5.1 Introduction:

The concept of faults has been already introduced in chapter 2 which was dedicated to the treatment of symmetrical faults. In this chapter, we shall deal with unsymmetrical faults. The unsymmetrical faults are basically categorized into two types, namely,

1)Shunt type of faults and

2)Series type of faults.

Shunt type of fault involves short circuit between conductors or between the conductors and ground. They are characterized by an increase in current and fall in voltage and frequency in the faulted phase. Shunt type of faults are in turn classified as:

1)Single line to ground (LG) fault

2)Line to line (LL) fault

3)Double line to ground (LLG) fault.

When one or two lines in a thee phase system get opened while other lines or line remain intact, such faults are called as series type of faults. They are characterized by increase in voltage and frequency and fall in current in the faulted phase series type of faults cab be grouped as:

1)One conductor open fault

2)Two conductor open fault

We will individually consider each of these faults in this chapter. Before that, let us look into the typical relative frequencies of different kinds of faults in a power system in order of decreasing severity.

Symmetrical faults (3L) -5%

Double line to ground (LLG) faults -10%

Double line (LL) faults -15%

Single line to ground (LG) fault- 70%

It can be observed that three phase faults (3L) has the maximum severity, though its occurrence is infrequent. Hence the rapturing capacity of circuit breakers are calculated on the basis of a three phase symmetrical fault. However, for relay setting, single phase switching and performing the system stability studies, the analysis of unsymmetrical faults are very important. Since any unsymmetrical fault causes unbalanced currents to flow in the system, the method of symmetrical components is very useful in an analysis to determine the currents and voltages in all parts of the system after the occurrence of the fault. Also the sequence networks of the system will come quite handy in this process. First, we shall discuss fault at the terminals of an unloaded synchronous generator. Then, we shall consider faults on a power system by applying Thevenin's theorem, which allows us to find the current in the fault by replacing the entire system by a single generator (voltage source) and series impedance.

5.2 Fault calculations of synchronous generator.

Consider a balanced three phase synchronous generator (alternator), which is subjected to some unsymmetrical fault F at the terminal, as shown in fig 5.1.

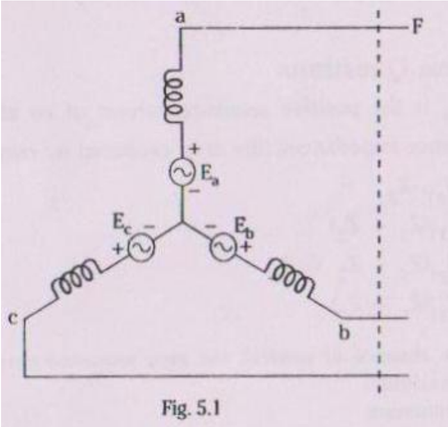

Fig. 5.1

The fault may be unsymmetrical one. But to the left of the fault point F, the system (alternator) is completely symmetrical. Hence, in such a system, currents of a given sequence produce voltage drops of the same sequence only. The sequence impedances are uncoupled. Since the generates balanced voltages only (positive sequence voltages only), the following equations are applicable to a synchronous generator, even during an unsymmetrical fault.

$V_{a1}=E_a-I_{a1}. Z_1$ 5.1

$V_{a2}=-I_{a2}. Z_2$ 5.2

$V_{a0}=-I_{a0}.Z_0$ 5.3

These equations cab be called the system equations. For any fault at the terminals of synchronous generator, the quantities that are to be determined are the three sequence currents (I_{a1}, I_{a2}, I_{a0}) and the three sequence terminal voltages (V_{a1}, V_{a2}, V_{a0}). Out of the six unknowns, only three quantities are linearly independent. Hence to determine these three linearly independent quantities, three terminal conditions are to be specified for any type of fault at the terminals of the generator.

Before proceeding to the analysis of faults at the terminals of an unloaded generator, it is good enough to remember that the single phase representation of the positive sequence network of a synchronous generator consists of positive sequence generated emf E_{a1} in series with positive sequence impedance Z_1(fig 4.5b). The negative sequence network consists of negative sequence impedance Z_2 with no negative sequence generated voltage (fig 4.6b). The zero sequence network consists of zero sequence impedance Z_0 with no zero sequence generated voltage (fig 4.7b).

5.2.1 Single line to ground (LG) fault on an unloaded generator:

The circuit diagram for an LG fault on an unloaded star connected generator with its neutral grounded through a reactance is shown in fig 5.2. Here it is assumed that phase a is shorted to ground directly. The condition at the fault are represented by the following terminal conditions.

Terminal conditions:

$V_a=0$ 5.4

$I_b=0$ 5.5

$I_c=0$ 5.6

These three terminal conditions in terms of line currents and phase voltage are to be transformed to conditions in terms of symmetrical components.

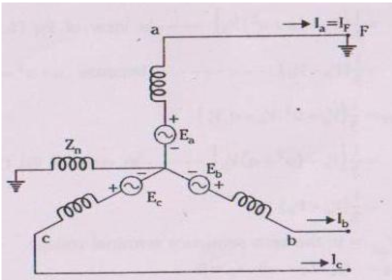

Fig. 5.2

Symmetrical components relations:

Since two conditions are available regarding the line currents, it is convenient to transform them to conditions in terms of symmetrical components.

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

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

$I_{a2}=(1/3)(I_a+a^2.I_b+a.I_c)=(1/3)(I_a+0+0)=(1/3).I_a$

so $I_{a1}=I_{a2}=I_{a0}=(1/3).I_a$ 5.7

The terminal conditions $V_a=0$ gives,

$V_{a0}+V_{a1}+V_{a2}=0$ 5.8

As per eq. 5.7, all sequence currents are equal and as per eq. 5.8, the sum of sequence voltage equals zero. Therefore, these equations suggest a series connection of sequence networks through a short circuit as shown in fig 5.3.

