CHAPTER 4: UNSYMMETRICAL FAULTS

[CONTENTS: Preamble, L-G, L-L, L-L-G and 3-phase faults on an unloaded alternator without and with fault impedance, faults on a power system without and with fault impedance, open conductor faults in power systems, examples]

4.1 PREAMBLE

The unsymmetrical faults will have faulty parameters at random. They can be analyzed by using the symmetrical components. The standard types of unsymmetrical faults considered for analysis include the following (in the order of their severity):

- Line–to–Ground (L-G) Fault
- Line–to–Line (L-L) Fault
- Double Line–to–Ground (L-L-G)Fault and
- Three-Phase–to–Ground (LLL-G) Fault.

Further the neutrals of various equipment may be grounded or isolated, the faults can occur at any general point F of the given system, the faults can be through a fault impedance, etc. Of the various types of faults as above, the 3-ϕ fault involving the ground is the most severe one. Here the analysis is considered in two stages as under: (i) Fault at the terminals of a Conventional (Unloaded) Generator and (ii) Faults at any point F, of a given Electric Power System (EPS).

Consider now the symmetrical component relational equations derived from the three sequence networks corresponding to a given unsymmetrical system as a function of sequence impedances and the positive sequence voltage source in the form as under:

$$\begin{aligned} V_{a0} &= -I_{a0}Z_0 \\ V_{a1} &= E_a - I_{a1}Z_1 \\ V_{a2} &= -I_{a2}Z_2 \end{aligned} \qquad (4.1)$$

These equations are refered as the *sequence equations*. In matrix Form the sequence equations can be considered as:

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = \begin{vmatrix} 0 \\ E_a \\ 0 \end{vmatrix} - \begin{vmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{vmatrix} \begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} \qquad (4.2)$$

This equation is used along with the equations i.e., conditions under fault (c.u.f.), derived to describe the fault under consideration, to determine the sequence current I_{a1} and hence the fault current I_f, in terms of E_a and the sequence impedances, Z_1, Z_2 and Z_0. Thus during unsymmetrical fault analysis of any given type of fault, two sets of equations as follows are considered for solving them simultaneously to get the required fault parameters:

- Equations for the conditions under fault (c.u.f.)

- Equations for the sequence components (sequence equations) as per (4.2) above.

4.2 SINGLE LINE TO GROUND FAULT ON A CONVENTIONAL (UNLOADED) GENERATOR

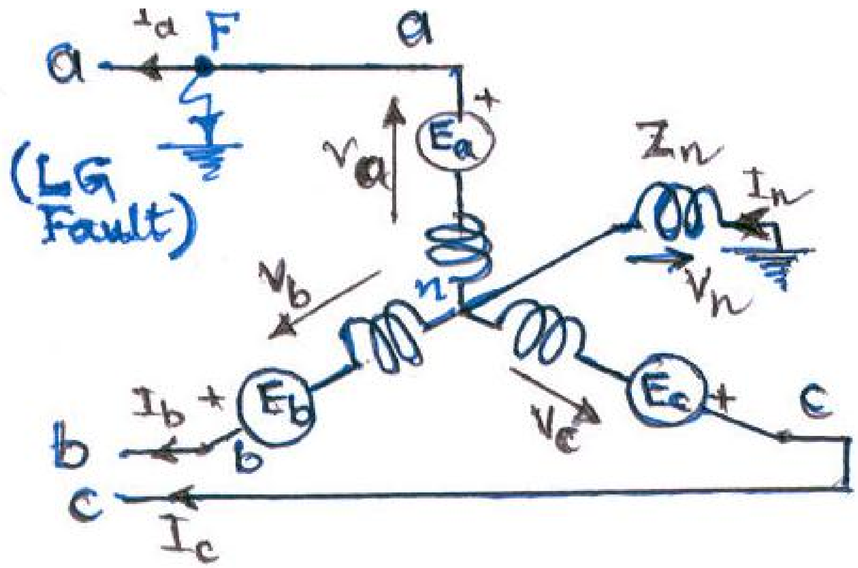

Figure 4.1 LG Fault on a Conventional Generator

A conventional generator is one that produces only the balanced voltages. Let Ea, nd Ec be the internally generated voltages and Zn be the neutral impedance. The fault is assumed to be on the phase'a' as shown in figure 4.1. Consider now the conditions under fault as under:

c.u.f.:

$$I_b = 0; \quad I_c = 0; \quad \text{and} \quad V_a = 0. \tag{4.3}$$

Now consider the symmetrical components of the current I_a with I_b=I_c=0, given by:

$$\begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} = (1/3) \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} I_a \\ 0 \\ 0 \end{vmatrix} \tag{4.4}$$

Solving (4.4) we get,

$$I_{a1} = I_{a2} = I_{a0} = (I_a/3) \tag{4.5}$$

Further, using equation (4.5) in (4.2), we get,

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

V_{a2} 0 0 0 Z_2 I_{a1} (4.6)

