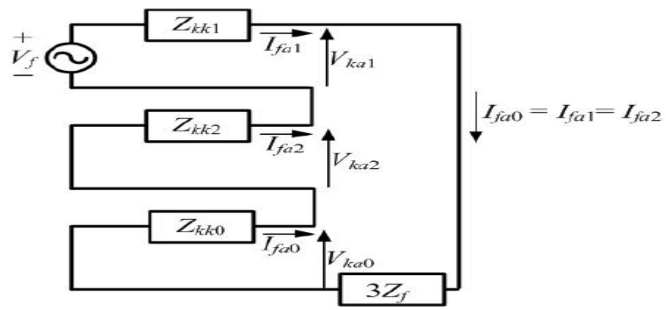


Fig 4.3: Thevenin equivalent of a 1LG fault.

4.3.1 LINE-TO-LINE FAULT

The faulted segment for an L-L fault is shown where it is assumed that the fault has occurred at node *k* of the network. In this the phases b and c got shorted through the impedance Z_f. Since the system is unloaded before the occurrence of the fault we have

$$I_{fa} = 0$$

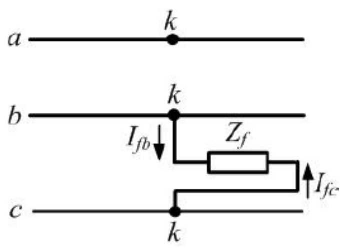


Fig 4.4: Representation of L-L fault.

Also since phases b and c are shorted we have

$$I_{fb} = -I_{fc}$$

$$I_{fa012} = C\begin{bmatrix} 0 \\ I_{fb} \\ -I_{fb} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 0 \\ (a-a^2)I_{fb} \\ (a^2-a)I_{fb} \end{bmatrix}$$

$$I_{fa0} = 0$$

$$I_{fa1} = -I_{fa2}$$

Therefore no zero sequence current is injected into the network at bus k and hence the zero sequence remains a dead network for an L-L fault. The positive and negative sequence currents are negative of each other.

The voltage at the faulted point

$$V_{kb} - V_{kc} = Z_f I_{fb}$$

$$\begin{aligned} V_{kb} - V_{kc} &= V_{kb0} + V_{kb1} + V_{kb2} - V_{kc0} - V_{kc1} - V_{kc2} \\ &= (V_{kb1} - V_{kc1}) + (V_{kb2} - V_{kc2}) \\ &= (a^2 - a)V_{ka1} + (a - a^2)V_{ka2} \\ &= (a^2 - a)(V_{ka1} - V_{ka2}) \end{aligned}$$

$$I_{fa0} = I_{fb0} = 0 \text{ and } I_{fa1} = -I_{fb2}$$

$$I_{fb} = I_{fb1} + I_{fb2} = a^2 I_{fa1} + aI_{fb2} = (a^2 - a)I_{fa1}$$

$$V_{ka1} - V_{ka2} = Z_f I_{fa1}$$

$$I_{fa1} = -I_{fa2} = \frac{V_f}{Z_{kk1} + Z_{kk2} + Z_f}$$

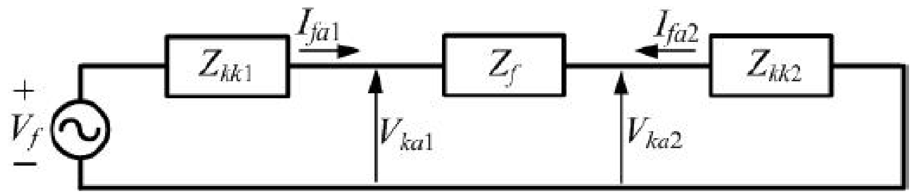


Fig 4.5: Thevenin equivalent of an LL fault.

5.5 DOUBLE-LINE-TO-GROUND FAULT

The faulted segment for a 2LG fault is shown where it is assumed that the fault has occurred at node *k* of the network. In this the phases b and c got shorted through the impedance Z_f to the ground. Since the system is unloaded before the occurrence of the fault we have the same condition as for the phase-a current. Therefore

$$I_{fa0} = \frac{1}{3}\left(I_{fa} + I_{fb} + I_{fc}\right) = \frac{1}{3}\left(I_{fb} + I_{fc}\right)$$

$$\Rightarrow 3I_{fa0} = I_{fb} + I_{fc}$$

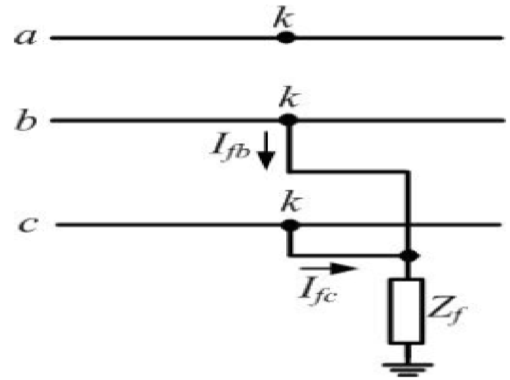


Fig. 4.6: Representation of 2LG fault.

Also the voltages of phases b and c are given by

$$V_{kb} = V_{kc} = Z_f\left(I_b + I_c\right) = 3Z_f I_{fa0}$$

$$V_{ka1} = V_{ka2}$$

$$3V_{ka0} = V_{ka} + 2V_{kb} = V_{ka0} + V_{ka1} + V_{ka2} + 2V_{kb}$$

$$V_{ka1} = V_{ka2} = V_{ka0} - 3Z_f I_{fa0}$$

since $I_{fa} = 0$ we have

$$I_{fa0} + I_{fa1} + I_{fa2} = 0$$

The Thevenin equivalent circuit for 2LG fault is shown

$$I_{fa1} = \frac{V_f}{Z_{kk1} + Z_{kk2}\|^{l}\left(Z_{kk0} + 3Z_f\right)} = \frac{V_f}{Z_{kk1} + \dfrac{Z_{kk2}\left(Z_{kk0} + 3Z_f\right)}{Z_{kk2} + Z_{kk0} + 3Z_f}}$$

The zero and negative sequence currents can be obtained using the current divider principle as

$$I_{fa0} = -I_{fa1}\left(\frac{Z_{kk2}}{Z_{kk2} + Z_{kk0} + 3Z_f}\right)$$

$$I_{fa2} = -I_{fa1}\left(\frac{Z_{kk0} + 3Z_f}{Z_{kk2} + Z_{kk0} + 3Z_f}\right)$$

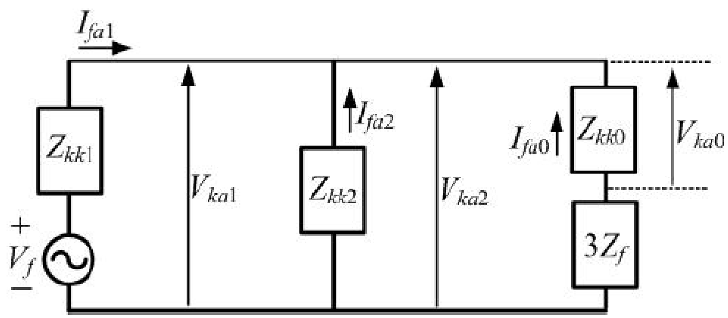


Fig. 4.7: Thevenin equivalent of a 2LG fault.

Course Outcome

At the end of the module, students will be able to:

Analyze unsymmetrical fault currents using symmetrical components. [L4]

Module-4

Unsymmetrical faults

If the balanced power system becomes unbalanced after the occurance of the fault, then the fault is called as an unsymmetrical fault.

About 95% of the faults that occur is unsymmetrical fault.

There are 2 types of unsymmetrical faults.

1) Shunt type
2) Series type.

Shunt type of faults involves short circuit between conductors or between the conductor & ground.

They are characterized by an increase in current & fall in voltage & frequency in the faulted phase.

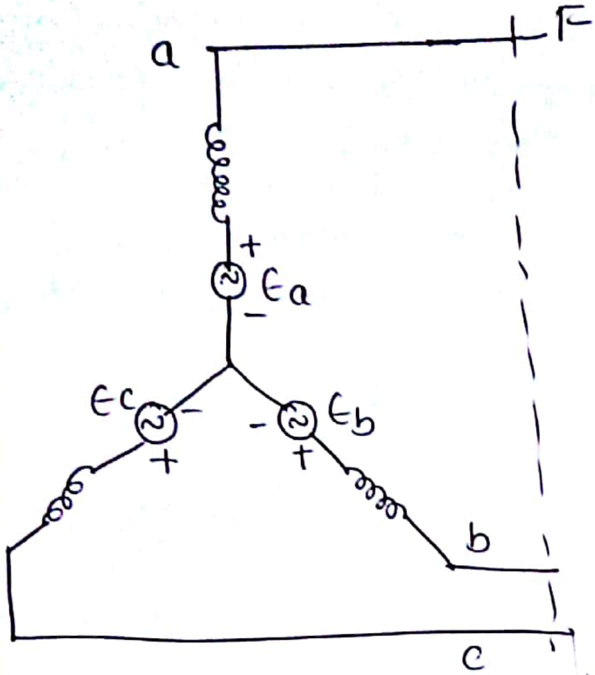
(a) Single L-G fault.
(b) L-L fault
(c) Double line to ground fault (LLG)

When one or two lines in a 3ϕ system get opened while the other lines or line remain intact. Such faults are called as "Series faults."

They are characterized by an increase in voltage & frequency & fall in current in the faulted phase.

(a) One conductor open fault
(b) Two conductor open fault.
(c) Three conductor open fault.

Analysis of unsymmetrical fault using Symmetrical component :-



Consider a balanced 3ϕ Synchronous generator which is subjected to unsymmetrical fault 'F' at terminal.

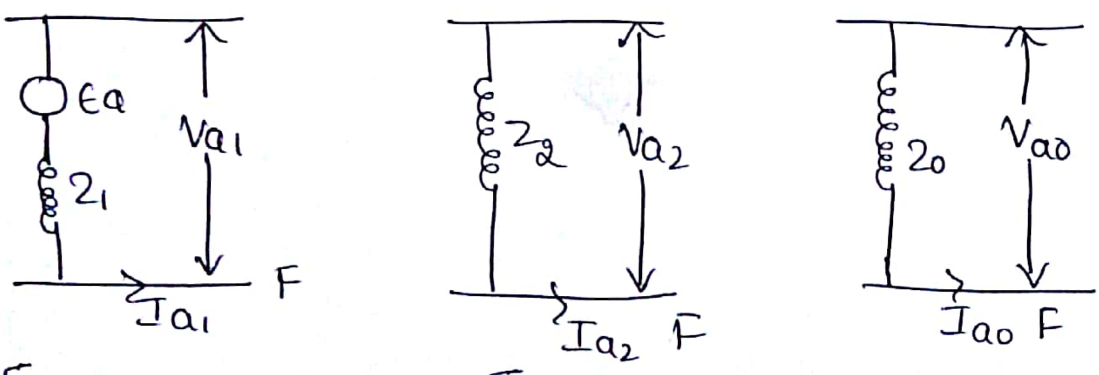
Before the occurance of fault the system is symmetrical. Then the current of given sequence produce voltage drop of that sequence only. Sequence impedances are uncoupled. They generate positive sequence voltage only.

Hence even during unsymmetrical faults will get the equation as,

$$V_{a1} = E_a - I_{a1} Z_1 \quad \text{——— (1)}$$

$$V_{a2} = -I_{a2} Z_2 \quad \text{——— (2)}$$

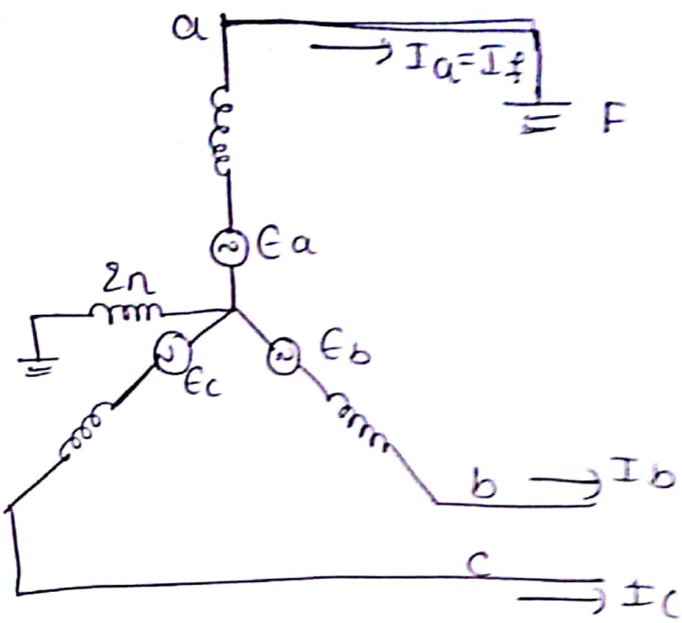
$$V_{a0} = -I_{a0} Z_0 \quad \text{——— (3)}$$



$$\begin{bmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ E_a \\ 0 \end{bmatrix} - \begin{bmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

For any fault at the terminals of synchronous generator. The quantities to be determined are 3ϕ currents (I_{a0}, I_{a1}, I_{a2}).

Single line to ground fault on unloaded generator



This circuit shows line to ground fault on unloaded star connected generator with its neutral connected to ground through Z_n.

It is assumed that phase 'a' is shorted to ground directly.

Terminal condition.

$V_a = 0$ ——— (1)

$I_b = 0$ ——— (2)

$I_c = 0$ ——— (3)

This terminal condition is transferred to symmetrical components as follows.