Interconnection of sequence networks:

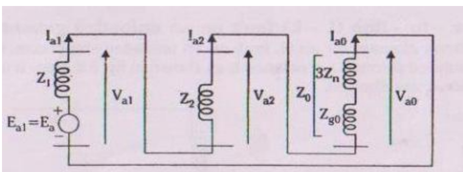

Fig. 5.3

Sequence quantities:

The following relations can be directly obtained from fig 5.3

$I_{a1}=I_{a2}=I_{a0}=E_a / (Z_1+Z_2+Z_0)$ 5.9

$V_{a1}=E_{a1} - I_{a1}.Z_1= E_a - (E_a/(Z_1+Z_2+Z_0)).Z_1$

$=E_a((Z_2+Z_0) / (Z_1+Z_2+Z_0))$ 5.10

$V_{a2}=-I_{a2}.Z_2= -(E_a.Z_2 /(Z_1+Z_2+Z_0))$ 5.11

$V_{a0}= -I_{a0}.Z_0 = -(E_a.Z_0 /(Z_1+Z_2+Z_0))$ 5.12

Fault current;

The fault current If in this case is equal to the current in phase a i.e I_a. Hence the fault current is given as,

$I_f=I_a=3.I_{a0}$ ....in view of eq. 5.7

$=3(E_a /(Z_1+Z_2+Z_0))$ 5.13

In case the neutral of the generator is not grounded, then

$Z_0=Z_g0+3Z_n=Z_{g0}+\infty=\infty$. Therefore, the fault current in such a condition is,

$If=3(E_a /(Z_1+Z_2+\infty)=0$ 5.14

Thus, it can be inferred that fault current in the system is zero if the neutral is not grounded in the case of an LG fault.

5.2.2 Line to line (L-L) fault on an unloaded generator:

The circuit diagram for an LL fault on an unloaded star connected generator with its neutral grounded through a reactance is as shown in fig 5.4. Here it is assumed that phase b and phase c are shorted.

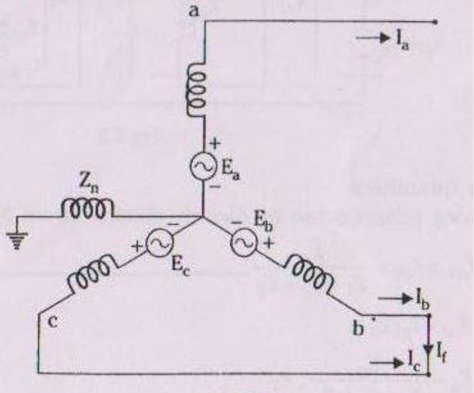

Fig. 5.4

Terminal conditions:

The condition at the fault are expressed by the following terminal conditions:

$I_a=0$ 5.15

$I_b+I_c=0$ i.e. $I_c= -I_b$ 5.16

$V_b=V_c$ 5.17

Symmetrical components relations:

Since there are two conditions regarding current, analysing them first, we get

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

$=(1/3)(0+I_b-I_b)$

$=0$ ....in view of eq. 5.16

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

$=(1/3)(0+a.I_b-a^2.I_b)$

$=(1/3)(a-a^2).I_b$

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

$=(1/3)(0+a^2.I_b-a.I_b)$

$=(1/3)(a^2-a).I_b$

So, we have,

$I_{a0}=0$ 5.18

$I_{a2}= -I_{a1}$ 5.19

Regarding sequence terminal voltages,

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

$=(1/3)(V_a+(a+a^2)V_b)$ ....in view of eq. 5.17

$=(1/3)(V_a-V_b)$ ....because $a+a^2= -1$

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

$=(1/3)(V_a+(a^2+a)V_a)$ ....in view of eq.5.17

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

Since $I_{a0}=0$; the zero sequence terminal voltage

$V_{a0}= -I_{a0}.Z_0= -0.Z_0 =0$

so, we have

$V_{a0}=0$ 5.20

$V_{a1}=V_{a2}$ 5.21

Equations 5.19 and 5.21 suggest parallel connection of positive and negative sequence networks. Since $I_{a0}=V_{a0}=0$, the zero sequence networks is connected separately and shorted on itself as shown in the following diagrams.

Interconnection of sequence networks:

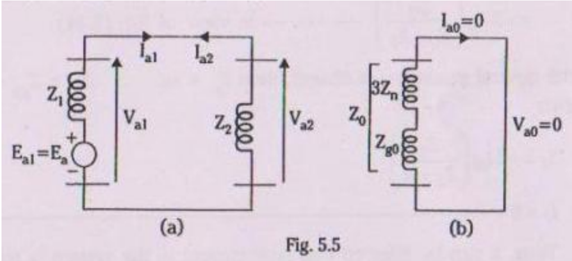

Fig. 5.5

Sequence quantities:

The following relations can be directly obtained from fig 5.5

$I_{a1}= -I_{a2} =E_a / (Z_1+Z_2)$ 5.22

$I_{a0}=V_{a0}=0$ 5.23

$V_{a1}=V_{a2}=E_a - I_{a1}.Z_1 = E_a (Z_2/Z_1+Z_2))$ 5.24

Fault current:

The fault current in this case is,

$I_f=I_b$ (or I_c)

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

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

$= -j\sqrt{3}I_{a1}$

or $|I_f|=\sqrt{3}\ I_{a1} = \sqrt{3}(E_a / (Z_1+Z_2))$ 5.25

In case the neutral is not grounded, then $Z_0=Z_{g0}+3Z_n=Z_{go}+\infty=\infty$. But since the expression for fault current is independent of the value of Z_0, the presence or absence of a grounded neutral at the generator does not affect the fault current.

5.2.3 Double line to ground (LLG) fault on an unloaded generator:

The circuit diagram for an LLG fault on an unloaded star connected alternator having grounded neutral is shown in fig 5.6. We assume that the fault takes place in phases b and c.