Pre-multiplying equation (4.6) throughout by [1 1 1], we get,

$$V_{a1}+V_{a2}+V_{a0} = - I_{a1}Z_0 + E_a - I_{a1}Z_1 - I_{a2}Z_2$$

i.e., $Va = E_a - I_{a1} (Z_1 + Z_2 + Z_0) = \text{zero},$

Or in other words,

$$\mathbf{I_{a1} = [E_a/(Z_1 + Z_2 + Z_0)]} \qquad (4.7)$$

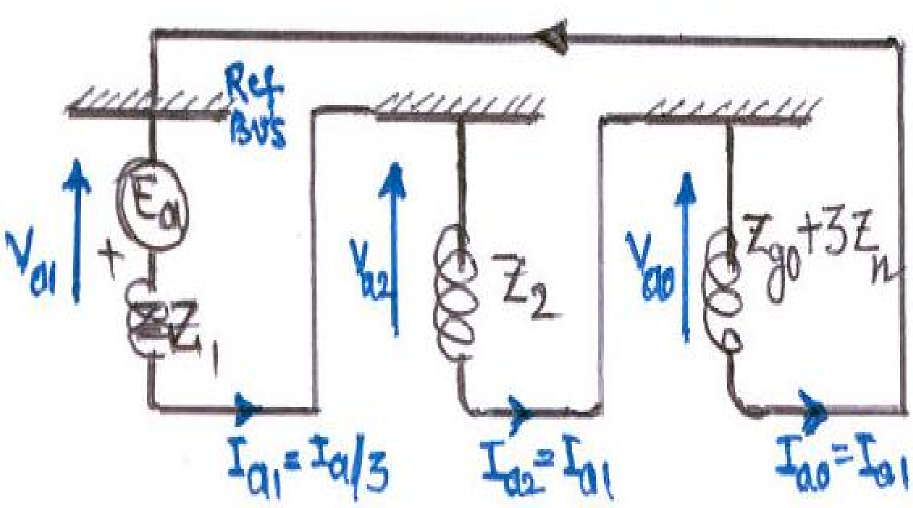

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Figure 4.2 Connection of sequence networks for LG Fault on phase a of a Conventional Generator

The equation (4.7) derived as above implies that the three sequence networks are connected in series to simulate a LG fault, as shown in figure 4.2. Further we have the following relations satisfied under the fault conditions:

1. $I_{a1} = I_{a2} = I_{a0} = (I_a/3) = [E_a/(Z_1 + Z_2 + Z_0)]$
2. **Fault current $\mathbf{I_f = I_a = 3I_{a1} = [3E_a/(Z_1 + Z_2 + Z_0)]}$**
3. $V_{a1} = E_a - I_{a1}Z_1 = E_a(Z_2+Z_0)/(Z_1+Z_2+Z_0)$
4. $V_{a2} = - E_aZ_2/(Z_1+Z_2+Z_0)$
5. $V_{a0} = - E_aZ_0/(Z_1+Z_2+Z_0)$
6. Fault phase voltage $V_a = 0$,
7. Sound phase voltages $V_b = a^2V_{a1}+aV_{a2}+V_{a0}$; $V_c = aV_{a1}+a^2V_{a2}+V_{a0}$
8. Fault phase power: $V_aI_a^* = 0$, Sound pahse powers: $V_bI_b^* = 0$, and $V_cI_c^* = 0$,
9. If $Z_n = 0$, then $Z_0 = Z_{g0}$,

10. If $Z_n = \infty$, then $Z_0 = \infty$, i.e., the zero sequence network is open so that then, $I_f=I_a=0$.

4.3 LINE TO LINE FAULT ON A CONVENTIONAL GENERATOR

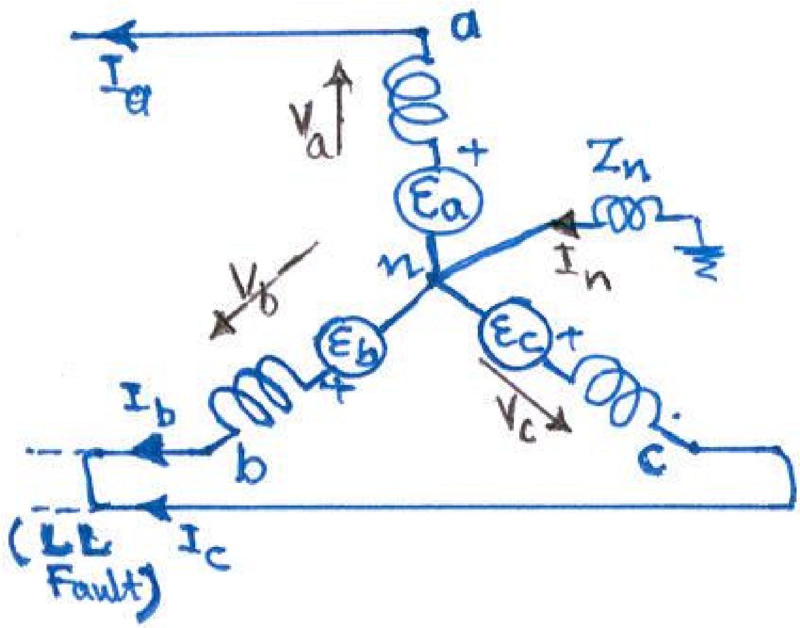


Figure 4.3 LL Fault on a Conventional Generator

Consider a line to line fault between phase 'b' and phase 'c' as shown in figure 4.3, at the terminals of a conventional generator, whose neutral is grounded through a reactance. Consider now the conditions under fault as under:

c.u.f.:

$$I_a = 0;\ I_b = -I_c;\ \text{and}\ V_b = V_c \tag{4.8}$$

Now consider the symmetrical components of the voltage V_a with $V_b=V_c$, given by:

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = (1/3) \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} V_a \\ V_b \\ V_b \end{vmatrix} \tag{4.9}$$

Solving (4.4) we get,

$$V_{a1} = V_{a2} \tag{4.10}$$

Further, consider the symmetrical components of current I_a with $I_b=-I_c$, and $I_a=0$; given by:

$$\begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} = (1/3) \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} 0 \\ I_b \\ -I_b \end{vmatrix} \tag{4.11}$$

Solving (4.11) we get,

$$I_{a0} = 0; \text{ and } I_{a2} = -I_{a1} \tag{4.12}$$

Using equation (4.10) and (4.12) in (4.2), and since $V_{a0} = 0$ (I_{a0} being 0), we get,

$$\begin{vmatrix} 0 \\ V_{a1} \\ V_{a1} \end{vmatrix} = \begin{vmatrix} 0 \\ E_a \\ 0 \end{vmatrix} - \begin{vmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{vmatrix} \begin{vmatrix} 0 \\ I_{a1} \\ -I_{a1} \end{vmatrix} \tag{4.13}$$