Symmetrical component of current is,

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c) = \frac{1}{3}(I_a + 0 + 0) = \frac{1}{3} I_a.$$

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c) = \frac{1}{3} I_a.$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c) = \frac{1}{3} I_a.$$

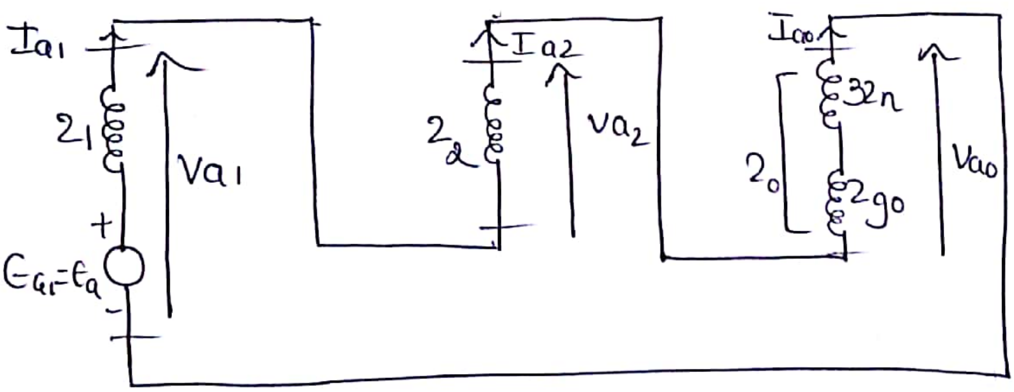
$$\text{So}, \quad I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a \quad \text{——} \ (4)$$

$$V_{a1} + V_{a0} + V_{a2} = V_a$$

The terminal condition, $V_a = 0$ gives,

$$V_{a1} + V_{a2} + V_{a0} = 0 \quad \text{——} \ (5).$$

As per equation (4), all the sequence currents are equal & as per eqn (5), the sum of sequence voltage equals zero. Therefore, these equation suggests a series connection of sequence networks, through a short circuit as shown below,



Sequence quantities:-

$$\therefore I_{a1} = I_{a0} = I_{a2} = \frac{E_a}{Z_1 + Z_2 + Z_0} \quad \text{——} \ (6)$$

$$V_{a1} = E_{a1} - I_{a1} Z_1$$

$$= E_a - \frac{E_a Z_1}{Z_1 + Z_2 + Z_0}$$

$$= \left(\frac{Z_1 + Z_2 + Z_0 - Z_1}{Z_1 + Z_2 + Z_0} \right) E_a$$

$$V_{a1} = \left(\frac{Z_2 + Z_0}{Z_1 + Z_2 + Z_0}\right) E_a \quad \text{——— (7)}$$

$$V_{a2} = -I_{a2} Z_2$$

$$V_{a2} = -\left(\frac{E_a Z_2}{Z_1 + Z_2 + Z_0}\right) \quad \text{——— (8)}$$

$$V_{a0} = -I_{a0} Z_0$$

$$V_{a0} = -\left(\frac{E_a Z_0}{Z_1 + Z_2 + Z_0}\right) \quad \text{——— (9)}$$

Fault current :-

In this fault current is equal to current in phase 'a' i,e,

$$I_f = I_a.$$

So fault current is given by,

$$I_f = I_a = 3I_{a0}$$

$$I_f = 3\left(\frac{E_a}{Z_1 + Z_2 + Z_0}\right) \quad \text{——— (10)}$$

If neutral of generator is not grounded,

$$Z_0 = 3Z_n + Z_{g0}$$

$$= \infty + Z_{g0}$$

$$Z_0 = \infty$$

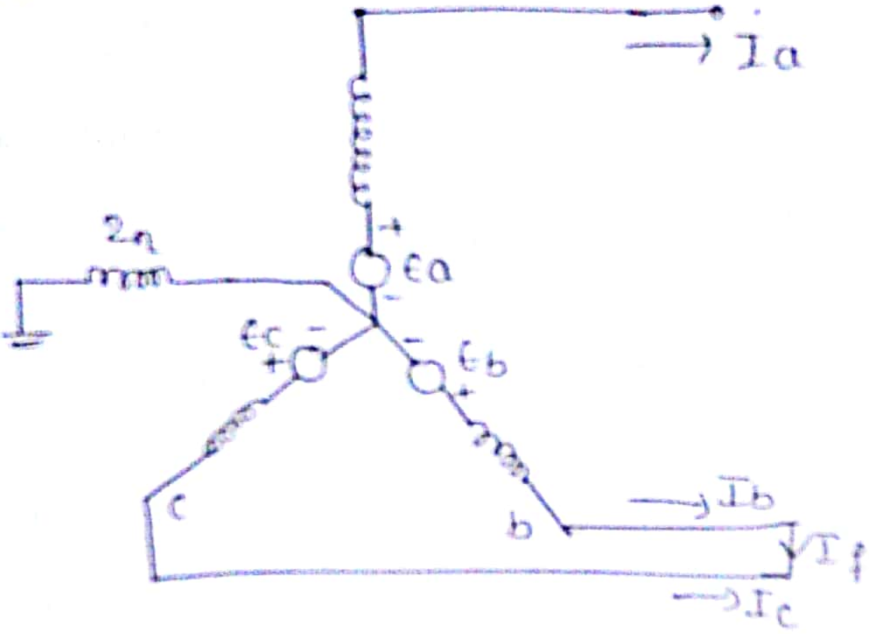
$$I_f = 3\left(\frac{E_a}{Z_1 + Z_2 + \infty}\right) = 0 \quad \text{——— (11)}$$

$$I_f = 0.$$

Hence fault current in system is zero, if neutral is not grounded in case of LG fault

Line-Line (L-L) fault on an unloaded Generator :-

The circuit diagram for an L-L fault on an unloaded star connected Generator with its neutral grounded through a reactance is as shown in fig. Here it is assumed that phase b & phase c are shorted.



Terminal condition :-

$$I_a = 0 \quad \text{——— (1)}$$

$$I_b + I_c = 0 \Rightarrow I_c = -I_b \quad \text{——— (2)}$$

$$V_b = V_c \quad \text{——— (3)}$$

Symmetrical component relation :-

$$I_{a0} = \tfrac{1}{3}(I_a + I_b + I_c)$$

$$I_{a0} = 0 \quad \text{——— (4)}$$

$$I_{a1} = \tfrac{1}{3}(I_a + a I_b + a^2 I_c)$$

$$= \tfrac{1}{3}(0 + a I_b - a^2 I_b)$$

$$I_{a1} = \tfrac{1}{3}(a - a^2) I_b \quad \text{——— (5)}$$

$$I_{a2} = \tfrac{1}{3}(I_a + a^2 I_b + a I_c)$$

$$I_{a2} = 1/3\,(0 + a^2 I_b - a I_b)$$

$$I_{a2} = 1/3\,(a^2 - a)\, I_b \quad \text{------} (6)$$

from equation (4), (5) & (6) we get.

$$I_{a0} = 0 \quad \text{------} (7)$$

$$I_{a2} = -I_{a1} \quad \text{------} (8)$$

Sequence terminal voltage :-

$$V_{a1} = 1/3\,(V_a + a V_b + a^2 V_c)$$

$\because V_b = V_c$

$\because 1 + a + a^2 = 0$

$a + a^2 = -1$

$$= 1/3\,(V_a + (a + a^2) V_b)$$

$$= 1/3\,(V_a - V_b)$$

$$V_{a2} = 1/3\,(V_a + a^2 V_b + a V_c)$$

$$= 1/3\,(V_a + (a^2 + a) V_b)$$

$$= 1/3\,(V_a - V_b)$$

since $I_{a0} = 0$, the zero sequence terminal voltage

$$V_{a0} = -I_{a0} Z_0, \quad \because Z_0 = 0.$$

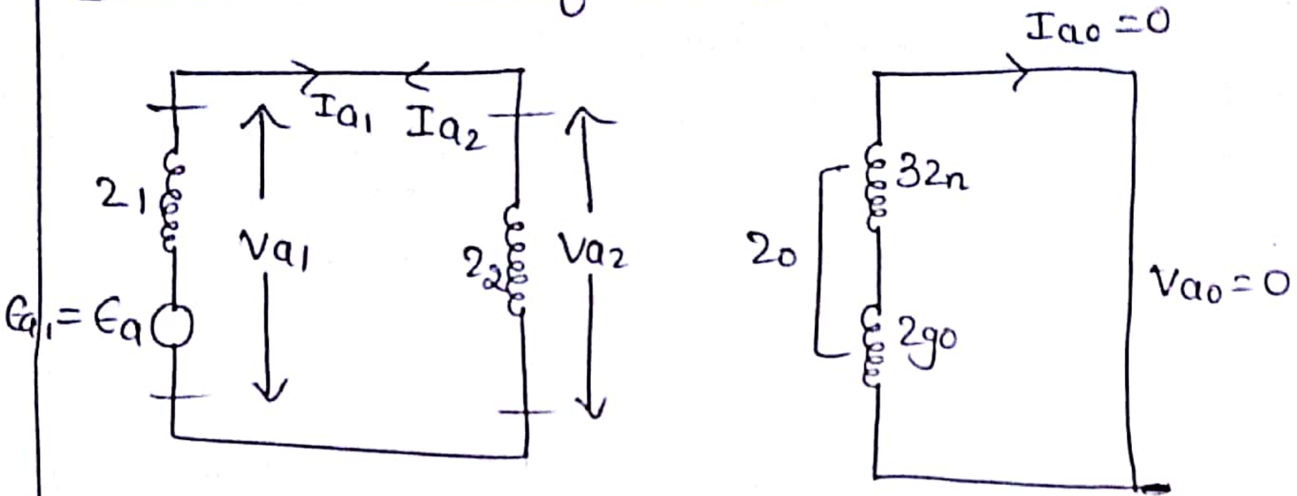
$$V_{a0} = 0 \quad \text{------} (9)$$

$$V_{a1} = V_{a2} \quad \text{------} (10)$$

equation (8) & (9) suggests parallel connection of positive & negative sequence networks. since $I_{a0} = V_{a0} = 0$, the zero sequence networks is connected seperately & shorted on itself.

P.T.O

Interconnection of sequence networks:-



$$\therefore \; I_{a1} = -I_{a2} = \frac{E_a}{Z_1+Z_2} \quad \text{———— (11)}$$

$$I_{a0} = V_{a0} = 0$$

$$V_{a1} = V_{a2} = E_{a1} - I_{a1}Z_1$$

$$= E_a - \frac{E_a Z_1}{Z_1+Z_2}$$

$$= \left(\frac{\cancel{Z_1} + Z_2 - \cancel{Z_1}}{Z_1+Z_2}\right) E_a$$

$$= \left(\frac{Z_2}{Z_1+Z_2}\right) E_a \quad \text{———— (12)}$$

Fault current,

$$I_f = I_b \text{ or } I_c \qquad \because I_{a1} = -I_{a2}$$

$$= I_{a0} + a^2 I_{a1} + a I_{a2}$$

$$= 0 + (a^2 - a) I_{a1}$$

$$\boxed{I_f = -j\sqrt{3}\, I_{a1}}$$

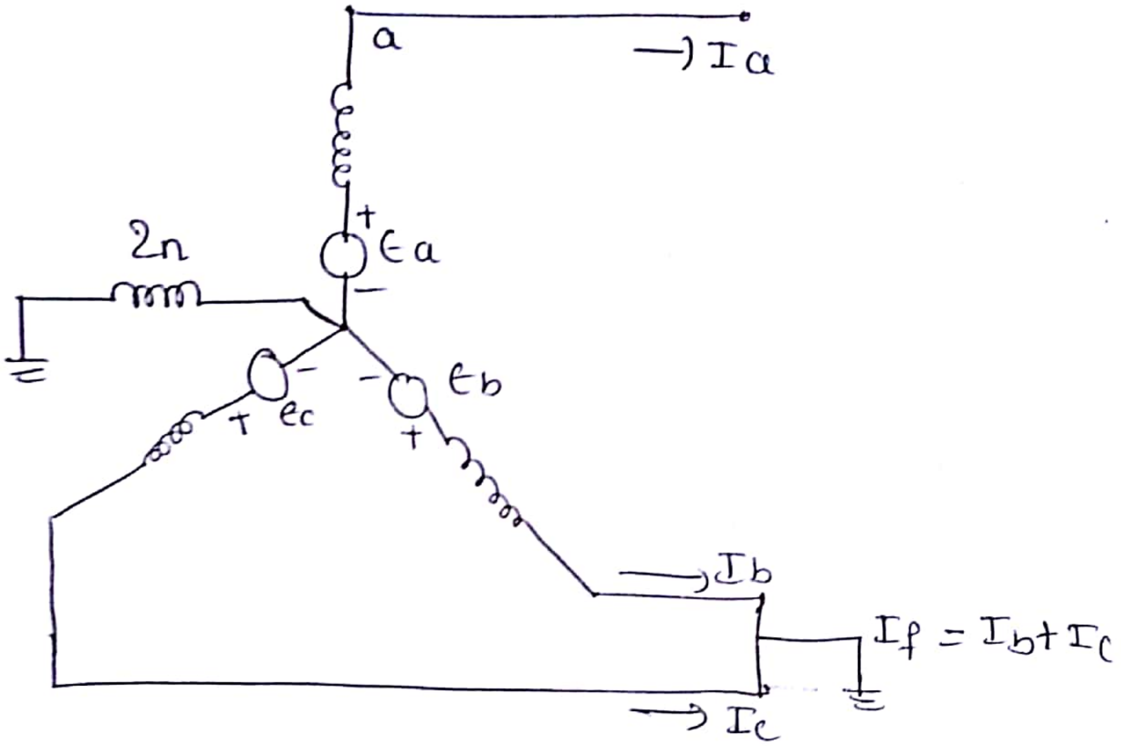
$$|I_f| = \sqrt{3}\, I_{a1}$$

$$|I_f| = \sqrt{3}\left(\frac{E_a Z_2}{Z_1+Z_2}\right) \quad \text{———— (13)}.$$

If neutral is not grounded then $Z_0 = \infty$.
since I_f is independent of Z_0. $\therefore$ It will not effect I_f.