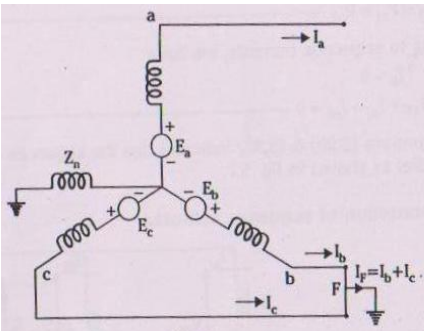

Fig. 5.6

Terminal conditions:

The conditions at the fault are expressed by the following equations:

$V_b=0$ 5.26

$V_c=0$ 5.27

$I_a=0$ 5.28

Symmetrical components relations:

Since there are the condition regarding the voltages analysing (transforming to symmetrical components) then first we get.

$V_{a0}=(1/3)(V_a+V_b+V_c)$

$=(1/3)(V_a+0+0)$

$=(1/3).V_a$

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

$=(1/3)(V_a+0+0)$

$=(1/3).V_a$

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

$=(1/3)(V_a+0+0)$

$=(1/3).V_a$

so, $V_{a0}=V_{a1}=V_{a2}$ 5.29

coming to sequence currents, we have,

$I_a=0$

i.e $I_{a0}+I_{a1}+I_{a2} = 0$ 5.30

Equations 5.29 and 5.30 indicates that the sequence networks should be connected in parallel as shown in fig. 5.7.

Interconnection of sequence networks:

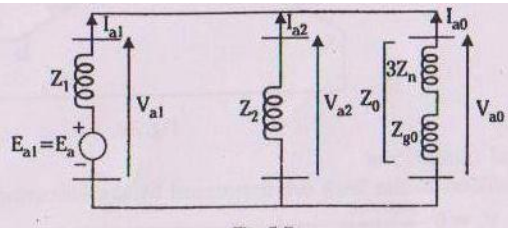

Fig. 5.7

Sequence quantities:

The following relations can be directly obtained from the fig 5.7

$V_{a1}=V_{a2}=V_{a0}=E_a=I_{a1}.Z_1$ 5.31

$I_{a1}=E_a/ [Z_1+\{Z_2Z_0/(Z_2+Z_0)\}]$ 5.32

$I_{a2}= -I_{a1}.[Z_0/(Z_2+Z_0)]$ 5.33

$I_{a0}= -I_{a1}.[Z_2/(Z_2+Z_0)]$ 5.34

Equations 5.33 and 5.34 are direct consequences of current division formula.

Fault Current:

The fault current I_f in this case is given by,

$I_f=I_b+I_c$

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

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

$=2I_{a0} - I_{a1} - I_{a2}$ because $(a+a^2)= -1$

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

It can be observed from fig 5.7 that $(I_{a1}+I_{a2})= -I_{a0}$.

Substituting this in the expression for fault current, we get

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

$=3I_{a0}$ 5.35

$=-3.I_{a1}.[Z_2/(Z_2+Z_0)]$ --------------in view of eq. 5.34

If the neutral grounding is absent, then $Z_n=\infty$.

Therefore, $Z_0=Z_{g0}+3Z_n=Z_{g0}+\infty=\infty$.

Hence,

$I_f = -3I_{a1}.[Z_2/(Z_2+\infty)]$

Therefore, $I_f=0$ 5.36

Thus, it can be inferred that fault current in the system is Zero, if the neutral is not grounded in the case of LLG fault.

5.3 Fault through impedances:

All the faults discussed in the preceding section consisted of direct short circuits between line and between one or two line to ground. In these cases, the impedance between the fault points is considered as zero. There may be situation in which the fault path includes an impedance between the faulted points. In these situation the analysis is carried similar to that of the previous section, except that the fault impedance is concluded at appropriate points in the circuits obtained by connecting sequence networks. Hence the theory is not elaborated in much detail.

5.3.1 Single line to ground (LG) 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 shown in fig 5.8.

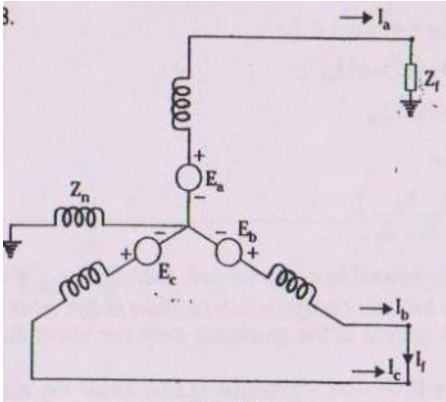

Fig. 5.8

Terminal conditions:

$V_a=I_a.Z_f$ 5.37

$I_b=0$ 5.38

$I_c=0$ 5.39

Symmetrical components relations:

The following relations can be obtained from the terminal conditions

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

$=(1/3)(I_a+0+0)$

$=(1/3).I_a$

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

$=(1/3)(I_a+0+0)$

$=(1/3).I_a$

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

$=(1/3)(I_a+0+0)$

$=(1/3).I_a$

So $I_{a1}=I_{a2}=I_{a0}=(1/3).I_a$ 5.40

The terminal condition $V_a=I_a.Z_f$ gives

$V_{a0}+V_{a1}+V_{a2}=I_a.Z_f=3.I_{a0}.Z_f$ 5.41

As per equations 5.40 and 5.41 all sequence currents are equal and the sum of sequence voltages equals $2.I_{a0}.Z_f$. Therefore, these equations suggest a series connection of sequence networks through an impedance $3.Z_f$ as shown in fig 5.9.