Pre-multiplying equation (4.13) throughout by [0 1 -1], we get,

$$V_{a1}-V_{a1} = E_a - I_{a1}Z_1 - I_{a1}Z_2 = 0$$

Or in other words,

$$\mathbf{I_{a1} = [E_a/(Z_1 + Z_2)]} \tag{4.14}$$

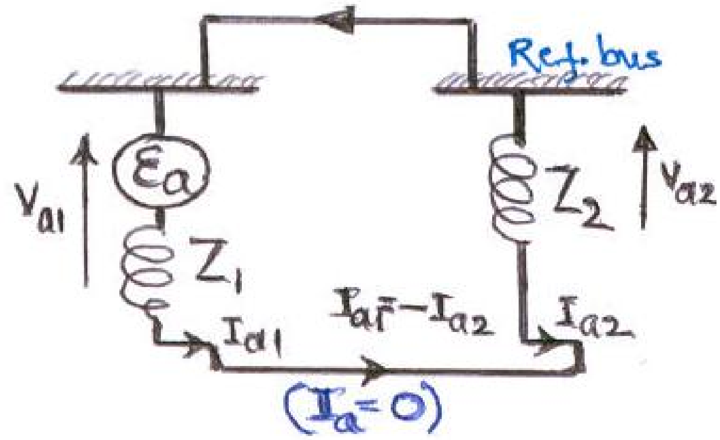


Figure 4.4 Connection of sequence networks for LL Fault on phases b & c of a Conventional Generator

The equation (4.14) derived as above implies that the three sequence networks are connected such that the zero sequence network is absent and only the positive and negative sequence networks are connected in series-opposition to simulate the LL fault, as shown in figure 4.4. Further we have the following relations satisfied under the fault conditions:

1. $I_{a1} = -I_{a2} = [E_a/(Z_1 + Z_2)]$ and $I_{a0} = 0$,
2. Fault current $\mathbf{I_f = I_b = -I_c = [\sqrt{3}E_a/(Z_1 + Z_2)]}$ (since $I_b = (a^2-a)I_{a1} = \sqrt{3}I_{a1}$)
3. $V_{a1} = E_a - I_{a1}Z_1 = E_aZ_2/(Z_1+Z_2)$
4. $V_{a2} = V_{a1} = E_aZ_2/(Z_1+Z_2)$
5. $V_{a0} = 0$,
6. Fault phase voltages; $V_b = V_c = aV_{a1}+a^2V_{a2}+V_{a0} = (a+a^2)V_{a1} = -V_{a1}$
7. Sound phase voltage; $Va = V_{a1}+V_{a2}+V_{a0} = 2V_{a1}$;
8. Fault phase powers are $V_bI_b^*$ and $V_cI_c^*$,
9. Sound phase power: $V_aI_a^* = 0$,

10. Since I_{a0}=0, the presence of absence of neutral impedance does not make any difference in the analysis.

4.4 DOUBLE LINE TO GROUND FAULT ON A CONVENTIONAL GENERATOR

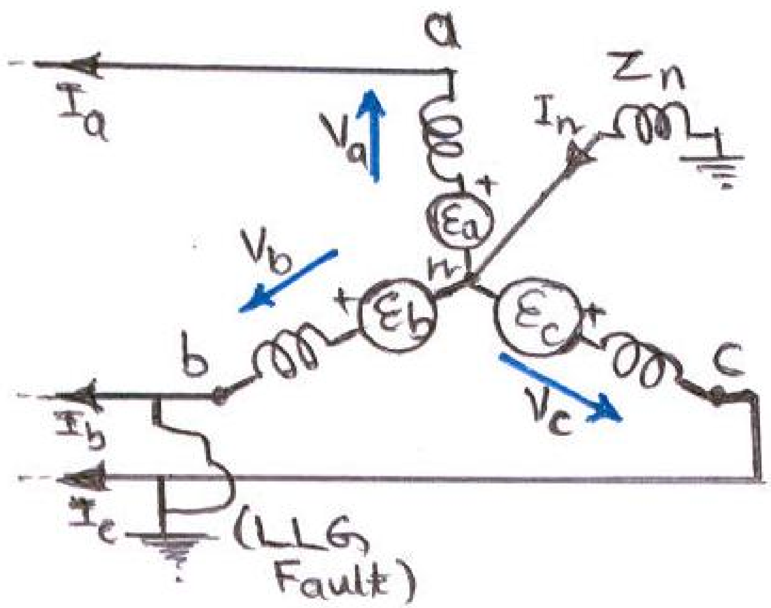


Figure 4.5 LLG Fault on a Conventional Generator

Consider a double-line to ground fault at the terminals of a conventional unloaded generator, whose neutral is grounded through a reactance, between phase 'b' and phase 'c' as shown in figure 4.5, Consider now the conditions under fault as under:

c.u.f.:

$$I_a = 0 \text{ and } V_b = V_c = 0 \qquad (4.15)$$

Now consider the symmetrical components of the voltage with V_b=V_c=0, given by:

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = (1/3) \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} V_a \\ 0 \\ 0 \end{vmatrix} \qquad (4.16)$$

Solving (4) we get,

$$V_{a1} = V_{a2} = V_{a0} = V_a/3 \qquad (4.17)$$

Consider now the sequence equations (4.2) as under,

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = \begin{vmatrix} 0 \\ E_a \\ 0 \end{vmatrix} - \begin{vmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{vmatrix} \begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} \qquad (4.18)$$

Pre-multiplying equation (4.18) throughout by

$$Z^{-1} = \begin{matrix} 1/Z_0 & 0 & 0 \\ 0 & 1/Z_1 & 0 \\ 0 & 0 & 1/Z_2 \end{matrix} \qquad (4.19)$$

We get,

$$Z^{-1}\begin{vmatrix} V_{a1} \\ V_{a1} \\ V_{a1} \end{vmatrix} = Z^{-1}\begin{vmatrix} 0 \\ E_a \\ 0 \end{vmatrix} - Z^{-1}\begin{vmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{vmatrix}\begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} \qquad (4.20)$$