Double line to Ground fault on unloaded Generator: (L-L-G)

The circuit diagram for an LLG fault on an unloaded star connected alternator having grounded neutral is shown in fig. Assume fault takes place in phases b & c.



Terminal condition:-

$$V_b = 0 \quad \text{--- (1)}$$
$$V_c = 0 \quad \text{--- (2)}$$
$$I_a = 0 \quad \text{--- (3)}$$

Symmetrical component Relation :-

$$I_a = 0$$

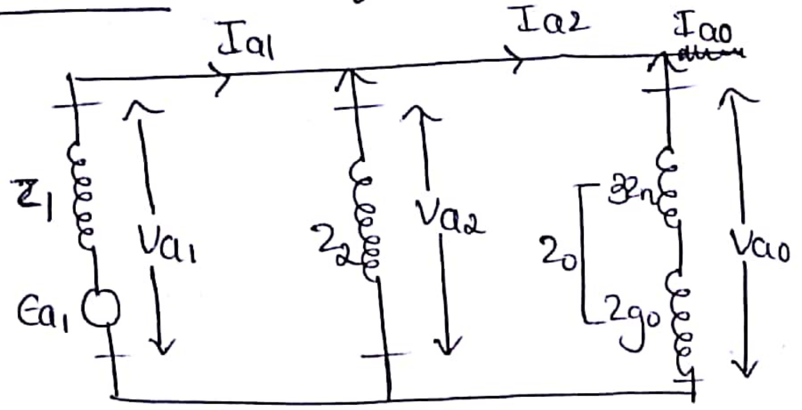
i.e $I_{a0} + I_{a1} + I_{a2} = 0$ --- (4).

$$V_{a0} = 1/3\,(V_a + V_b + V_c) = 1/3\, V_a$$
$$V_{a1} = 1/3\,(V_a + a V_b + a^2 V_c) = 1/3\, V_a$$
$$V_{a2} = 1/3\,(V_a + a^2 V_b + a V_c) = 1/3\, V_a.$$

$$V_{a0} = V_{a1} = V_{a2} = \tfrac{1}{3} V_a \quad \text{--- (5)}$$

from eqn (4) & (5) sequence networks should be connected in parallel.

Interconnection of sequence networks:-



$$V_{a1} = V_{a2} = V_{a0} = E_a - I_{a1} Z_1$$

$$I_{a1} = \frac{E_a}{Z_1 + \left(\frac{Z_2 Z_0}{Z_2 + Z_0}\right)}$$

By using current Division formula,

$$I_{a2} = -I_{a1}\left(\frac{Z_0}{Z_2 + Z_0}\right)$$

$$I_{a0} = -I_{a1}\left(\frac{Z_2}{Z_0 + Z_2}\right)$$

Fault current,

$$I_f = I_b + I_c$$

$$= (I_{a0} + a^2 I_{a1} + a I_{a2}) + (I_{a0} + a I_{a1} + a^2 I_{a2})$$

$$= 2I_{a0} + (a + a^2) I_{a1} + (a + a^2) I_{a2}$$

$$= 2I_{a0} - I_{a1} - I_{a2} \qquad \because [\text{because } (a + a^2) = -1]$$

$$= 2I_{a0} - (I_{a1} + I_{a2}).$$

$$\because I_{a1} + I_{a2} = -I_{a0}.$$

$$So,\ I_f = 2I_{a0} - (-I_{a0})$$
$$= 3I_{a0}$$
$$= -3I_{a1}\left(\frac{Z_2}{Z_2+Z_0}\right)$$

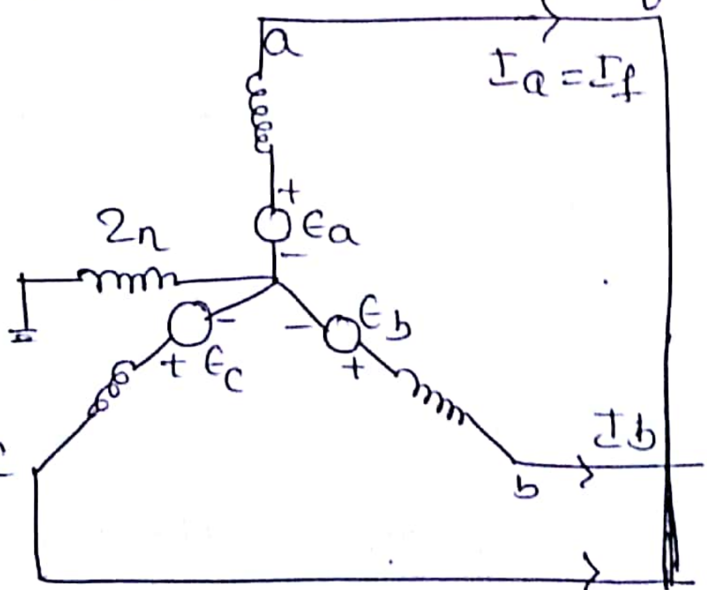
If neutral is not grounded then $Z_n = \infty$.

$$Z_0 = Z_{g0} + 3Z_n$$
$$= \infty$$
$$I_f = -3I_{a1}\left(\frac{Z_2}{Z_2+\infty}\right)$$
$$I_f = 0$$

Hence, fault current is zero in LLG fault if neutral is not grounded.

Three Phase fault (3L)

The circuit diagram for the fault condition is shown in fig.



Terminal condition:-

$$I_a + I_b + I_c = 0 \quad \text{——— (1)}$$
$$V_a = V_b = V_c \quad \text{——— (2)}$$

Symmetrical component Relation:-

Taking I_a as reference,

$$I_b = a^2 I_a$$

$$I_c = a I_a$$

use the above relation in the following equation.

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$

$$= \frac{1}{3}(I_a + a^3 I_a + a^3 I_a)$$

$$= \frac{1}{3}(3 I_a)$$

$$I_{a1} = I_a. \quad \text{——— (3)}$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c)$$

$$= \frac{1}{3}(I_a + a^4 I_a + a^2 I_a)$$

$$= \frac{1}{3}(I_a + a I_a + a^2 I_a)$$

$$= \frac{I_a}{3}(1 + a + a^2)$$

$$I_{a2} = 0 \quad \text{——— (4)}$$

IIIly, $I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$

$$= \frac{1}{3}(I_a + a^2 I_a + a I_a)$$

$$= \frac{I_a}{3}(1 + a + a^2)$$

$$I_{a0} = 0. \quad \text{——— (5)}$$

From equ. (4) & (5) indicate that for a 3ϕ fault zero sequence & negative sequence currents are absent.

From equ (3) it is evident that for the positive.

using equation (2) the following relation, we get,

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2 V_c).$$

$$= \frac{V_a}{3}(1+a+a^2)$$

$$V_{a1} = 0. \quad \text{——— (6)}$$

|||ly, $V_{a0} = V_{a2} = 0$ ——— (7)

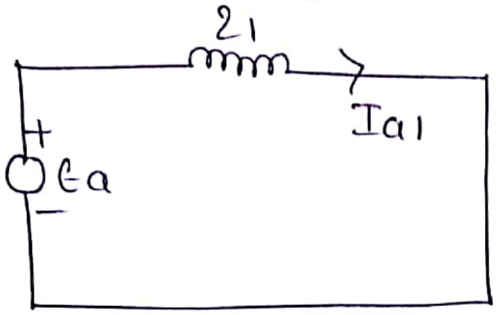
Since $V_{a1} = E_a - I_{a1}Z_1$

$$0 = E_a - I_{a1}Z_1$$

$$0 = E_a - I_a Z_1$$

$$I_a = \frac{E_a}{Z_1} \quad \text{——— (8)}$$

Interconnection of sequence n/w:-



Fault current,

The magnitude of the fault current in case of symmetrical fault is,

$$|I_f| = |I_a| = |I_b| = |I_c|$$

Here, $|I_a| = |I_{a1}|$

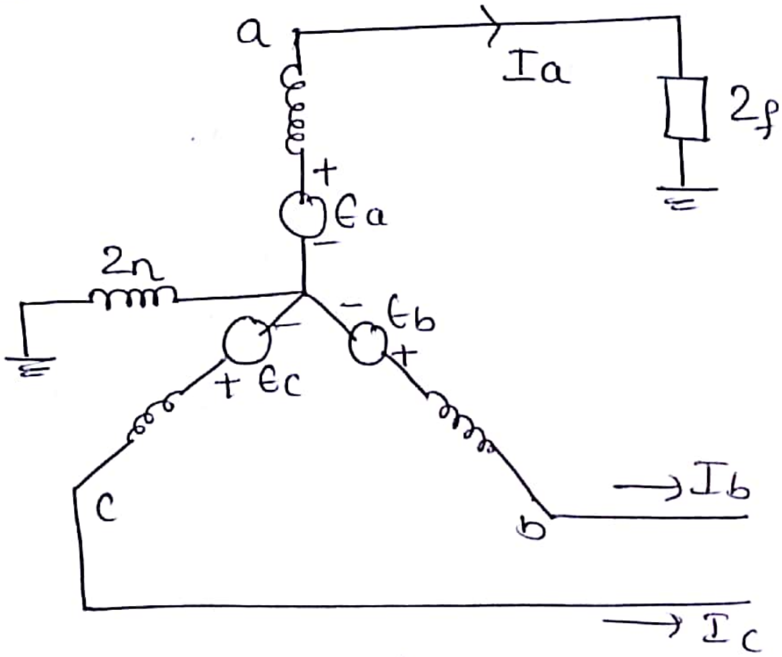
$$|I_f| = |I_{a1}|$$

Grounding or not grounding the neutral point doesnot have an impact of the fault current. The fault current in the three phases are equal in magnitude, but are displaced by 120° from each other.

Faults Through Impedance :-

Single Line-Ground (L-G) fault on an unloaded generator through a fault impedance :-

The circuit diagram for an LG fault on an unloaded generator through a fault impedance Z_f is as shown in fig.



Terminal condition :-

$V_a = I_a \cdot Z_f$ ——— (1)

$I_b = 0$ ——— (2)

$I_c = 0$ ——— (3)

Symmetrical component Relations :-

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$$

$$= \frac{1}{3}(I_a + 0 + 0)$$

$$I_{a0} = \frac{1}{3} I_a$$

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c)$$

$$= \frac{1}{3} I_a$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c) = \frac{1}{3} I_a.$$

So, $I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a$ ——— (4).

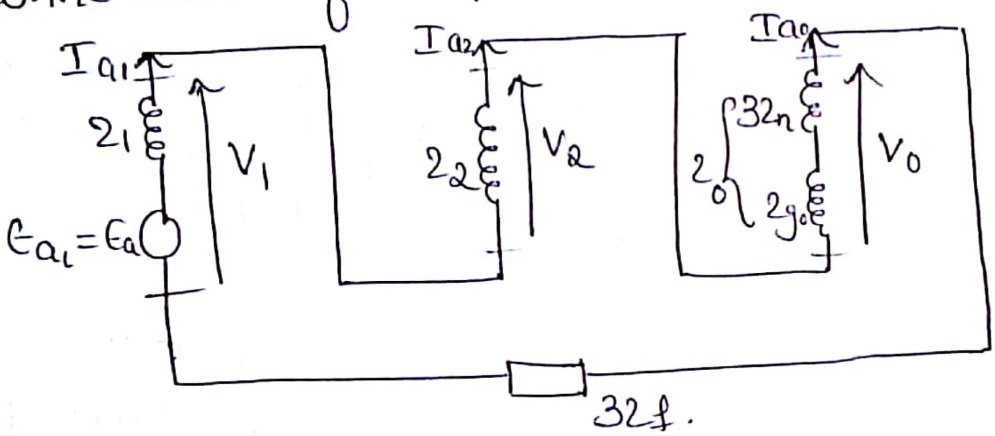
The terminal condition,

$V_a = I_a . Z_f$ gives,

$V_{a1} + V_{a2} + V_{a0} = I_a Z_f$

$= 3 I_{a0} Z_f$ ——— (5)

As per the eqn (4) & (5) all sequence currents are equal & the sum of sequence voltages equal. Therefore, these equations suggest a series connection of sequence network through impedance.