Interconnection of sequence networks:

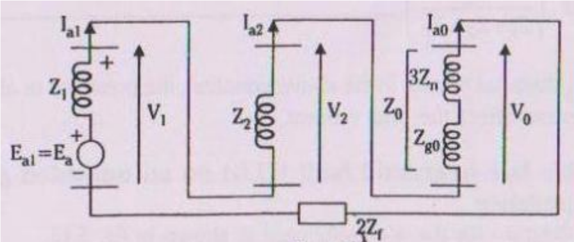

Fig. 5.9

Sequence quantities:

The following equations can be directly obtained from the fig 5.9

$I_{a0}=I_{a1}=I_{a2}=E_a / (Z_1+Z_2+Z_0+3Z_f)$ 5.42

$V_{a1}=E_a-I_{a1}.Z_1=E_a.(Z_2+Z_0+3Z_f) /(Z_1+Z_2+Z_0+3Z_f)$ 5.43

$V_{a2}= -I_{a2}.Z_2 = -E_aZ_2 / (Z_1+Z_2+Z_0+3Z_f)$ 5.44

$V_{a0}= -I_{a0}Z_0= -E_aZ_0 / (Z_1+Z_2+Z_0+3Z_f)$ 5.45

Fault current:

The fault current in this case is given as,

$I_f=I_a=3.I_{a0}=3 [E_a / (Z_1+Z_2+Z_0+3Z_f)]$ 5.46

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

i.e $Z_0=\infty$ and hence $I_f=0$.

5.3.2 Line to line (LL) fault on an unloaded generator through a fault impedance:

The circuit diagram for an LL fault on an unloaded generator through a fault impedance Zf is shown in fig 5.10.

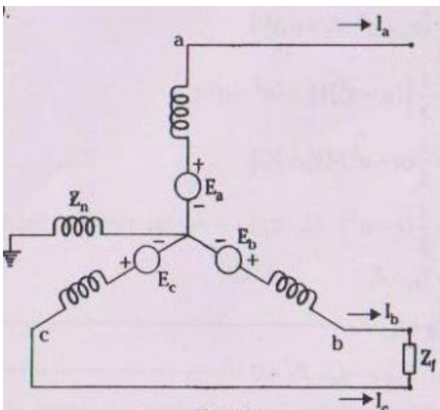

Fig. 5.10

Terminal conditions:

$I_a=0$ 5.47

$I_b+I_c=0$; $I_c=-I_b$ 5.48

$V_b=V_c+I_b.Z_f$ 5.49

Symmetrical components relations:

The following relations can be obtained from the terminal conditions

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

$=(1/3)(I_a+I_b-I_b)$

$=0$

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

$=(1/3)(0+a.I_b-a^2.I_c)$

$=(1/3)(a-a^2)I_b$

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

$=(1/3)(0+a^2 .I_b-a.I_c)$

$=(1/3)(a^2-a)I_b$

so, $I_{a0}=0$ 5.50

$I_{a1}= -I_{a2}$ 5.51

Next,

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

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

Therefore,

$V_{a1}-V_{a2}= (1/3) [(a-a^2)V_b+(a^2-a)V_c]$

$=(1/3) [(a-a^2)(V_b-V_c)]$

$=(1/3) (a-a^2)(I_b.Z_f)$ ------------in view of eq. 5.49

$= I_{a1}.Z_f$

Thus, $V_{a1}=V_{a2}+I_{a1}.Z_f$ 5.52

Since, $I_{a0}=0$, $V_{a0}= -I_{a0}.Z_0=0$ 5.53

Equations 5.51 and 5.52 suggest parallel connection of positive and negative sequence networks through a series impedance Z_f as shown in fig 5.11. Since $I_{a0}=V_{a0}=0$, the zero sequence network is connected separately through a short as shown in fig 5.12.

Interconnection sequence networks:

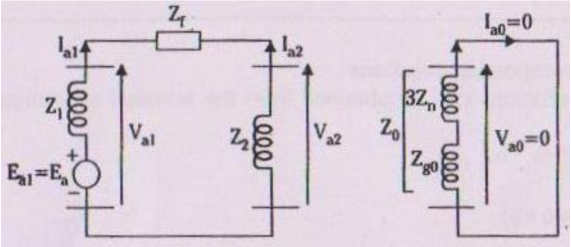

Fig. 5.11 Fig. 5.12

Sequence quantities:

The following equations can be directly obtained from the diagrams shown above.

$I_{a1}= -I_{a2} =E_a / (Z_1+Z_2+Z_f)$ 5.54

$I_{a0}=V_{a0}=0$ 5.55

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

$=E_a.(Z_2+Z_f) /(Z_1+Z_2+Z_f)$ 5.56

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

$= - E_a.Z_2 /(Z_1+Z_2+Z_f)$ 5.57

Fault current:

In this case the fault current is equal to the current in phase-b (or phase c). Hence

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

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

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

$= - j\sqrt{3}I_{a1}$

or $|I_f|=\sqrt{3}.I_{a1}$

$=\sqrt{3}.E_a / (Z_1+Z_2+Z_f)$ 5.58

Since Z_0 does not appear in the above equation, the presence or absence of a grounded neutral does not affect the fault current.

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

The circuit diagram for the aforesaid case is shown in fig 5.13

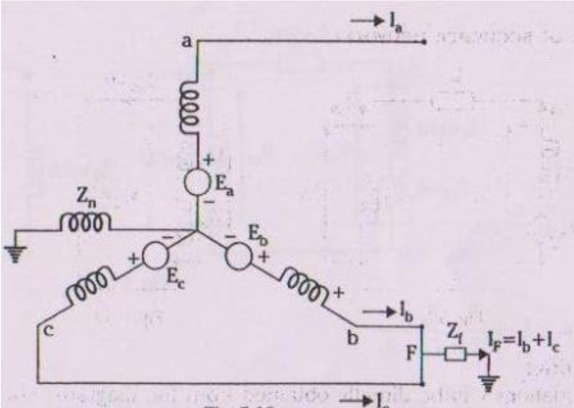

Fig. 5.13

Terminal conditions:

$I_a=0$ 5.59

$V_b=(I_b+I_c)Z_f$ 5.60

$V_c=(I_b+I_c)Z_f$ 5.61

Symmetrical component relations:

Consider,

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

$=(1/3)[(V_a+(a+a^2)V_b]$

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

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

$=(1/3)[(V_a+(a^2+a)V_b]$

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

$V_{a0}=(1/3)(V_a+V_b+V_c)$

$=(1/3)(V_a+2.V_b)$

Thus,

$V_{a1}=V_{a2}$ 5.62

$V_{a0}-V_{a2}=(1/3).3V_b$

$=V_b$

$=(I_b+I_c)Z_f$ ....from eq. 5.60

$=3.I_{a0}.Z_f$ --------This will be proved to the expression for fault current.