Using the identity: $V_{a1}= (E_a - I_{a1}Z_1)$ in equation (4.19), pre-multiplying throughout by [1 1 1] and finally adding, we get,

$$E_a/Z_0 - I_{a1}(Z1/Z_0) + (E_a/Z_1) - I_{a1} + E_a/Z_2 - I_{a1}(Z1/Z_2) = (E_a/Z_1) - (I_{a0}+I_{a1}+I_{a2})$$

$$= (E_a/Z_1) - I_a \qquad = (E_a/Z_1) \qquad (4.21)$$

Since $I_a = 0$, solving the equation (4.21), we get,

$$\mathbf{I_{a1} = \{ E_a/ [Z_1 + Z_2Z_0/(Z_2+Z_0)] \}} \qquad (4.22)$$

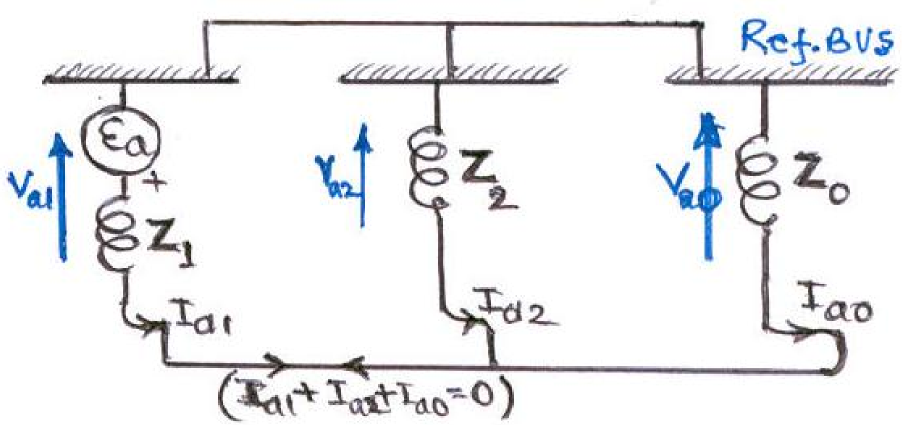


Figure4.6 Connection of sequence networks for LLG Fault on phases b and c of a Conventional Generator

The equation (4.22) derived as above implies that, to simulate the LLG fault, the three sequence networks are connected such that the positive network is connected in series with the parallel combination of the negative and zero sequence networks, as shown in figure 4.6. Further we have the following relations satisfied under the fault conditions:

1. $I_{a1} = \{E_a/ [Z_1+Z_2Z_0/(Z_2+Z_0)]\}$; $I_{a2}= -I_{a1}Z_0/(Z_2 + Z_0)$ and $I_{a0} = -I_{a1}Z_2/(Z_2 + Z_0)$,
2. Fault current I_f: $I_{a0}=(1/3)(I_a+I_b+I_c) = (1/3)(I_b+I_c) = I_f/3$, Hence $\mathbf{I_f = 3I_{a0}}$
3. $I_a = 0$, $V_b=V_c=0$ and hence $V_{a1}=V_{a2}=V_{a0}=V_a/3$
4. Fault phase voltages; $V_b = V_c = 0$
5. Sound phase voltage; $Va = V_{a1}+V_{a2}+V_{a0} = 3V_{a1}$;
6. Fault phase powers are $V_bI_b^* = 0$, and $V_cI_c^* = 0$, since $V_b=V_c=0$

7. Healthy phase power: $V_a I_a^* = 0$, since $I_a=0$
8. If $Z_0=\infty$, (i.e., the ground is isolated), then $I_{a0}=0$, and hence the result is the same as that of the LL fault [with $Z_0=\infty$, equation (4.22) yields equation (4.14)].

4.5 THREE PHASE TO GROUND FAULT ON A CONVENTIONAL GENERATOR

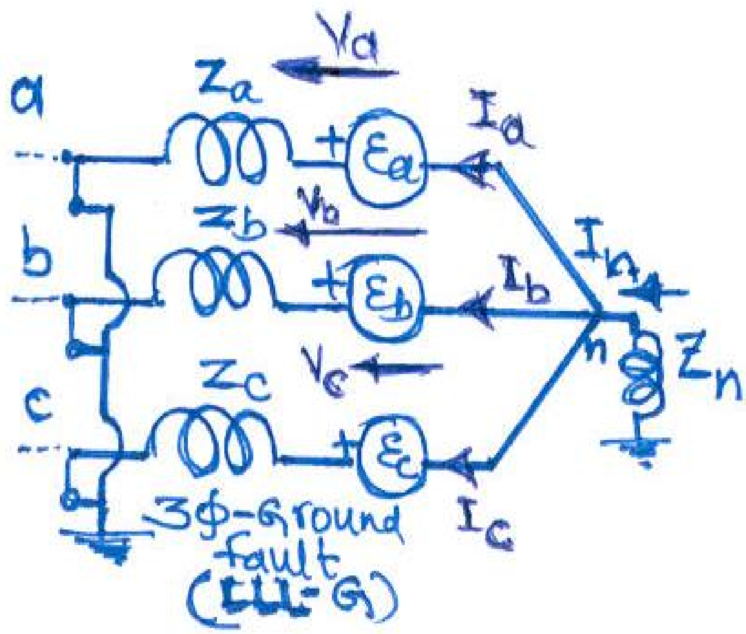


Figure 4.7 Three phase ground Fault on a Conventional Generator

Consider a three phase to ground (LLLG) fault at the terminals of a conventional unloaded generator, whose neutral is grounded through a reactance, between all its three phases a, b and c, as shown in figure 4.7, Consider now the conditions under fault as under:

c.u.f.:

$$V_a = V_b = V_c = 0, \quad I_a + I_b + I_c = 0 \tag{4.23}$$

Now consider the symmetrical components of the voltage with $V_a=V_b=V_c= 0$, given by:

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = (1/3) \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} 0 \\ 0 \\ 0 \end{vmatrix} \tag{4.24}$$