Sequence Quantities:-

$$I_{a0} = I_{a1} = I_{a2} = \frac{E_a}{Z_0 + Z_1 + Z_2 + 3Z_f} \quad \text{——— (6).}$$

$$V_{a1} = E_a - I_{a1} Z_1 = E_a - \frac{E_a Z_1}{Z_0 + Z_1 + Z_2 + 3Z_f}$$

$$= \left(\frac{Z_0 + \cancel{Z_1} + Z_2 + 3Z_f - \cancel{Z_1}}{Z_0 + Z_1 + Z_2 + 3Z_f} \right) E_a$$

$$V_{a1} = \left(\frac{Z_0 + Z_2 + 3Z_f}{Z_0 + Z_1 + Z_2 + 3Z_f} \right) E_a \quad \text{——— (7)}$$

$$V_{a2} = -I_{a_2} Z_2$$

$$= -\left(\frac{E_a Z_2}{Z_0 + Z_1 + Z_2 + 3Z_f}\right) \quad (8)$$

$$V_{a0} = -I_{a0} Z_0$$

$$= -\left(\frac{E_a Z_0}{Z_0 + Z_1 + Z_2 + 3Z_f}\right) \quad (9)$$

Fault current :-

$$I_f = I_a = 3I_{a0}$$

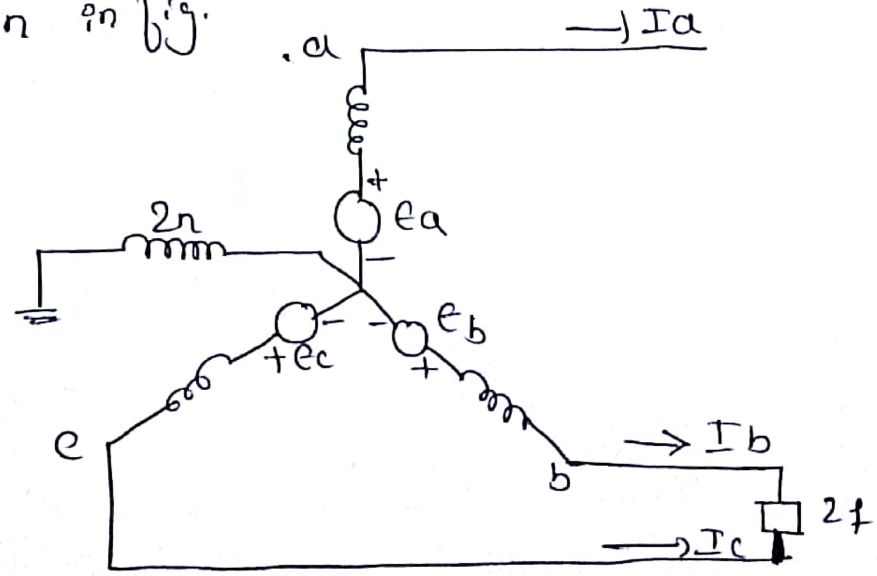
$$I_f = 3\left(\frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}\right) \quad (10)$$

From the above expression, it can be observed that the fault current is reduced by the fault impedance. If neutral is left ungrounded, $Z_n = \infty$.

$Z_0 = \infty$ & hence $I_f = 0$.

Line-Line (L-L) fault on an unloaded generator through a fault impedance :-

The circuit diagram for an LL fault on an unloaded generator through a fault impedance Z_f is as shown in fig.



Terminal condition:

$I_a = 0$ —— (1)

$I_b + I_c = 0$, $I_c = -I_b$ —— (2)

$V_b = V_c + I_b Z_f$ —— (3)

Symmetrical component Relation:-

$I_{a0} = \frac{1}{3}(I_a + I_b + I_c) = 0$

$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c)$

$= \frac{1}{3}(0 + (a - a^2) I_b)$

$= \frac{1}{3}(a - a^2) I_b$

$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c)$

$= \frac{1}{3}(a^2 - a) I_b$

So, $\left. \begin{array}{l} I_{a0} = 0 \\ I_{a1} = -I_{a2} \end{array} \right\}$ —— (4)

$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2 V_c)$

$V_{a2} = \frac{1}{3}(V_a + a^2 V_b + a V_c)$

$\therefore V_{a1} - V_{a2} = \frac{1}{3}\left[(\cancel{V_a} + aV_b + a^2 V_c) - (\cancel{V_a} - a^2 V_b - a V_c)\right]$

$= \frac{1}{3}\left[(a - a^2) V_b + (a^2 - a) V_c\right]$.

$= \frac{1}{3}\left[(a - a^2)(V_b - V_c)\right]$

$= \frac{1}{3}[a - a^2] I_b Z_f$

$\boxed{\because V_b - V_c = I_b Z_f \text{ from eq (3)}}$

$V_{a1} - V_{a2} = I_{a1} Z_f$

Thus, $V_{a1} = V_{a2} + I_{a1} Z_f$ —— (5)

Since, $I_{a0} = 0$, $V_{a0} = -I_{a0} \cdot Z_0 = 0$ —— (6).

Equation (5) & (6) suggest parallel connection of positive & negative sequence networks through a series impedance Z_f as shown in fig (b).

Since $I_{a0} = V_{a0} = 0$, the zero sequence network is connected seperately through a short.

Interconnection of Sequence Network :-

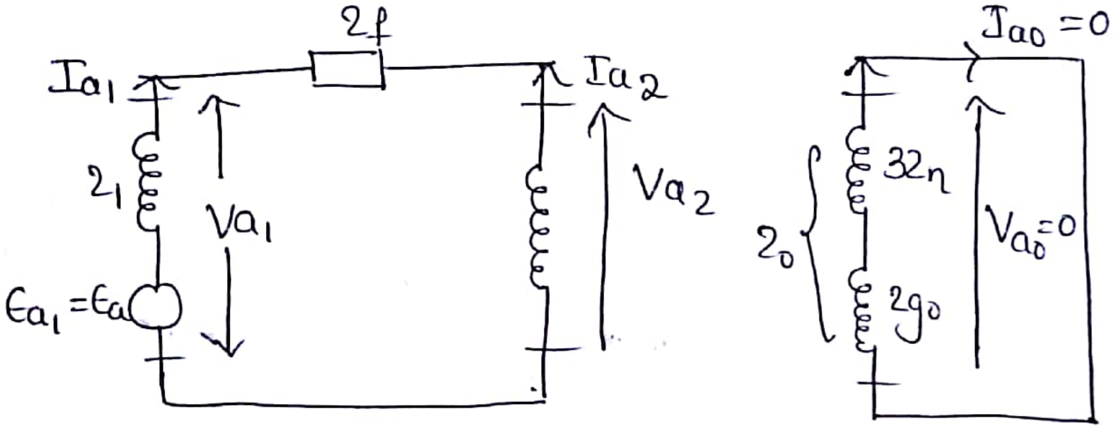


fig. (b).

Sequence quantities :-

$$I_{a1} = -I_{a2} = \frac{E_a}{Z_1 + Z_2 + Z_f}$$

$$I_{a0} = V_{a0} = 0$$

$$V_{a1} = E_a - I_{a1} Z_1$$
$$= E_a \left(\frac{Z_2 + Z_f}{Z_1 + Z_2 + Z_f} \right)$$

$$V_{a2} = -I_{a2} Z_2$$
$$= -\left(\frac{E_a Z_2}{Z_1 + Z_2 + Z_f} \right)$$

Fault current :-

Fault current is equal to the current in the phase b or c.

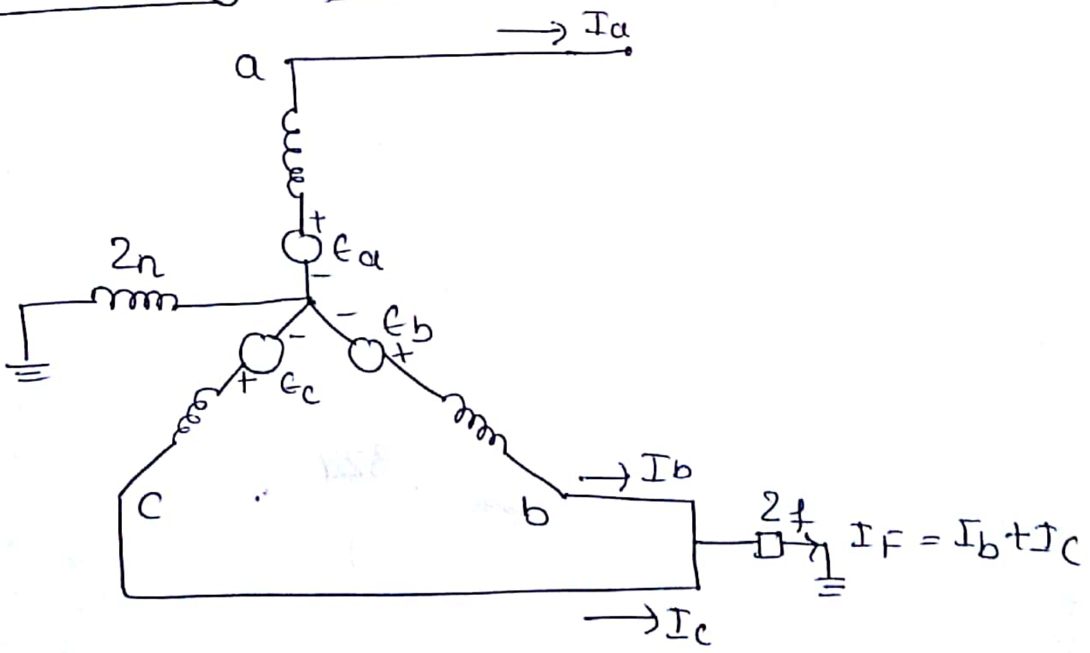
$$I_f = I_b = I_{a0} + a^2 I_{a1} + a I_{a2}$$
$$= 0 + a^2 I_{a1} - a I_{a1}$$
$$= (a^2 - a) I_{a1}$$
$$= -j\sqrt{3}\, I_{a1}$$

$$|I_f| = \sqrt{3}\, I_{a1}$$

$$|I_f| = \left(\frac{\sqrt{3}\, E_a}{Z_1 + Z_2 + Z_f} \right)$$

Since Z_0 doesnot appear in the above equation, the presence or absence of a grounded neutral doesnot affect the fault current.

Double line - to ground fault (LLG) on an unloaded generator through a fault impedance :-



Terminal conditions :-

$$I_a = 0 \quad \text{——— (1)}$$

$$V_b = (I_b + I_c) Z_f \quad \text{——— (2)}$$

$$V_c = (I_b + I_c) Z_f \quad \text{——— (3)}$$

Hence $V_b = V_c$.

Symmetrical component Relation:-

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c)$$
$$= \frac{1}{3}(V_a + (a + a^2)V_b)$$
$$= \frac{1}{3}[V_a - V_b]$$

$$V_{a2} = \frac{1}{3}[V_a + a^2V_b + aV_c]$$
$$= \frac{1}{3}[V_a + (a^2 + a)V_b]$$
$$= \frac{1}{3}[V_a - V_b]$$

$$V_{a0} = \frac{1}{3}[V_a + V_b + V_c]$$
$$= \frac{1}{3}[V_a + 2V_b].$$

Thus, $V_{a1} = V_{a2}$ ——— (4)

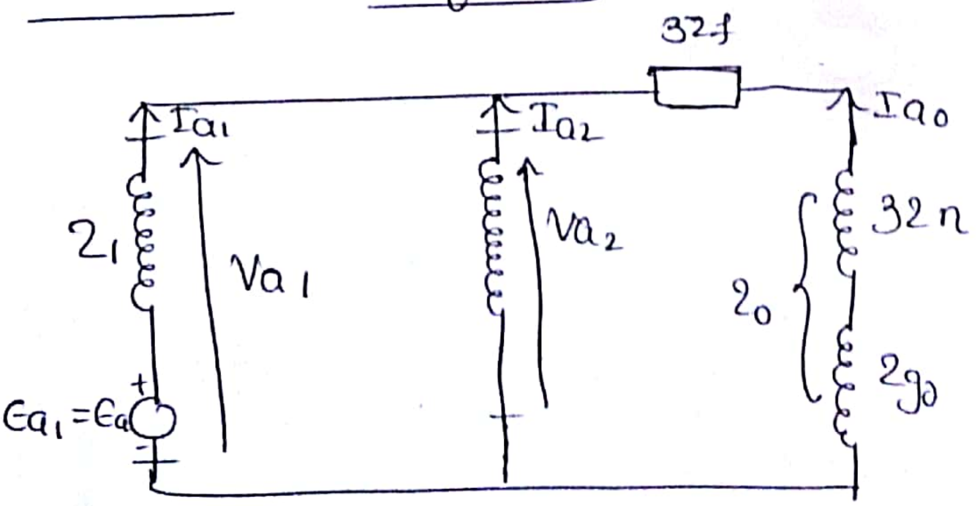
$$V_{a0} - V_{a2} = \frac{1}{3}(3V_b)$$
$$= V_b.$$
$$= (I_b + I_c) Z_f \quad = 3I_{a0}Z_f \quad \text{——— (5).}$$

$$V_{a0} = V_{a2} + 3I_{a0} Z_f \quad \text{——— (6).}$$

$\because I_a = 0$

$I_{a0} + I_{a1} + I_{a2} = 0$ ——— (7).