Thus, $V_{a0}=V_{a2}+3.I_{a0}.Z_f$ 5.63

The condition $I_a=0$ gives $I_{a0}+I_{a1}+I_{a2}=0$ 5.64

Equations 5.62 , 5.63 and 5.64 suggest the connection of sequence network as shown in fig 5.14.

Interconnection of sequence networks:

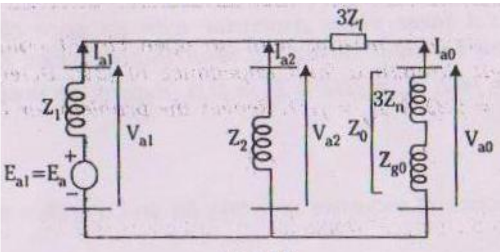

Fig. 5.14

$I_{a1} = E_a / [Z_1+\{Z_2.(3Z_f+Z_0)/(Z_2+3Z_f+Z_0)\}]$ 5.65

$I_{a2} =-I_{a1}. (Z_0+3Z_f)/(Z_0+Z_2+3Z_f)$ 5.66

$I_{a0} = -I_{a1}.Z_2/(Z_0+Z_2+3Z_f)$;using current division eq.)...........................5.67

Equations 5.66 and 5.67 are obtained from the current division fromula.

Fault current:

In this case, the fault current is given as,

$I_f=I_b+I_c$

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

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

$=2I_{a0} - I_{a1} - I_{a2}$ because $(a+a^2)= -1$

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

It can be observed from fig 5.64 that $(I_{a1}+I_{a2})= -I_{a0}$.

Substituting this in the expression for fault current, we get

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

$=3I_{a0}$ 5.68

$=-3.I_{a1}.[Z_2/(Z_0+Z_2+3Z_f)]$ --------------in view of eq. 5.69

In absence of the neutral grounding, $Z_n=\infty$. That is, $Z_0=\infty$ and Hence, $I_f=0$.

Note:

1)Instead of remembering the various results for a particular fault, it is often easier to visualize the connection of sequence networks to represent the fault and then proceed suitably.

2)The fault current in the case of faults involving ground(LG,LLG) is given as,

$I_f=3.|I_{a0}|$

3)In case of LL fault, the fault current is given as If=$\sqrt{3}.|I_{a1}|$

Example 5.1:

A three phase generator with an open circuit voltage of 400V is subjected to an LG fault through a fault impedance of j2Ω. Determine the fault current if Z_1=j4Ω, Z_2=j2Ω and Z_0=j1Ω. Repeat the problem for LL and LLG fault.

Solution:

i)LG fault:

The interconnection of sequence networks for an LG fault is shown in fig. 5.15

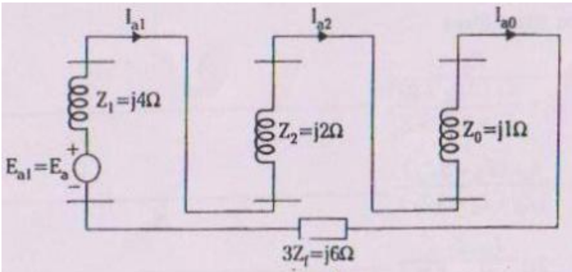

Fig. 5.15

In this case,

$I_{a1}=i_{a2}=I_{a0}=E_a / (Z_1+Z_2+Z_0+3Z_f)$

$=(400\angle 0° /\sqrt{3}) / j(4+2+1+6)$

$=-j17.765$ A

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

$=3(17.765)$

$=53.295$ A

ii)LL fault:

The interconnection of sequence networks to represent an LL fault is shown if fig 5.16.

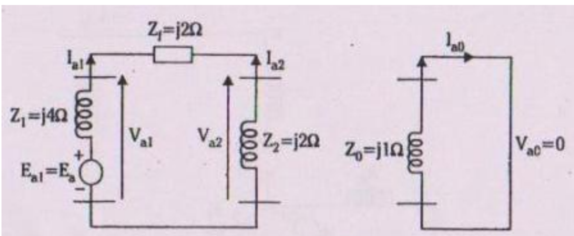

Fig. 5.16

Here, $I_{a1}=E_a / (Z_1+Z_2+Z_f)$

$=(400\angle 0° /\sqrt{3}) / j(4+2+2)$

$= -j28.87$ A

Therefore, fault current, $I_f = \sqrt{3}.|I_{a1}|$

$= \sqrt{3}(28.87)$

$= 50A.$

Iii) LLG fault:

The sequence networks are interconnected as shown in fig 5.17

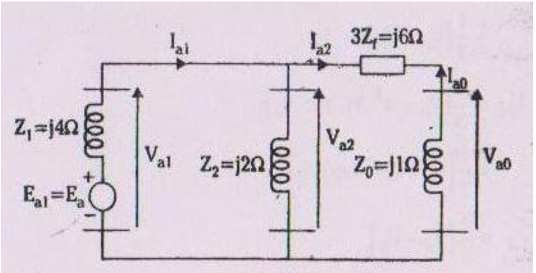

Fig. 5.17

Here, $I_{a1} = E_a / [Z_1+\{Z_2.(Z_0+3Z_f)/(Z_2+Z_0+3Z_f)\}]$

$= (400\angle 0° /\sqrt{3}) / [4+\{2(1+6)/(2+1+6)\}]$

$= -j41.57$ A

Therefore, using current division equation,

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

$= -j41.57 (2/ ((2+1+6))$

$= j9.24$ A

Hence, the fault current is,

$I_f = 3.|I_{a0}|$

$= 3(9.24)$

$= 27.72$ A

-------------END-------------

5.4 Unsymmetrical faults on power system:

The unsymmetrical faults on the power system are analyzed using Thevenin's theorem. The Thevenin's equivalent of positive, negative and zero sequence networks are obtained with respect to the fault point.