Solving (4.24) we get,

$$V_{a1} = V_{a2} = V_{a0} = 0 \tag{4.25}$$

Thus we have

$$V_{a1} = E_{a1} - I_{a1}Z_1 \tag{4.26}$$

So that after solving for I_{a1} we, get,

$$\mathbf{I_{a1} = [\ E_a / Z_1\ ]} \tag{4.27}$$

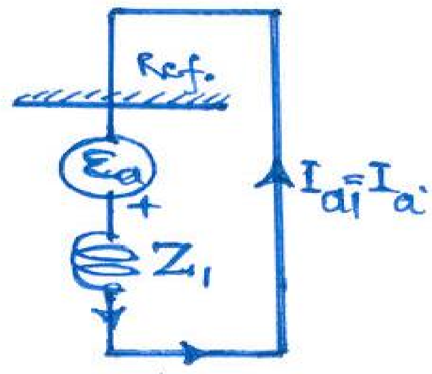


Figure 4.8 Connection of sequence networks for 3-phase ground Fault on phases b and c of a Conventional Generator

The equation (4.26) derived as above implies that, to simulate the 3-phase ground fault, the three sequence networks are connected such that the negative and zero sequence networks are absent and only the positive sequence network is present, as shown in figure 4.8. Further the fault current, I_f in case of a 3-phase ground fault is given by

$$\mathbf{I_f = I_{a1} = I_a = (E_a/Z_1)} \tag{4.28}$$

It is to be noted that the presence of a neutral connection without or with a neutral impedance, Z_n will not alter the simulated conditions in case of a three phase to ground fault.

4.6 UNSYMMETRICAL FAULTS ON POWER SYSTEMS

In all the analysis so far, only the fault at the terminals of an unloaded generator have been considered. However, faults can also occur at any part of the system and hence the power system fault at any general point is also quite important. The analysis of unsymmetrical fault on power systems is done in a similar way as that followed thus far for the case of a fault at the terminals of a generator. Here, instead of the sequence impedances of the generator, each and every element is to be replaced by their corresponding sequence impedances and the fault is analyzed by suitably connecting them together to arrive at the Thevenin equivalent impedance if that given sequence. Also, the internal voltage of the generators of the equivalent circuit for the positive sequence network is now V_f (and not E_a), the pre-fault voltage to neutral at the point of fault (PoF) (ref. Figure 4.9).

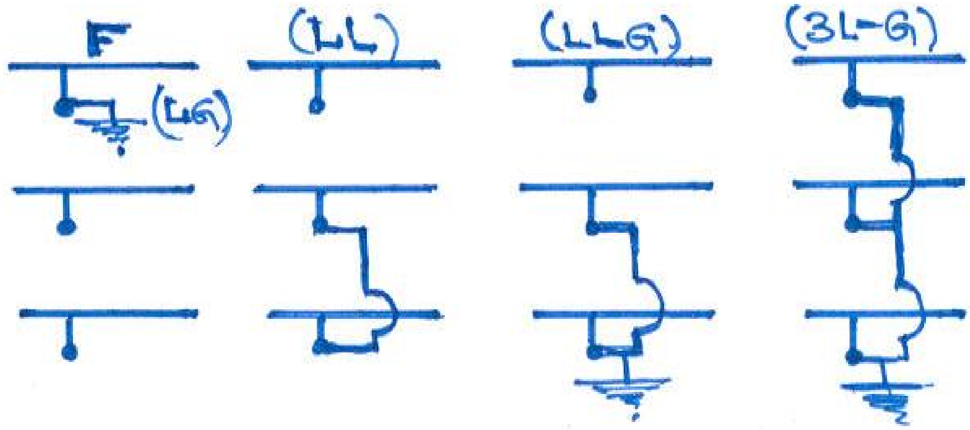


Figure 4.9 Unsymmetrical faults in Power Systems

Thus, for all the cases of unsymmetrical fault analysis considered above, the sequence equations are to be changed as under so as to account for these changes:

$$\begin{vmatrix} V_{a0} \\ V_{a1} \\ V_{a2} \end{vmatrix} = \begin{vmatrix} 0 \\ V_f \\ 0 \end{vmatrix} - \begin{vmatrix} Z_0 & 0 & 0 \\ 0 & Z_1 & 0 \\ 0 & 0 & Z_2 \end{vmatrix} \begin{vmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{vmatrix} \tag{4.29}$$

(i) LG Fault at any point F of a given Power system

Let phase 'a' be on fault at F so that then, the c.u.f. would be:

$I_b = 0$; $I_c = 0$; and $V_a = 0$.

Hence the derived conditions under fault would be:

$I_{a1} = I_{a2} = I_{a0} = (I_a/3)$

$I_{a1} = [V_f / (Z_1 + Z_2 + Z_0)]$ and

$I_f = 3I_{a1}$ (4.30)

(ii) LL Fault at any point F of a given Power system

Let phases 'b' and 'c' be on fault at F so that then, the c.u.f. would be:

$I_a = 0$; $I_b = - I_c$; and $V_b = V_c$

Hence the derived conditions under fault would be:

$V_{a1} = V_{a2}$; $I_{a0} = 0$; $I_{a2} = -I_{a1}$

$I_{a1} = [V_f / (Z_1 + Z_2)]$ and

$I_f = I_b = - I_c = [\sqrt{3}\, V_f / (Z_1 + Z_2)]$ (4.31)

(ii) LLG Fault at any point F of a given Power system

Let phases 'b' and 'c' be on fault at F so that then, the c.u.f. would be:

$I_a = 0$ and $V_b = V_c = 0$

Hence the derived conditions under fault would be:

$V_{a1} = V_{a2} = V_{a0} = (V_a/3)$

$I_{a1} = \{V_f / [Z_1+Z_2Z_0/(Z_2+Z_0)]\}$

$I_{a2}= -I_{a1}Z_0/(Z_2 + Z_2)$; $I_{a0} = -I_{a1}Z_2/(Z_2 + Z_2)$ and
$\mathbf{I_f = 3I_{a0}}$ (4.32)

(ii) Three Phase Fault at any point F of a given Power system

Let all the 3 phases a, b and c be on fault at F so that then, the c.u.f. would be:

$V_a = V_b = V_c = 0$, $I_a + I_b + I_c = 0$

Hence the derived conditions under fault would be:

$V_{a1} = V_{a2} = V_{a0} = V_a/3$

$V_{a0} = V_{a1} = V_{a2} = 0$; $I_{a0} = I_{a2} = 0$,

$I_{a1} = [V_f /Z_1]$ and $I_f = I_{a1}=I_a$ (4.33)

4.7 OPEN CONDUCTOR FAULTS

Various types of power system faults occur in power systems such as the *shunt type faults* (LG, LL, LLG, LLLG faults) and *series type faults* (open conductor and cross country faults). While the symmetrical fault analysis is useful in determination of the rupturing capacity of a given protective circuit breaker, the unsymmetrical fault analysis is useful in the determination of relay setting, single phase switching and system stability studies.