Interconnection of sequence network:-



Sequence Quantities :-

$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_2(3Z_f + Z_0)}{Z_2 + 3Z_f + Z_0}} \quad \text{--- (8)}$$

$$I_{a2} = -\frac{I_{a1}(Z_0 + 3Z_f)}{Z_0 + Z_2 + 3Z_f} \quad \text{--- (9)}$$

$$I_{a0} = \frac{-I_{a1} Z_2}{Z_0 + Z_2 + 3Z_f} \quad \text{--- (10)}$$

Fault current :-

$$I_f = I_b + I_c.$$

$$= (I_{a0} + a^2 I_{a1} + a I_{a2}) + (I_{a0} + a I_{a1} + a^2 I_{a2})$$

$$= 2 I_{a0} + I_{a1}(a^2 + a) + (a + a^2) I_{a2}$$

$$= 2 I_{a0} - I_{a1} - I_{a2}$$

$$= 2 I_{a0} - (I_{a1} + I_{a2})$$

$$= 2 I_{a0} - (-I_{a0}) \quad \text{from equ (7)}$$

$$I_f = 3 I_{a0}$$

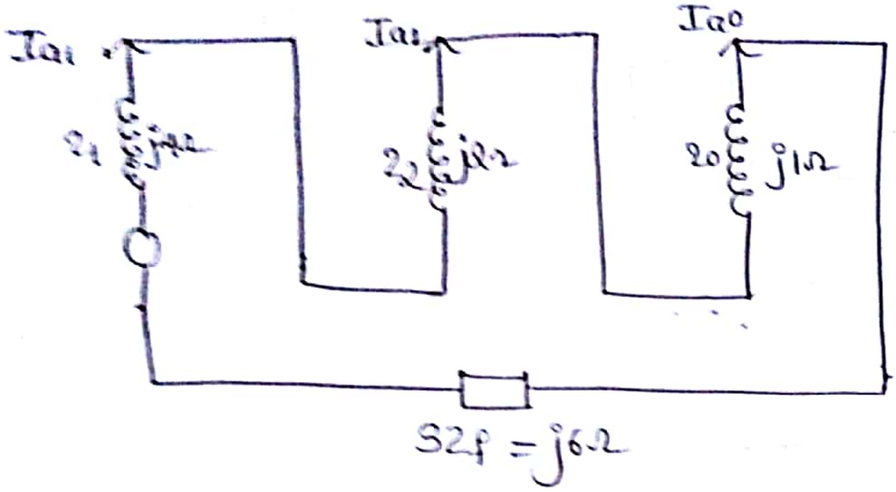
$$I_f = 3\left(\frac{-I_{a1} Z_2}{Z_0 + Z_2 + 3Z_f}\right) \quad \text{--- (11)}$$

If ungrounded then $Z_0 = \infty$, $I_f = 0$.

Problem :-

1) A 3ϕ Generator with an open circuit voltage of 400V is subjected to an LG fault through a fault impedance of $2j\Omega$. Determine the fault current if $Z_1 = j4\Omega$, $Z_2 = j2\Omega$ & $Z_0 = j1\Omega$. Repeat the problem for L-L & L-L-G fault.

Sol:- (i) LG fault :-



Note :

∵ line volt 400V is given.

$V_L = \sqrt{3}\, V_{ph}$.

$V_{ph} = V_L/\sqrt{3}$.

$$I_{a_1} = I_{a_2} = I_{a_0} = \frac{E_a}{Z_1 + Z_2 + Z_0 + 3Z_f}$$

$$= \frac{400/\sqrt{3}}{j(4+2+1+6)}$$

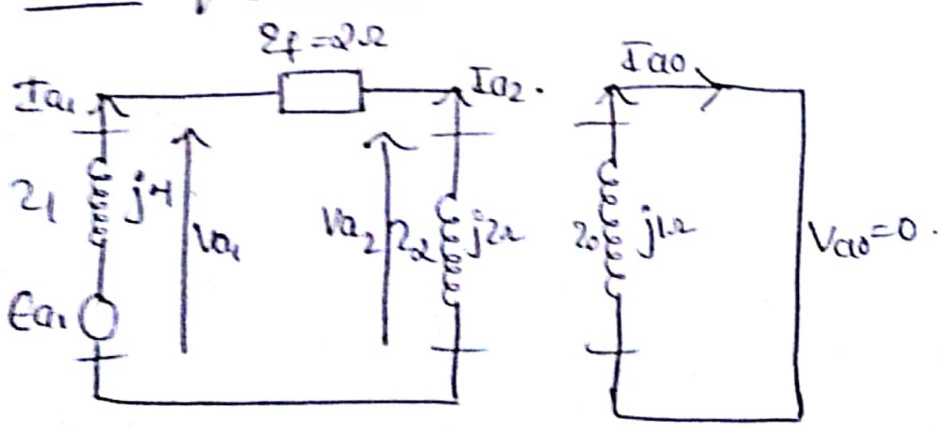
$$= -j17.76A.$$

Fault current, $I_f = 3|I_{a0}|$

$= 3\,(17.76)$

$= 53.29A$

(ii) L-L fault :-



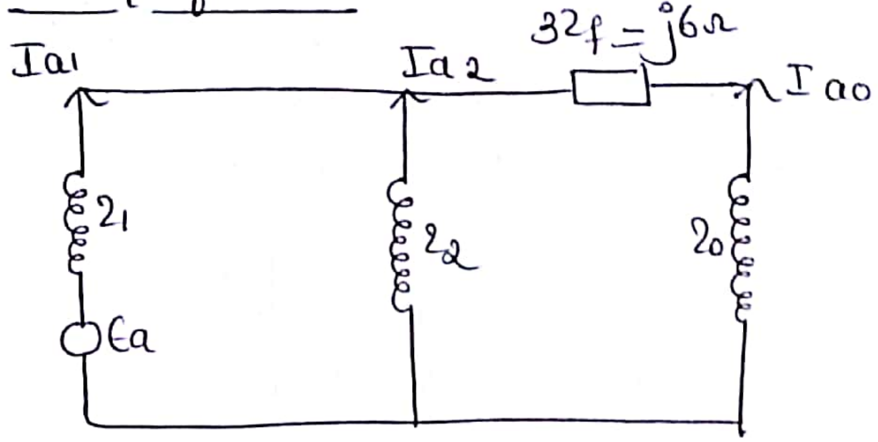
Here, $I_{a1} = \dfrac{E_a}{Z_1 + Z_2 + Z_f} = \dfrac{400/\sqrt{3}}{j(4+2+2)} = -j\,28.87A$

Fault current, $I_f = \sqrt{3}\,|I_{a1}|$

$= \sqrt{3}\,(28.87)$

$= \underline{50\,A}$.

(iii) LLG fault:-



$$I_{a1} = \frac{E_a}{Z_1 + \dfrac{Z_2(Z_0+3Z_f)}{(Z_2+Z_0+3Z_f)}}$$

$$= \frac{400/\sqrt{3}}{j\left[4 + \dfrac{2(1+6)}{2+1+6}\right]} = -j41.57\,A.$$

Therefore, using current Division,

$$I_{a0} = -I_{a1}\left(\frac{Z_2}{Z_2+Z_0+3Z_f}\right)$$

$$= j41.57\left(\frac{2}{2+1+6}\right)$$

$$= j9.24\,A.$$

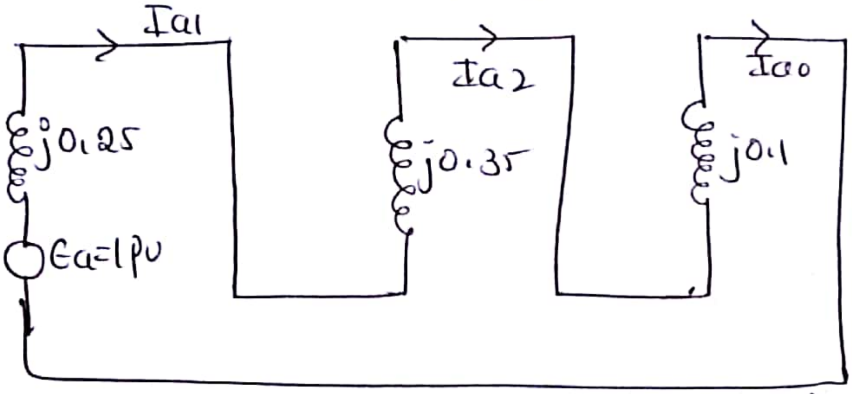
Fault current,

$$I_f = 3\,|I_{a0}|$$

$$= 3(9.24) = 27.72\,A.$$

2) A salient pole generator without dampers is rated 20MVA, 13.8 kV & has a subtransient reactance of 0.25 p.u. The negative & zero sequence reactance are 0.35 p.u & 0.1 p.u respectively. The neutral of the generator is solidly grounded. Calculate the fault current when a single line to ground fault occurs at the terminals of the generator. Assume prefault current is zero.

Solⁿ:–



Let us choose the generator ratings as base values

$$(MVA)_B = 20.$$

$$(kV)_B = \frac{13.8/\sqrt{3}}{13.8/\sqrt{3}} = 1 \text{ p.u.}$$

$$\text{Base current } I_B = \frac{20 \times 10^6}{13.8 \times 10^{-3} \times \sqrt{3}}$$

$$= 836.7 \text{ A.}$$

$$I_{a1} = I_{a2} = I_{a0} = \frac{E_a}{Z_1 + Z_2 + Z_0}$$

$$= \frac{1}{j(0.25 + 0.35 + 0.1)}$$

$$= 1.43 \angle -90^\circ \text{ p.u.}$$

Subtransient fault current, $I_f = 3|I_{a0}|$

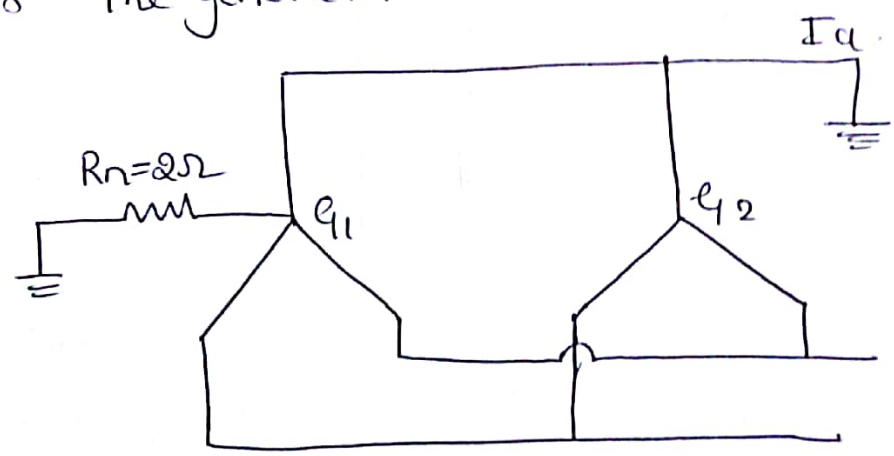
$= 3(1.43)$

$= 4.29$ P.U.

Actual value of Subtransient fault current $= 4.29 \times 836.7$

$= 3.589$ KA.

3) Two 11kV, 20MVA, 3-ϕ, Star connected generators operate in parallel as shown in fig. the positive, negative & zero sequence reactances of each being respectively. j0.18, j0.15, j0.10 p.u. The star point of each one of the generators is isolated & that of the other is earthed through a 2Ω resistor, a single line to ground fault occurs at the terminals of one of the generators. estimate (i) the fault current, (ii) current in the grounding resistor (iii) the voltage across the generator resistor.



solu:-

Since the generators operate in parallel, the interconnection of sequence networks during fault is, Taking the generator ratings as base values.

$(MVA)_B = 20\,MVA$

$(KV)_B = 11\,KV.$

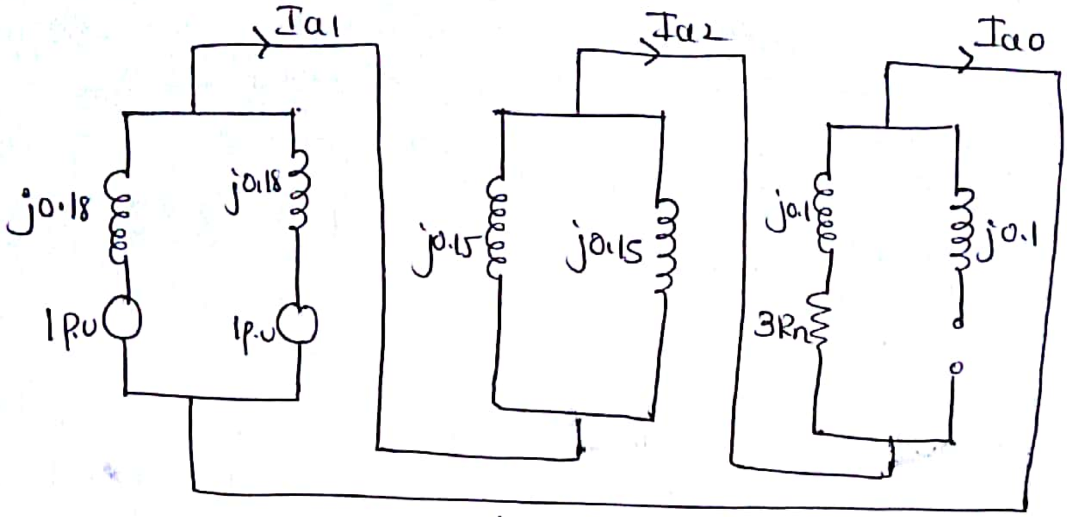


fig (a)

Also R_n in $p.u = R_n\,\Omega \times \frac{(MVA)_B}{(KV)_B^2}$

$= \frac{2 \times 20}{(11)^2} = 0.33\ p.u.$

The equivalent circuit of the system shown in fig (a) is shown below.

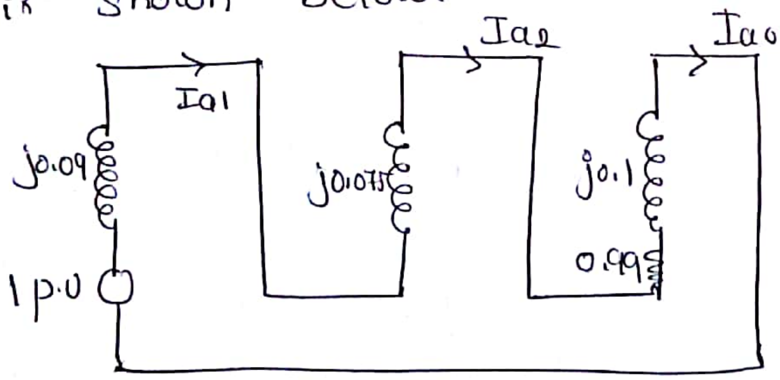


fig (b).