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

Let,

Z_1= Thevenin's impedance of positive sequence network.

Z_2= Thevenin's impedance of negative sequence network.

Z_0= Thevenin's impedance of zero sequence network.

V_{TH}=prefault voltage at the fault point.

=Thevenin's impedance of positive sequence network.

Thevenin's equivalent of positive, negative and zero sequence networks of the power system with respect to the fault point will be as shown in fig 5.29, 5.30 and 5.31 respectively.

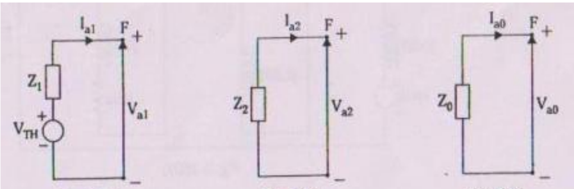

Fig. 5.29 Fig. 5.30 Fig. 5.31

Using Using Kirchoff's law to the circuits shown below, we get

$V_{a1}=V_{TH}-I_{a1}.Z_1$ 5.70

$V_{a2}= -I_{a2}.Z_2$ 5.71

$V_{a0}= -I_{a0}.Z_0$ 5.72

These equations are similar to that of a synchronous generator. They are useful in the analysis of unsymmetrical faults on the power system. We shall now consider the various types of unsymmetrical faults on a general power system.

5.4.1 Single line to ground (LG) fault:

fig 5.32 shows an LG fault at F in a power system through a fault impedance Z_f. The phases are so labeled that the fault occurs on phase a.

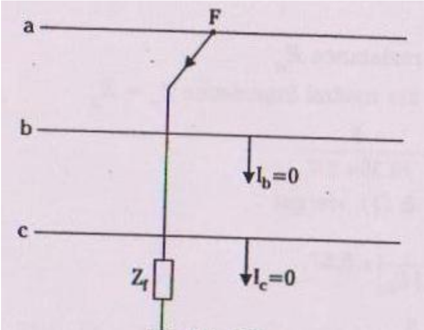

Fig. 5.32

Terminal conditions:

$V_a=I_a.Z_f$ 5.73

$I_b=0$ 5.74

$I_c=0$ 5.75

Symmetrical component relations:

The following relations can be obtained from the terminal conditions.

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

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

$I_{a2}=(1/3)(I_a+a^2.I_b+a.I_c)=(1/3)(I_a+0+0)=(1/3).I_a$

so $I_{a1}=I_{a2}=I_{a0}=(1/3).I_a$ 5.76

The terminal condition $V_a=I_a.Z_f$ gives

$V_{a0}+V_{a1}+V_{a2}=I_a.Z_f=3I_{a0}.Z_f$ 5.77

Equations 5.76 and 5.77 suggest a series connection of sequence networks through a impedance $3.Z_f$ as shown in fig 5.33

Interconnection of sequence networks:

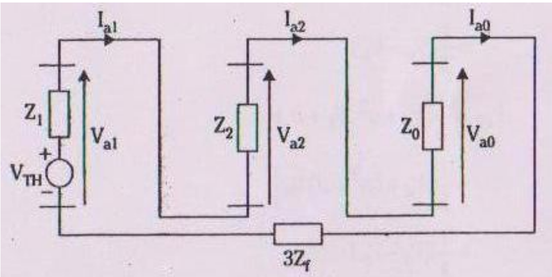

Fig. 5.33

Fault current:

The fault current in this case in given as,

$I_f=I_a=3I_{a0}= 3V_{TH} / (Z_1+Z_2+Z_0+3Z_f)$ 5.78

Note:

In the absence of fault impedance, replace Z_f by zero in the above calculations.

5.4.2 Line to line (LL) fault:

Fig 5.34 shows a LL fault at F in a power system on phase b and c through a fault impedance Z_f

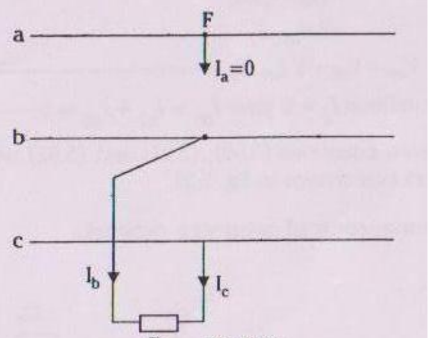

Fig. 5.34

Terminal conditions:

$I_a=0$ 5.79

$I_b+I_c=0$; $I_c=-I_b$ 5.80

$V_b=V_c+I_b.Z_f$ 5.81

Symmetrical components relations:

The following relations can be obtained from the terminal conditions

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

$=(1/3)(I_a+I_b-I_b)$

$=0$

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

$=(1/3)(0+a.I_b-a^2.I_c)$

$=(1/3)(a-a^2)I_b$

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

$=(1/3)(0+a^2 .I_b-a.I_c)$

$=(1/3)(a^2-a)I_b$

so, $I_{a0}=0$ 5.82

$I_{a1}= -I_{a2}$ 5.83

Next,

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

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

Therefore,

$V_{a1}-V_{a2}= (1/3)\ [(a-a^2)V_b+(a^2-a)V_c]$

$=(1/3)\ [(a-a^2)(V_b-V_c)]$

$=(1/3)\ (a-a^2)(I_b.Z_f)$

$= I_{a1}.Z_f$

Thus, $V_{a1}=V_{a2}+I_{a1}.Z_f$ 5.84

Since, $I_{a0}=0$, $V_{a0}= -I_{a0}.Z_0=0$ 5.85

Equations 5.83 and 5.85 suggest parallel connection of positive and negative sequence networks through a series impedance Z_f as shown in fig 5.35. Since $I_{a0}=V_{a0}=0$, the zero sequence network is connected separately and a shorted as shown in fig 5.36.