When one or two of a three-phase circuit is open due to accidents, storms, etc., then unbalance is created and the asymmetrical currents flow. Such types of faults that come in series with the lines are refered as the *open conductor faults*. The open conductor faults can be analyzed by using the sequence networks drawn for the system under consideration as seen from the point of fault, F. These networks are then suitably connected to simulate the given type of fault. The following are the cases required to be analyzed (ref. fig.4.10).

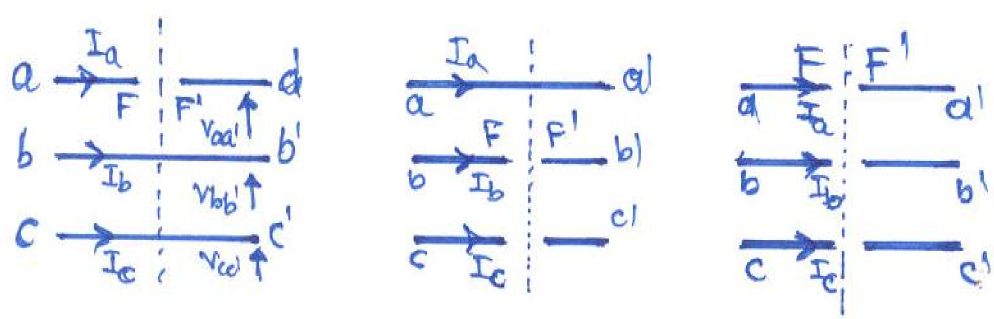


Figure 4.10 Open conductor faults.

(i) Single Conductor Open Fault: consider the phase 'a' conductor open so that then the conditions under fault are:

$I_a = 0$; $V_{bb'} = V_{cc'} = 0$

The derived conditions are:

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

$V_{aa1'} = V_{aa2'} = V_{aa0'} = (V_{aa'}/3)$ (4.34)

These relations suggest a parallel combination of the three sequence networks as shown in fig. 4.11.

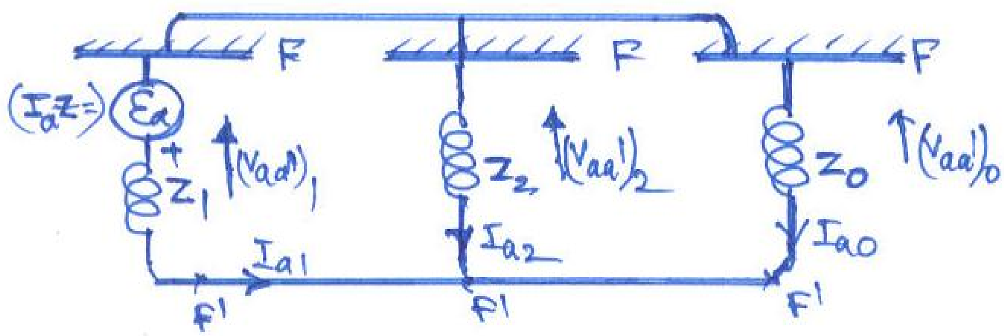


Figure 4.11 Sequence network connection for 1-conductor open fault

It is observed that a single conductor fault is similar to a LLG fault at the fault point F of the system considered.

(ii) Two Conductor Open Fault: consider the phases 'b' and 'c' under open condition so that then the conditions under fault are:

$I_b = I_c = 0$; $V_{aa'} = 0$

The derived conditions are:

$I_{a1} = I_{a2} = I_{a0} = I_a/3$ and

$V_{aa1'} = V_{aa2'} = V_{aa0'} = 0$ (4.35)

These relations suggest a series combination of the three sequence networks as shown in fig. 4.12. It is observed that a double conductor fault is similar to a LG fault at the fault point F of the system considered.

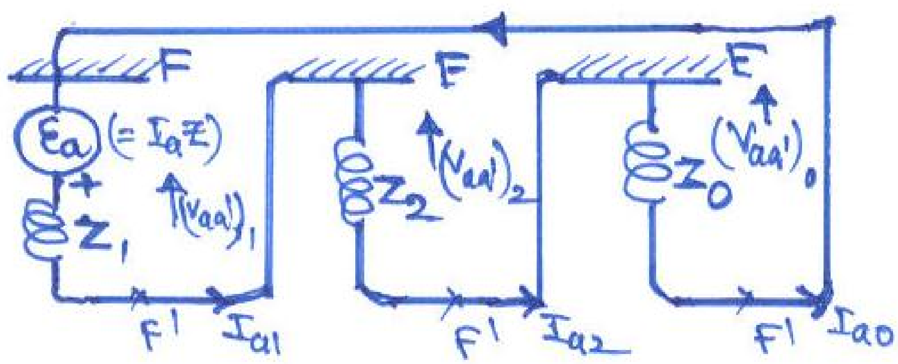


Figure 4.12 Sequence network connection for 2-conductor open fault.

(iii) Three Conductor Open Fault: consider all the three phases a, b and c, of a 3-phase system conductors be open. The conditions under fault are:

$I_a + I_b + I_c = 0$

The derived conditions are:

$I_{a1} = I_{a2} = I_{a0} = 0$ and

$V_{a0} = V_{a2} = 0$ and $V_{a1} = V_f$ (4.36)

These relations imply that the sequence networks are all open circuited. Hence, in a strict analytical sense, this is not a fault at all!

4.8 FAULTS THROUGH IMPEDANCE

All the faults considered so far have comprised of a direct short circuit from one or two lines to ground. The effect of impedance in the fault is found out by deriving equations similar to those for faults through zero valued neutral impedance. The connections of the hypothetical stubs for consideration of faults through fault impedance Z_f are as shown in figure 4.13.