$I_{a1} = I_{a2} = I_{a0} = \frac{1\angle 0^\circ}{0.99 + j0.265}$

$= 0.943 - j0.252.$

(i) Fault current for LG fault $= I_f = 3I_{a0}$

$= 3(0.943 - j0.252)$

$= (2.829 - j0.756)\ p.u.$

(ii) we know that it is the zero sequence currents that flow in the neutral. Hence the current in the grounding resistor =

$$I_n = 3I_{a0}$$

$$= (2.829 - j0.756)\ p.u.$$

The base current

$$I_B = \frac{20 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 1.05\ KA.$$

$$I_n = (2.829 - j0.756)\ 1.05\ KA.$$

$$= (2.97 - j0.7938)\ KA.$$

$$|I_n| = \underline{3.07\ KA.}$$

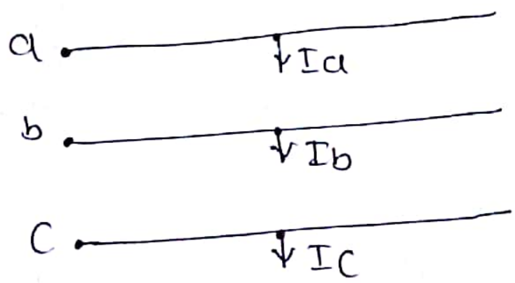
(iii) voltage across the grounding resistance,

$$= R_n \times I_n$$

$$= 2 \times 3.07$$

$$= \underline{6.14\ KV}$$

unsymmetrical faults on power system:-



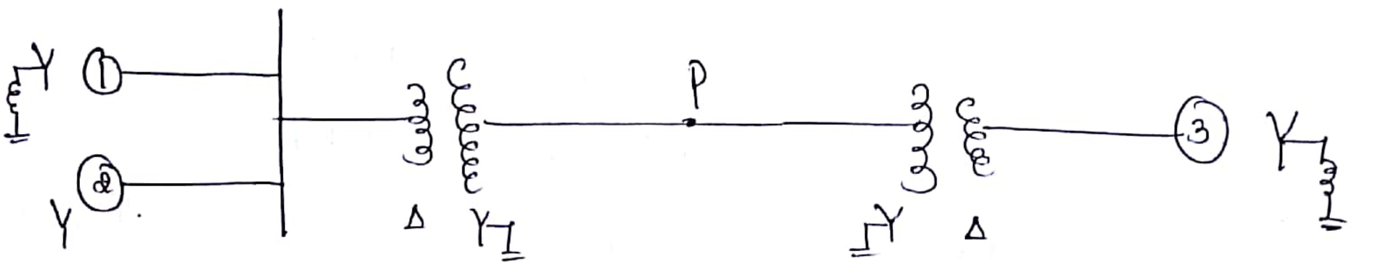
The above fig represents the 3 lines of a 3ϕ power system, which is a part of the network at which the fault occurs.

I_a, I_b & I_c are the currents that are flowing out of the balanced system at the fault from phases a, b & c respectively.

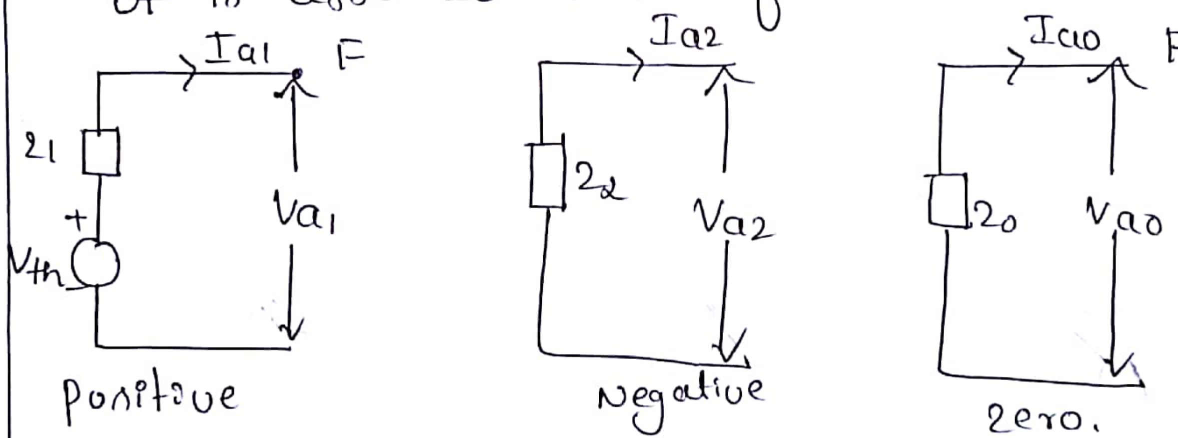
The line to ground voltage at fault are designated by V_a, V_b & V_c.

Before fault occurs, the voltage of phase a, at the fault is designated as V_f.

consider a simple power system consisting of 3 synchronous Machine.



It is assumed that fault occurs at point p.



The prefault voltage at the fault point is the thevenin's voltage of positive sequence network. The negative & zero sequence components of prefault voltage is absent at the fault. point.

From Kirchoff's law we get,

$$V_{a1} = V_{th} - I_{a1} Z_1 \quad \text{——— (1)}$$

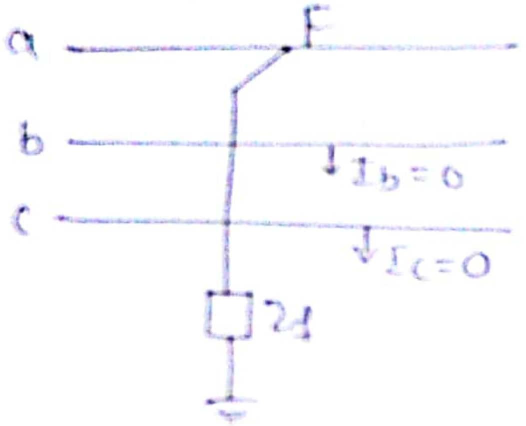
$$V_{a2} = -I_{a2} Z_2 \quad \text{——— (2)}$$

$$V_{a0} = -I_{a0} Z_0 \quad \text{——— (3)}$$

This equation is similar to synchronous generator & is useful in analysis of unsymmetrical faults on power system.

Single line to ground fault :-

The fig shows an LG fault at F in a power system through a fault impedance Z_f. Fault occurs on phase 'a'.



Terminal condition :-

$V_a = I_a Z_f$ —— ①

$I_b = 0$ —— ②

$I_c = 0$ —— ③

Symmetrical component Relation :-

$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$

$= \frac{1}{3} I_a$

$I_{a1} = \frac{1}{3}(I_a + a I_b + a^2 I_c)$

$= \frac{1}{3} I_a$

$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c)$

$= \frac{1}{3} I_a$

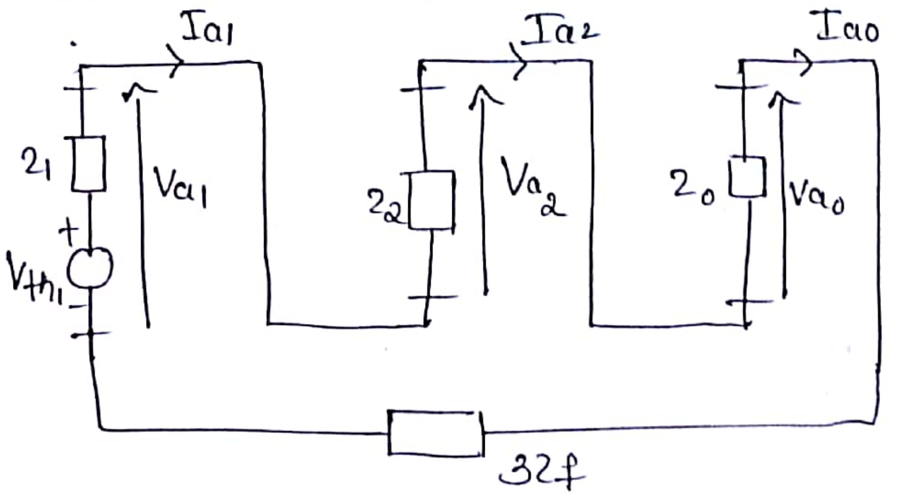
$$\therefore\ I_{a0} = I_{a1} = I_{a2} = \tfrac{1}{3} I_a \quad \text{— (4)}$$

we know that, $V_a = I_a Z_f$ from Terminal condition

So, $V_{a0} + V_{a1} + V_{a2} = I_a Z_f$

$$= 3 I_{a0} Z_f \quad \text{— (5)}$$

Interconnection of sequence networks :-

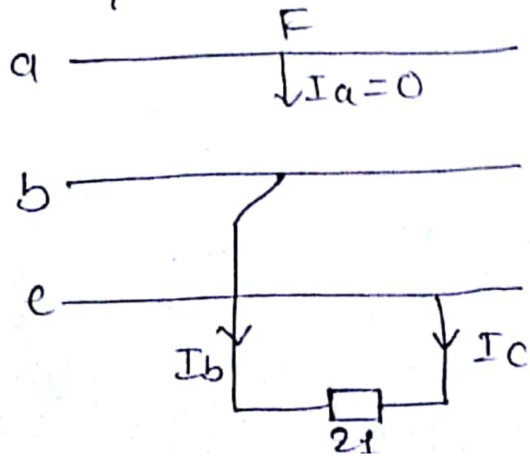


Fault current :-

$$I_f = I_a = 3 I_{a0} = \frac{3 V_{Th}}{Z_1 + Z_2 + Z_0 + 3Z_f}.$$

Line - Line fault (L-L).

The fig. shown a LL fault at F in a power system on phases b & c through a fault impedance Z_f.



Terminal condition:-

$$I_a = 0 \quad \text{——— (1)}$$

$$I_b + I_c = 0 \Rightarrow I_c = -I_b \quad \text{——— (2)}$$

$$V_b = V_c + I_b Z_f \quad \text{——— (3)}$$

Symmetrical component Relation:-

$$I_{a0} = \frac{1}{3}(I_a + I_b + I_c)$$
$$= 0$$

$$I_{a1} = \frac{1}{3}(I_a + aI_b + a^2 I_c).$$
$$= \frac{1}{3}(a - a^2) I_b.$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + aI_c)$$
$$= \frac{1}{3}(a^2 - a) I_b.$$

So, $I_{a0} = 0$
$I_{a1} = -I_{a2}.$

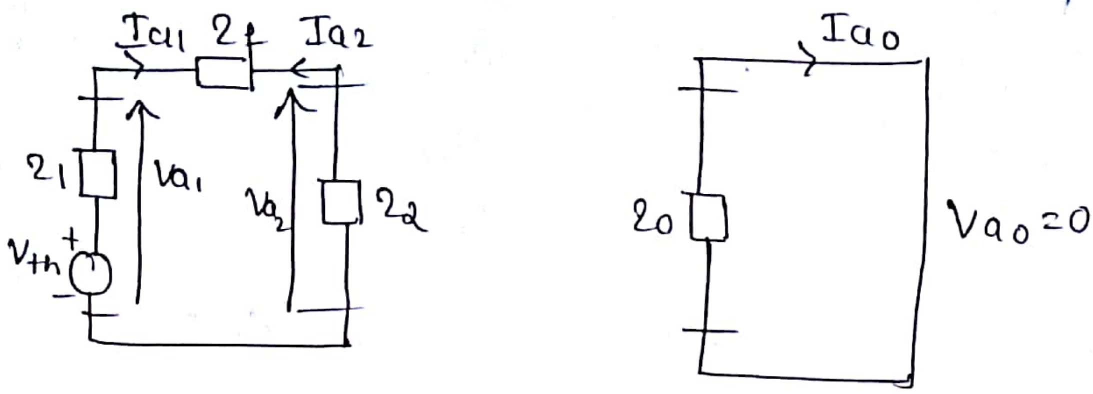
consider,

$$V_{a1} - V_{a2} = \frac{1}{3}\left[V_a + aV_b + a^2 V_c - \{V_a + a^2 V_b + aV_c\}\right]$$
$$= \frac{1}{3}\left[(a - a^2) V_b + (a^2 - a) V_c\right].$$
$$= \frac{1}{3}\left[a - a^2\right](V_b - V_c).$$
$$= \frac{1}{3}(a - a^2) I_b Z_f.$$
$$= I_{a1} Z_f$$

$$V_{a1} = V_{a2} + I_{a1} Z_f.$$

since, $I_{a0} = 0$, $V_{a0} = 0$.//

Interconnection of sequence network :-

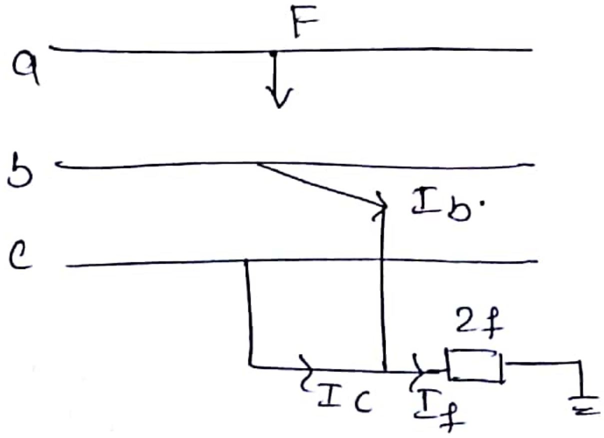


Fault current :-

$$I_f = I_b.$$
$$= I_{a0} + a^2 I_{a1} + a I_{a2}$$
$$= -j\sqrt{3}\, I_{a1}$$
$$|I_f| = \sqrt{3}\, I_{a1}$$
$$\boxed{|I_f| = \sqrt{3}\left(\frac{V_{th}}{Z_1+Z_2+Z_f}\right)}$$

Double line to ground fault (LLG) :-

The fig shows an LLG fault at F in a power system. ~~The~~



Terminal condition :-

$I_a = 0$ ——— ①

$V_b = (I_b + I_c) Z_f$ ——— ②

$V_c = (I_b + I_c) Z_f$ ——— ③.