Interconnection sequence networks:

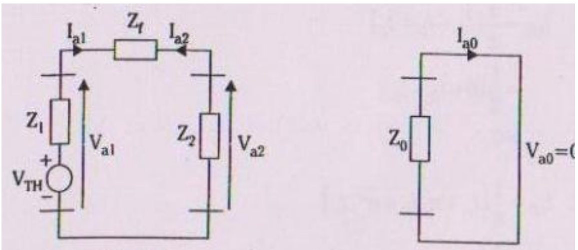

Fig. 5.35 Fig. 5.36

Fault current:

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

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

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

$= - j\sqrt{3}I_{a1}$

or $|I_f|=\sqrt{3}.I_{a1}$

$=\sqrt{3}.V_{TH} / (Z_1+Z_2+Z_f)$ 5.86

Note:

In the absence of fault impedance, replace Z_f by zero in the above calculations.

5.4.3 Double line to ground fault (LLG):

Fig 5.37 shows an LLG fault at F in a power system. The fault may in general have an impedance Z_f as shown.

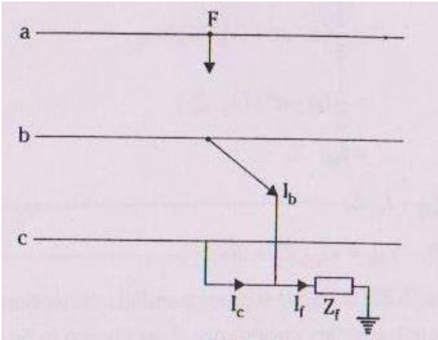

Fig. 5.37

Terminal conditions:

$I_a=0$ 5.87

$V_b=(I_b+I_c)Z_f$ 5.88

$V_c=(I_b+I_c)Z_f$ 5.89

Symmetrical component relations:

Consider,

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

$=(1/3)[(V_a+(a+a^2)V_b]$

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

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

$=(1/3)[(V_a+(a^2+a)V_b]$

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

$V_{a0}=(1/3)(V_a+V_b+V_c)$

$=(1/3)(V_a+2.V_b)$

Thus,

$V_{a1}=V_{a2}$ 5.90

$V_{a0}-V_{a2}=(1/3).3V_b$

$=V_b$

$=(I_b+I_c)Z_f$

$=3.I_{a0}.Z_f$ --------This will be proved to the expression for fault current.

Thus, $V_{a0}=V_{a2}+3.I_{a0}.Z_f$ 5.91

The condition $I_a=0$ gives $I_{a0}+I_{a1}+I_{a2}=0$ 5.92

From equations 5.90 , 5.91 and 5.92 we can draw connection of sequence networks as shown in fig 5.38

Interconnection of sequence networks:

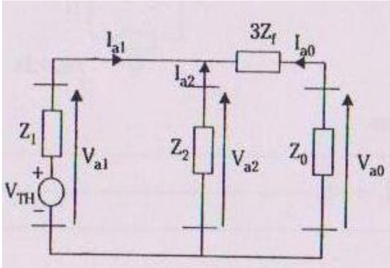

Fig. 5.38

Fault current:

In this case, the fault current is given as,

$I_f=I_b+I_c$

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

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

$=2I_{a0} - I_{a1} - I_{a2}$ because $(a+a^2)= -1$

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

It can be observed that $(I_{a1}+I_{a2})= -I_{a0}$.

Substituting this in the expression for fault current, we get

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

$=3I_{a0}$

$=-3.I_{a1}.[Z_2/(Z_0+Z_2+3Z_f)]$ 5.93

Note:

In the absence of fault impedance, Z_f is replaced by zero in the calculations.

The steps briefed below are used in solving the following problems:

1)The positive, negative and zero sequence networks for the given system are drawn.

2)The Thevenin's equivalent circuit of each of the networks with respect to the fault point is calculated.

3)These networks are interconnected suitably to simulate the particular type of fault condition.

Example 3.8:

A synchronous motor is receiving 10MW of power at 0.8pf lag at 6kV. An LG fault takes place at the middle point of the transmission line as shown in fig 5.39. Find the fault current. The ratings of the generator motor and transformer are as under.

Generator: 20MVA, 11kV, X_1=0.2p.u; X_2=0.1p.u; X_0=0.1p.u.
Transformer T_1: 18MVA, 11.5Y-34.5Y kV, X=0.1p.u.
Transmission line: X_1=X_2=5Ω; X_0=10Ω.
Transformer T_2: 15MVA, 6.9Y-34.5Y kV, X=0.1p.u.
Motor : 15MVA, 6.9kV, X_1=0.2p.u; X_2=X_0=0.1p.u.

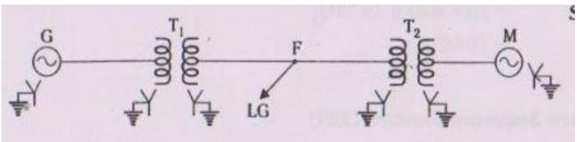

Fig. 5.39

Solution:
base values:
Let we choose,
base MVA=20
base kV on the generator=11
we calculate,
base kV on the transmission line=11(34.5/11.5)=33
base kV on the motor= 33(6.9/34.5)=6.6

Sequence reactances of generator:

$X_1 = X_{1,p.u, old} \times ((MVA)_{B, new} / (MVA)_{B, old}) \times ((kV)^2_{B, old} / (kV)^2_{B, new})$
$= j0.2 \times (20 / 20) \times (11^2 / 11^2)$
$= j\,0.2$ p.u

$X_2 = X_{2,p.u, old} \times ((MVA)_{B, new} / (MVA)_{B, old}) \times ((kV)^2_{B, old} / (kV)^2_{B, new})$
$= j0.1 \times (20 / 20) \times (11^2 / 11^2)$
$= j\,0.1$ p.u

$X_0 = X_{0,p.u, old} \times ((MVA)_{B, new} / (MVA)_{B, old}) \times ((kV)^2_{B, old} / (kV)^2_{B, new})$
$= j0.1 \times (20 / 20) \times (11^2 / 11^2)$
$= j\,0.1$ p.u