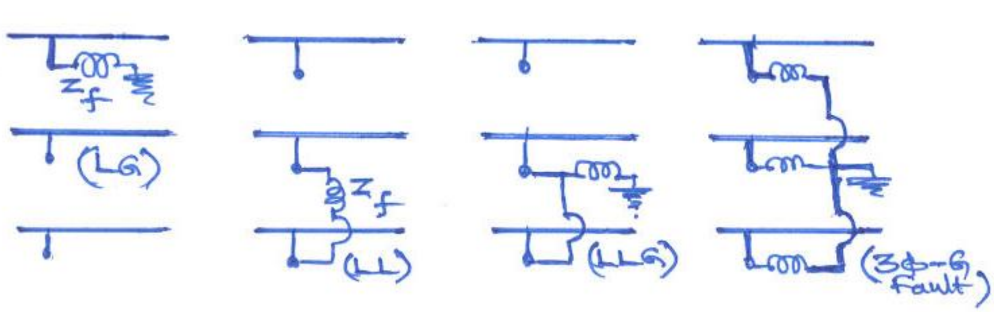


Figure 4.13 Stubs Connections for faults through fault impedance Z_f.

(i) LG Fault at any point F of a given Power system through Z_f

Let phase 'a' be on fault at F *through Z_f*, so that then, the c.u.f. would be:

$I_b = 0$; $I_c = 0$; and $V_a = 0$.

Hence the derived conditions under fault would be:

$I_{a1} = I_{a2} = I_{a0} = (I_a/3)$

$I_{a1} = [V_f / (Z_1 + Z_2 + Z_0+3Z_f)]$ and

$I_f = 3I_{a1}$ (4.37)

(ii) LL Fault at any point F of a given Power system through Z_f

Let phases 'b' and 'c' be on fault at F *through Z_f*, so that then, the c.u.f. would be:

$I_a = 0$; $I_b = - I_c$; and $V_b = V_c$

Hence the derived conditions under fault would be:

$V_{a1} = V_{a2}$; $I_{a0} = 0$; $I_{a2} = -I_{a1}$

$I_{a1} = [V_f / (Z_1 + Z_2+Z_f)]$ and

$I_f = I_b = - I_c = [\sqrt{3}\, V_f / (Z_1 + Z_2+Z_f)]$ (4.38)

(iii) LLG Fault at any point F of a given Power system through Z_f

Let phases ‘b’ and ‘c’ be on fault at F *through Z_f,* so that then, the c.u.f. would be:

$I_a = 0$ and $V_b = V_c = 0$

Hence the derived conditions under fault would be:

$V_{a1} = V_{a2} = V_{a0} = (V_a/3)$

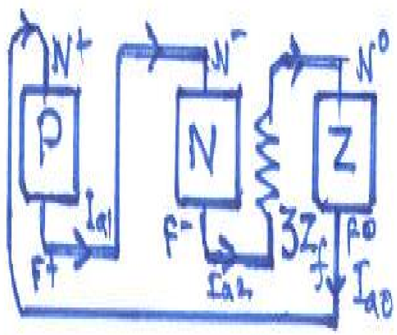
$I_{a1} = \{V_f / [Z_1+Z_2(Z_0+3Z_f)/(Z_2+Z_0+3Zf)]\}$

$I_{a2}= -I_{a1}(Z_0+3Z_f)/(Z_2+Z_0+3Z_f)$; $I_{a0} = -I_{a1}Z_2/(Z_2+(Z_0+3Z_f)$ and

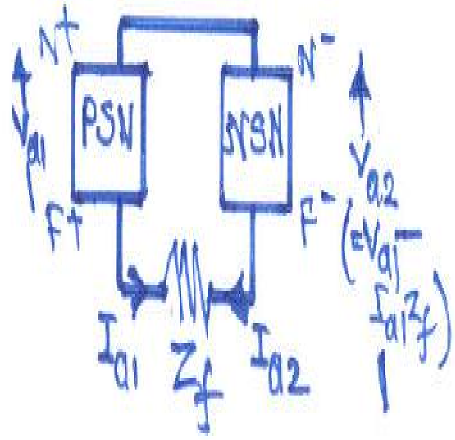
$\mathbf{I_f = 3I_{a0}}$ (4.39)

(iv) Three Phase Fault at any point F of a given Power system through Z_f

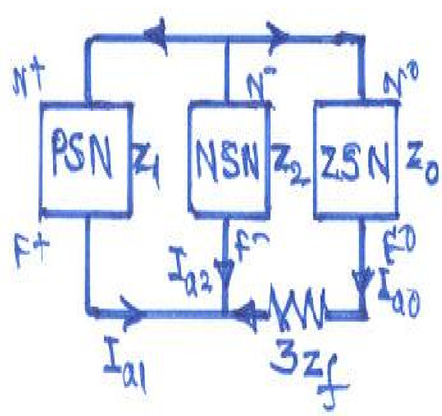
Let all the 3 phases a, b and c be on fault at F, through Z_f so that the c.u.f. would be: $V_a = I_aZ_f$; Hence the derived conditions under fault would be: $I_{a1} = [V_f /(Z_1+Z_f)$; The connections of the sequence networks for all the above types of faults through Z_f are as shown in figure 4.14.



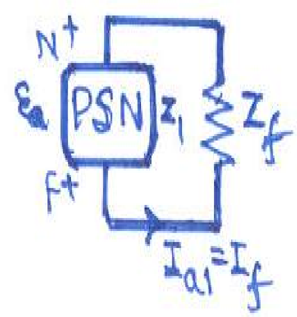
LG Fault



LL Fault



LLG Fault



3-Ph. Fault

Figure 4.15 Sequence network connections for faults through impedance

4.9 EXAMPLES

Example-1: A three phase generator with constant terminal voltages gives the following currents when under fault: 1400 A for a line-to-line fault and 2200 A for a line-to-ground fault. If the positive sequence generated voltage to neutral is 2 ohms, find the reactances of the negative and zero sequence currents.