Symmetrical component Relation :-

$$V_{a1} = \frac{1}{3}(V_a + aV_b + a^2V_c).$$
$$= \frac{1}{3}(V_a + (a+a^2)V_b)$$
$$= \frac{1}{3}(V_a - V_b).$$

$$V_{a2} = \frac{1}{3}(V_a + a^2V_b + aV_c).$$
$$= \frac{1}{3}(V_a + (a^2+a)V_b)$$
$$= \frac{1}{3}(V_a - V_b)$$

$$V_{a0} = \frac{1}{3}(V_a + V_b + V_c)$$
$$= \frac{1}{3}(V_a + 2V_b).$$

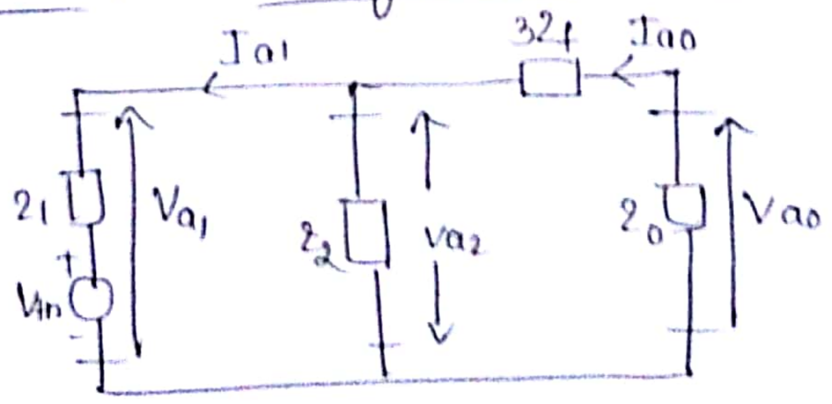
So, $V_{a1} = V_{a2}$.

$$V_{a0} - V_{a2} = \frac{1}{3}(3V_b).$$
$$= V_b$$
$$= (I_b + I_c)Z_f.$$
$$= 3I_{a0}Z_f.$$

Thus, $V_{a0} = V_{a2} + 3I_{a0}Z_f$

$\because I_a = 0$, gives $I_{a0} + I_{a1} + I_{a2} = 0$,

Interconnection of sequence network:-



Fault current:-

$$I_f = I_b + I_c.$$
$$= (I_{a0} + a^2I_{a1} + aI_{a2}) + (I_{a0} + aI_{a1} + a^2I_{a2}).$$

$$= 2I_{a0} + (a^2+a)I_{a1} + (a+a^2)I_{a2}.$$

$$= 2I_{a0} - I_{a1} - I_{a2}$$

$$= 2I_{a0} - (I_{a1} + I_{a2}).$$

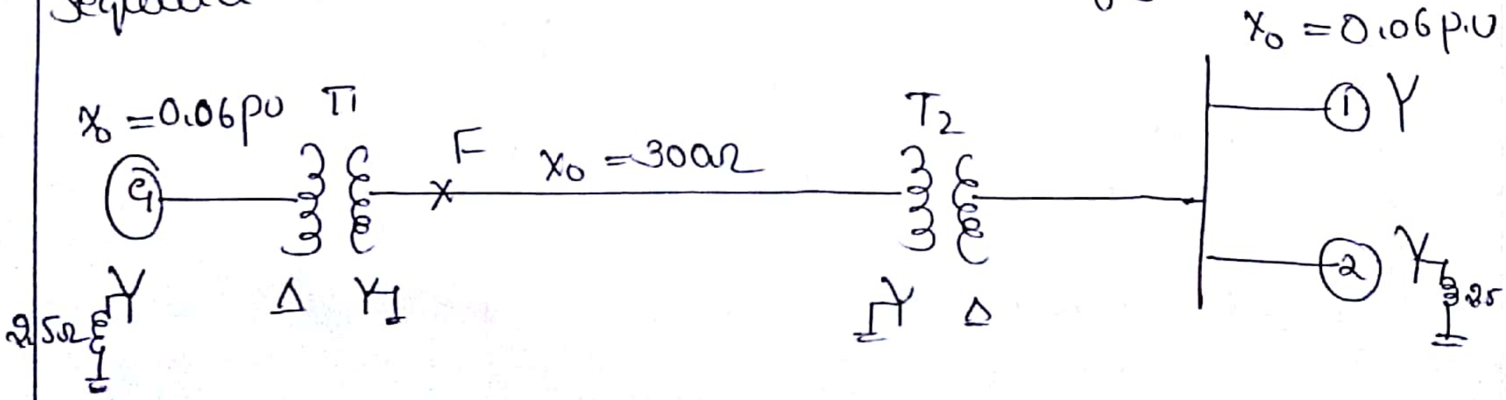
$$= 2I_{a0} - (-I_{a0})$$

$$= 3I_{a0}.$$

$$I_f = -3I_{a1}\left(\frac{Z_2}{Z_0 + Z_2 + 3Z_f}\right).$$

Problem:-

1) A 25 MVA, 11kV, 3ϕ generator has a subtransient reactance of 20%. The generator supplies 2 Motors over a transmission line with transformers at both ends as shown in fig. The Motors have rated input of 15 & 7.5 MVA, both 10 kV with 25% subtransient reactances. The 3ϕ transformers are both rated 30 MVA, 10.8/121 kV, connected Δ-Y with leakage reactance of 10% each. The series reactance of line is 100Ω. Calculate the fault current when a single line-to-ground fault occurs at F. The Motors are Loaded to draw 15 & 7.5 MW at 0.8 pf. loading. Assume that negative sequence reactance is equal to positive sequence reactance. The zero sequence reactances are shown in fig.



Solu :- Base values :-

Base Power in the Generator

$(MVA)_{B, new} = 25 MVA.$

Base volt on the generator $= 11 KV.$

Base volt on the transmission line $= 11 \times \frac{121}{10.8}$

$= 123.2 KV.$

Base voltage on the Motor circuit =

$123.2 \times \frac{10.8}{121} = 11 KV.$

Sequence reactance of Generator :-

$x_1 = x_2 = 20\% = 0.2 p.u.$

$X_0 = 0.06 pu$

Reactance of current limiting reactance is,

$$X_n = X_n(\Omega) \times \frac{(MVA)_{B, new}}{(KV)_B^2}$$

$$= 2.5 \times \frac{25}{(11)^2}$$

$$= 0.517 \ p.u.$$

Sequence reactance of transformer

$$x_1 = x_2 = x_0 = X \times \frac{(MVA)_{B, new}}{(MVA)_{B, old}} \times \frac{(KV)_{B, old}^2}{(KV)_{B, new}^2}.$$

$$= 0.1 \times \left(\frac{25}{30}\right) \times \left(\frac{121.0}{123.2}\right)^2$$

$$= 0.0804 \ p.u$$

Reactance of transmission line :-

$$x_1 = x_2 = x_1 \text{ in } \Omega \times \frac{(MVA)_{B, new}}{(KV)_B^2} = 100 \times \frac{25}{(123.2)^2}$$

$$X_1 = X_2 = 0.164 \text{ p.u.}$$

$$X_0 = \frac{300 \times 25}{(123.2)^2}$$

$$= 0.492 \text{ p.u.}$$

Sequence reactance of Motor - 1 :-

$$X_1 = X_2 = 0.25 \times \left(\frac{25}{15}\right) \times \left(\frac{10}{11}\right)^2$$

$$= 0.345 \text{ p.u.}$$

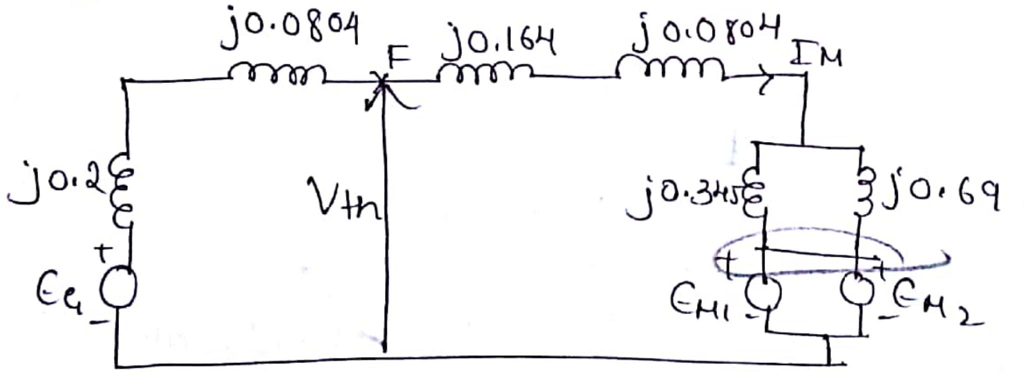
$$X_0 = 0.06 \times \left(\frac{25}{15}\right) \times \left(\frac{10}{11}\right)^2 = 0.083 \text{ p.u.}$$

Sequence reactance of Motor - 2 :-

$$X_1 = X_2 = 0.25 \times \left(\frac{25}{7.5}\right) \times \left(\frac{10}{11}\right)^2 = 0.69 \text{ p.u.}$$

$$X_0 = 0.06 \times \left(\frac{25}{15}\right) \times \left(\frac{10}{11}\right)^2 = 0.166 \text{ p.u.}$$

Positive sequence network :-



we consider.

Find V_{th},

The current drawn by the Motors,

$$I_m = \frac{(15 + 7.5) \times 10^6 \angle -\cos^{-1} 0.8}{\sqrt{3} \times 10 \times 10^3 \times 0.8}$$

$$= 1623.8 \angle 36.87° \text{ A.}$$

The base current in the Motor circuit,

$$(I_m)_B = \frac{25\times10^6}{\sqrt{3}\times11\times10^3} = 1312.2\,A.$$

$$\therefore I_m \text{ in p.u} = \frac{I_m}{(I_m)_B} = \frac{1623.8\angle{+36.7}}{1312.2} = 1.24\angle{36.87^\circ}$$

$$V_m \text{ in p.u} = \frac{10}{11} = 0.909 \text{ p.u.}$$

Hence the volt at the fault point is,

$$V_{th} = V_m + I_m . Z_{fm}.$$

$$= 0.909 + 1.24\angle{36.87}\,(0.164 + 0.0804)\angle{90^\circ}.$$

$$= 0.909 - 0.1818 + j0.242.$$

$$= 0.727 + j0.242.$$

$$V_{th} = 0.766\angle{18.4^\circ} \text{ p.u.}$$

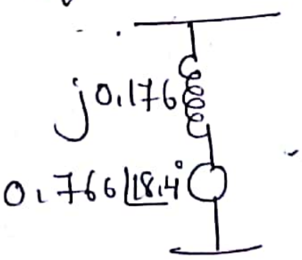
To find Z_{1th},

$$Z_{1th} = j[(0.2 + 0.0804) \,||\, (0.164 + 0.0804 + 0.23)]$$

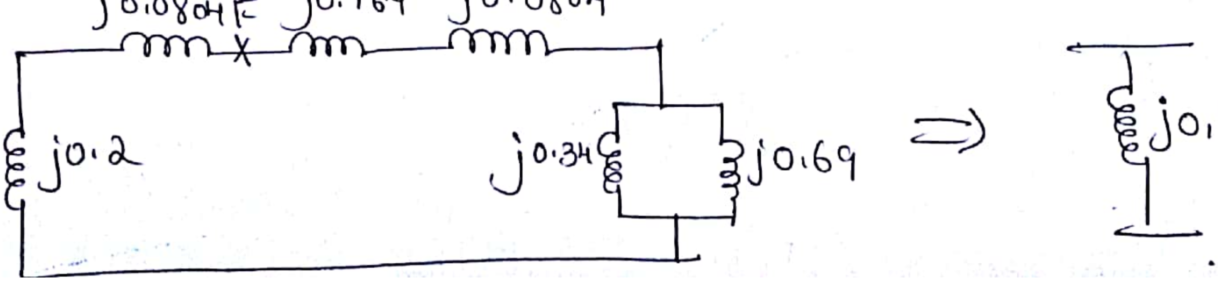
$$= j\,(0.2804 \,||\, 0.4744)$$

$$= j0.176 \text{ p.u.}$$

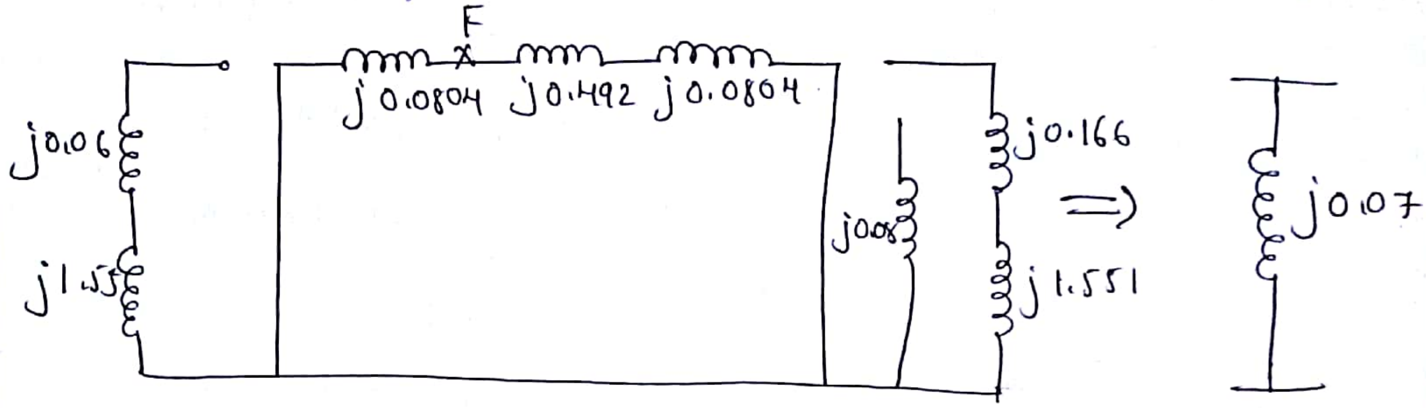
Hence equivalent positive sequence network.