Solution: Case a) Consider the conditions w.r.t. the LL fault:

$I_{a1} = [E_{a1}/(Z_1 + Z_2)]$

$I_f = I_b = - I_c = \sqrt{3}\, I_{a1}$

$= \sqrt{3}\, E_{a1} / (Z_1 + Z_2)$ or

$(Z_1 + Z_2) = \sqrt{3}\, E_{a1} / I_f$

i.e., $2 + Z_2 = \sqrt{3}\, [2000/1400]$

Solving, we get, $Z_2 = 0.474$ ohms.

Case b) Consider the conditions w.r.t. a LG fault:

$I_{a1} = [E_{a1}/(Z_1 + Z_2+Z_0)]$

$I_f = 3\, I_{a1}$

$= 3\, E_{a1} / (Z_1 + Z_2+Z_0)$ or

$(Z_1 + Z_2+Z_0) = 3\, E_{a1} / I_f$

i.e., $2 + 0.474 + Z_0 = 3\, [2000/2200]$

Solving, we get, $Z_0 = 0.253$ ohms.

Example-2: A dead fault occurs on one conductor of a 3-conductor cable supplied y a 10 MVA alternator with earhed neutral. The alternator has +ve, -ve and 0-sequence components of impedances per phase respectively as: (0.5+j4.7), (0.2+j0.6) and (j0.43) ohms. The corresponding LN values for the cable up to the point of fault are: (0.36+j0.25), (0.36+j0.25) and (2.9+j0.95) ohms respectively. If the generator voltage at no load (E_{a1}) is 6600 volts between the lines, determine the (i)Fault current, (ii)Sequence components of currents in lines and (iii)Voltages of healthy phases.

Solution: There is LG fault on any one of the conductors. Consider the LG fault to be on conductor in phase a. Thus the fault current is given by:

(i) Fault current: $I_f = 3I_{a0} = [3E_a/(Z_1 + Z_2 + Z_0)]$

$= 3(6600/\sqrt{3})/ (4.32+j7.18)$

$= 1364.24 \angle 58.97^0$.

(ii) Sequence components of line currents:

$I_{a1} = I_{a2} = I_{a0} = I_a/3 = I_f/3 = 454.75 \angle 58.97^0$.

(iii) Sound phase voltages:

$V_{a1} = E_a - I_{a1}Z_1 = E_a(Z_2+Z_0)/(Z_1+Z_2+Z_0) = 1871.83 \angle -26.17^0$,
$V_{a2} = - E_aZ_2/(Z_1+Z_2+Z_0) = 462.91 \angle 177.6^0$,
$V_{a0} = - E_aZ_0/(Z_1+Z_2+Z_0) = 1460.54 \angle 146.5^0$,

Thus,

Sound phase voltages $V_b = a^2V_{a1}+aV_{a2}+V_{a0} = 2638.73 \angle -165.8^0$ Volts,
And $V_c = aV_{a1}+a^2V_{a2}+V_{a0} = 3236.35 \angle 110.8^0$ Volts.

Example-3: A generator rated 11 kV, 20 MVA has reactances of X_1=15%, X_2=10% and X_0=20%. Find the reactances in ohms that are required to limit the fault current to 2 p.u. when a a line to ground fault occurs. Repeat the analysis for a LLG fault also for a fault current of 2 pu.

<u>Solution:</u> **Case a:** Consider the fault current expression for LG fault given by:

$I_f = 3\ I_{a0}$

i.e., $2.0 = 3Ea / j[X_1+X_2+X_0]$

$= 3(1.0\angle 0^0) / j[0.15+0.1+0.2+3X_n]$

Solving we get

$3X_n = 2.1$ pu

$= 2.1\ (Z_b)$ ohms $= 2.1\ (11^2/20) = 2.1(6.05)$

$= 12.715$ ohms.

Thus $X_n = 4.235$ ohms.

Case b: Consider the fault current expression for LLG fault given by:

$\mathbf{I_f = 3I_{a0} = 3\ \{} -I_{a1}X_2/(X_2 + X_0+3X_n)\}= 2.0$,

where, $I_{a1} = \{E_a/ [X_1+X2(X0+3X_n)/(X_2+X_0+3X_n)]\}$

Substituting and solving for X_n we get,

Xn = 0.078 pu
= 0.47 ohms.

Example-4: A three phase 50 MVA, 11 kV generator is subjected to the various faults and the surrents so obtained in each fault are: 2000 A for a three phase fault; 1800 A for a line-to-line fault and 2200 A for a line-to-ground fault. Find the sequence impedances of the generator.

<u>Solution:</u> Case a) Consider the conditions w.r.t. the three phase fault:

$I_f = I_a = I_{a1} = E_{a1}/Z_1$

i.e., $2000 = 11000/ (\sqrt{3}Z_1)$

Solving, we get, $Z_1 = 3.18$ ohms (1.3 pu, with $Z_b = (11^2/50) = 2.42$ ohms).

Case b) Consider the conditions w.r.t. the LL fault:

$I_{a1} = [E_{a1}/(Z_1 + Z_2)]$

$I_f = I_b = - I_c = \sqrt{3}\, I_{a1}$

$= \sqrt{3}\, E_{a1} / (Z_1 + Z_2)$ or

$(Z_1 + Z_2) = \sqrt{3}\, E_{a1} / I_f$

i.e., $3.18 + Z_2 = \sqrt{3}\, (11000/\sqrt{3})/1800$

Solving, we get, $Z_2 = 2.936$ ohms = 1.213 pu.

Case c) Consider the conditions w.r.t. a LG fault:

$I_{a1} = [E_{a1}/(Z_1 + Z_2+Z_0)]$

$I_f = 3\, I_{a1}$

$= 3\, E_{a1} / (Z_1 + Z_2+Z_0)$ or

$(Z_1 + Z_2+Z_0) = 3\, E_{a1} / I_f$

i.e., $3.18+ 2.936 + Z_0 = 3\, (11000/\sqrt{3})/ 2200$

Solving, we get, $Z_0 = 2.55$ ohms = 1.054 pu.