Negative sequence network:-



Zero Sequence network:-

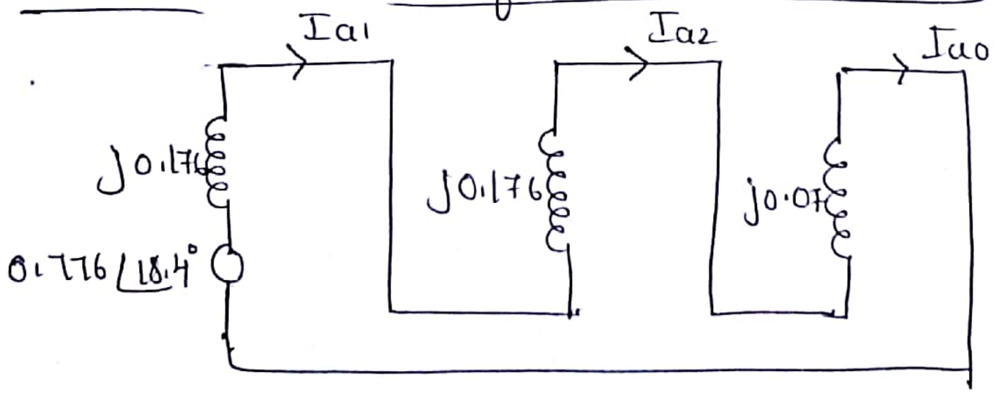


with respect to the fault point F, the thevenin's equivalent reactance is,

$Z_{0th} = j[0.0804 \parallel (0.492 + 0.0804)]$.

$= j0.07$ p.u.

Interconnection of sequence network:-



Here, $I_{a1} = I_{a2} = I_{a0} = \dfrac{0.766 \angle 18.4^\circ}{j(0.176 + 0.176 + 0.07)}$

$= 1.815 \angle -71.6^\circ$ p.u.

Fault current in case of LG fault, $|I_f| = 3|I_{a0}|$

$= 3 \times 1.815$

$= 5.445$ p.u.

I_f in amperes is given as

$|I_f| = 5.445 \times \left[\dfrac{25 \times 10^6}{\sqrt{3} \times 123.2 \times 10^3}\right]$

$|I_f| = 637.92$ A //.

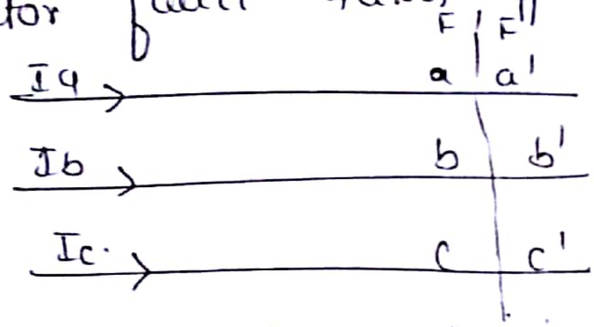
Series type of faults :-

It is also called as "open conductor fault".

One of the or two conductor of a Transmission line may get opened, due to Mechanical damage. These faults are in series with the T.L & hence are called Series faults.

(i) one conductor open
(2) Two conductor open.
(3) Three conductor open.

Fig. shows a system where in an open conductor fault takes place.

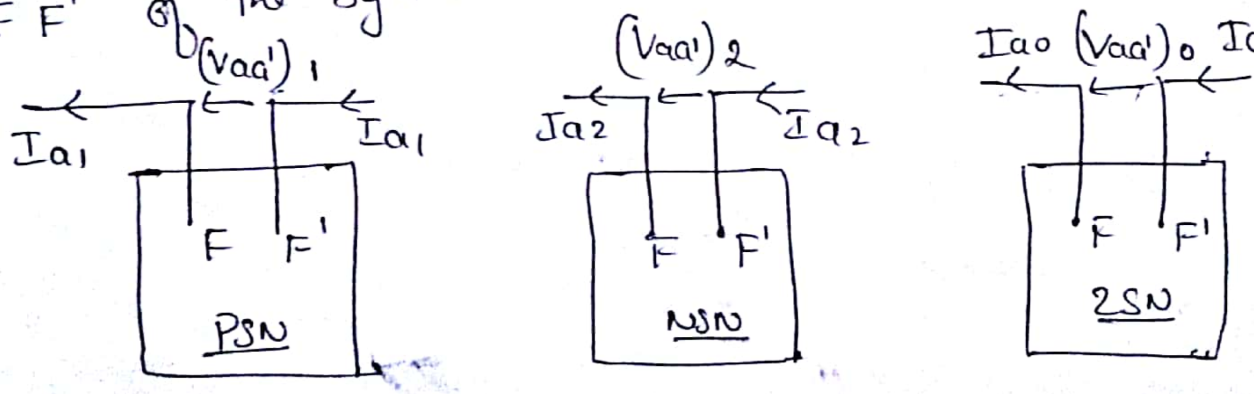


The ends of the system on the sides of the faults are identified as F, F', while the conductor ends are denoted by aa', bb' & cc'.

The volt across the conductors are denoted by $V_{aa'}$, $V_{bb'}$, $V_{cc'}$.

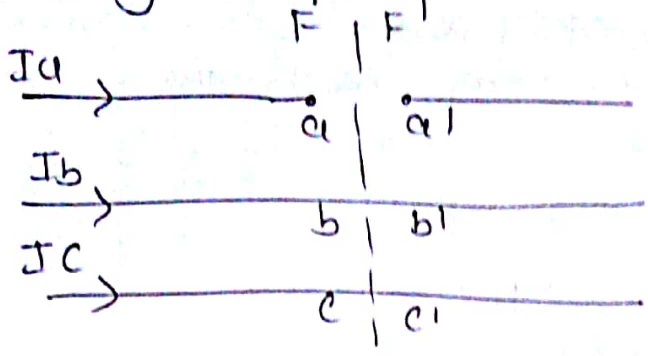
The symmetrical components of these volts are $(V_{aa'})_1$, $(V_{aa'})_2$, $(V_{aa'})_0$.

The sequence Networks as seen from the 2 ends. FF' of the system are.



1) One conductor open fault :-

Let us assume that the conductor 'a' of a system gets opened.



Terminal condition :-

As seen from the 2 ends F & F',

$I_a = 0$ ——— (1)

$V_{bb'} = 0$ ——— (2)

$V_{cc'} = 0$ ——— (3).

Symmetrical component Relation :-

$(V_{aa'})_1 = 1/3 \, (V_{aa'} + a V_{bb'} + a^2 V_{cc'})$.

$= 1/3 \, (V_{aa'} + 0 + 0)$.

$= 1/3 \, (V_{aa'})$.

$(V_{aa'})_2 = 1/3 \, (V_{aa'} + a^2 V_{bb'} + a V_{cc'})$.

$= 1/3 \, V_{aa'}$,

$(V_{aa'})_3 = 1/3 \, (V_{aa'} + V_{bb'} + V_{cc'})$

$= 1/3 \, V_{aa'}$.

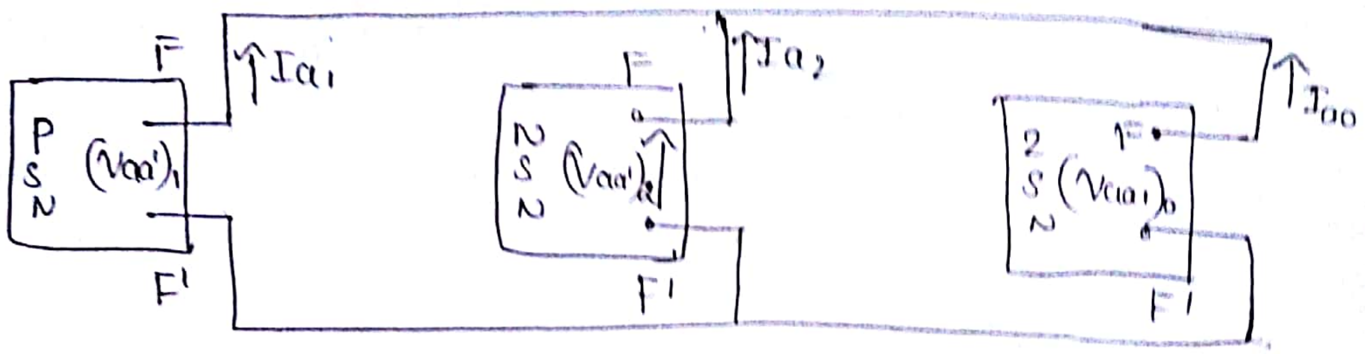
Thus, $(V_{aa'})_1 = (V_{aa'})_0 = (V_{aa'})_2 = 1/3 \, V_{aa'}$ ——— (4)

The condition $I_a = 0$ gives,

$I_{a0} + I_{a1} + I_{a2} = 0$.

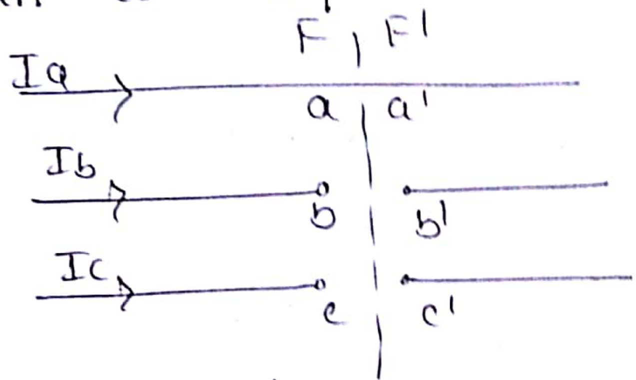
condition (4) & (5) in terms of symmetrical components are similar to LLG fault.

Hence 3 sequence networks should be connected in parallel.



2) Two conductor open fault :-

Let us assume that the 2 conductors b & c get open at the points F, F' as shown in fig.



Terminal condition.

$I_b = 0$ —— (1)

$I_c = 0$ —— (2)

$V_{aa'} = 0$ —— (3).

Symmetrical component Relation :-

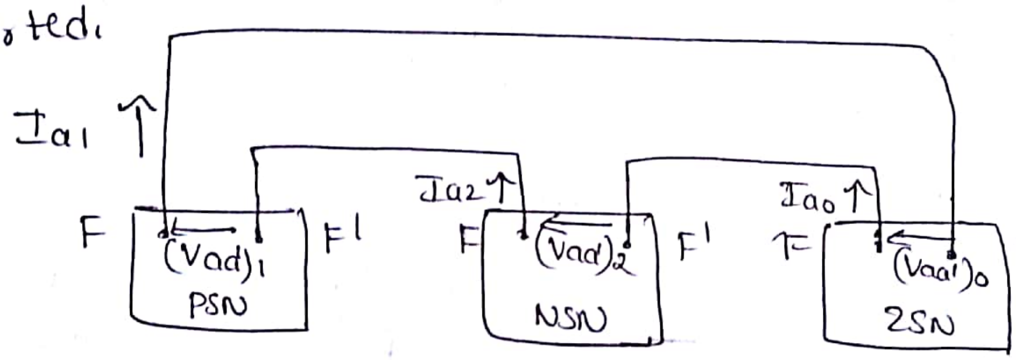
$$I_{a0} = 1/3 (I_a + I_b + I_c).$$
$$= 1/3 (I_a + 0 + 0).$$
$$= 1/3 I_a.$$
$$I_{a1} = 1/3 (I_a + a I_b + a^2 I_c)$$
$$= 1/3 I_a.$$

$$I_{a2} = \frac{1}{3}(I_a + a^2 I_b + a I_c)$$
$$= \frac{1}{3} I_a.$$

Thus, $I_{a0} = I_{a1} = I_{a2} = \frac{1}{3} I_a$ —— (4)

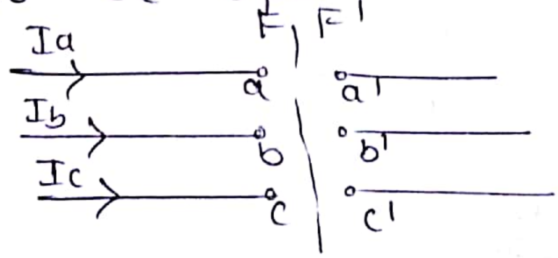
The condition $V_{aa'} = 0$,
$$(V_{aa'})_0 + (V_{aa'})_1 + (V_{aa'})_2 = 0 \quad \text{—— (5)}$$

These conditions are similar to 1-ϕ fault & suggest that 3 sequence networks be connected in series & shorted.



3) Three conductor open fault:-

Consider all the 3 phases a, b & c of a 3ϕ system to be open.



Terminal conditions:-

$$I_a + I_b + I_c = 0 \quad \text{—— (1)}$$

This implies,
$$I_{a0} = I_{a1} = I_{a2} = 0$$

These relations imply that the sequence networks are all open circuited.