Sequence reactances of transformer T_1: (calculated primary side of it)

$X_1 = X_2 = X_0 = X_{p.u, old} \times ((MVA)_{B, new} / (MVA)_{B, old}) \times ((kV)^2_{B, old} / (kV)^2_{B, new})$
$= j0.1 \times (20 / 18) \times (11.5^2 / 11^2)$
$= j\,0.12$ p.u

Sequence reactances of transmission line:

$X_{1TL} = X_{2TL} = X_{TL}(\Omega) \times (MVA)_B / (kV)^2_B$
$= 5 \times 20 / 33^2$
$= 0.092$p.u

$X_{0TL} = 10 \times 20 / 30^2$
$= 0.184$p.u

Sequence reactances of transformer T_2: (calculated secondary side of it)

$X_1 = X_2 = X_0 = X_{p.u,\ old} \times ((MVA)_{B,\ new} / (MVA)_{B,\ old}) \times ((kV)^2_{B,\ old} / (kV)^2_{B,\ new})$

$= j0.1 \times (20 / 15) \times (6.9^2 / 6.6^2)$

$= j\ 0.146$ p.u

Sequence reactances of motor:

$X_1 = X_{1,p.u,\ old} \times ((MVA)_{B,\ new} / (MVA)_{B,\ old}) \times ((kV)^2_{B,\ old} / (kV)^2_{B,\ new})$

$= j0.2 \times (20 / 15) \times (6.9^2 / 6.9^2)$

$= j\ 0.29$ p.u

$X_2 = X_0 = X_{2,p.u,\ old} \times ((MVA)_{B,\ new} / (MVA)_{B,\ old}) \times ((kV)^2_{B,\ old} / (kV)^2_{B,\ new})$

$= j0.1 \times (20 / 15) \times (6.9^2 / 6.9^2)$

$= j\ 0.145$ p.u

Positive sequence Network (PSN):

Using the calculated values of positive sequence impedances, the PSN is drawn as shown in fig 5.40.

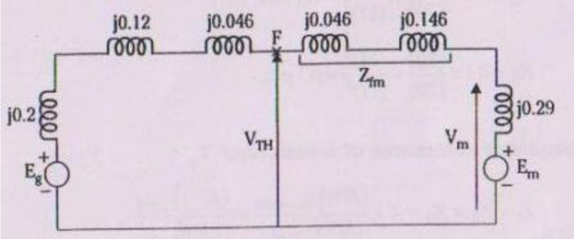

Fig. 5.40

To find the voltage at the fault point (V_{TH}):

The current drawn by the motor $I_m = ((10\times10^6) / (\sqrt{3}\times6\times10^3\times0.8)) \angle -\cos^{-1}0.8$

$= 1202.8\angle -36.87°$ A

The base current in the motor $(I_m)_B = (1000\times20) / (\sqrt{3}\times6.6)$

$= 1749.55$ A

Therefore,

I_m in p.u $= I_m/(I_m)_B = (1202.8/ 1749.55) \angle -36.87°$

$= 0.687\angle -36.87°$ p.u

Vm in p.u $= 6/6.6 = 0.909\angle 0°$ p.u

$V_{TH} = V_m + I_m .\ Z_{fm}$

$= 0.909 + ((0.687\angle -36.87°)(0.182\angle 90°))$, where $Z_{fm} = j0.046 + j0.146 = 0.182\angle 90°$

$= 0.909 + 0.132\angle 53.13°$

$= 0.909 + 0.0792 + j0.106$

$= 0.9882 + j0.106$

$= 0.994\angle 6.1°$

To find the Thevenin's impedance Z_{1TH}

The Thevenin's impedance as seen from point F is,

$Z_{1TH} = j[(0.2+0.12+0.046)||(0.046+0.146+0.29)]$

$= j(0.366||0.482)$

$= j0.208$ p.u

Hence the equivalent PSN of the system is as shown below:

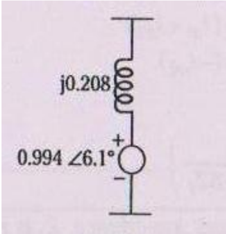

Fig. 5.41

Negative sequence Network (NSN):

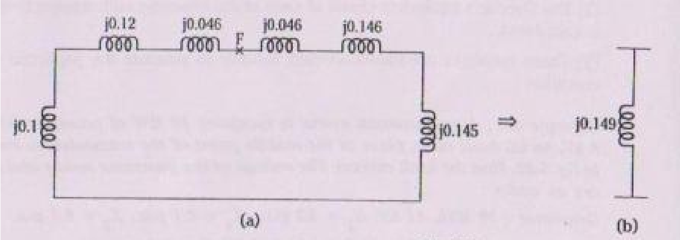

Fig. 5.42

The Thevenin's equivalent impedance with respect to the fault point is:

Z_{2TH}=j[(0.1+0.12+0.092)||(0.046+0.146+0.145)]
=j(0.266||0.337)
=j0.149 p.u

Zero sequence network (ZSN):

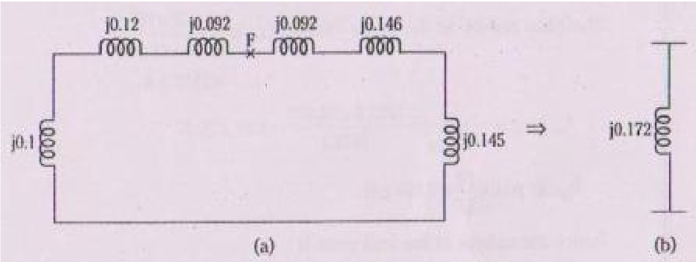

Fig. 5.43

The Thevenin's zero sequence impedance is,

Z_{0TH}=j[(0.1+0.12+0.092)||(0.092+0.146+0.145)]
=j(0.312||0.383)
=j0.172 p.u

Interconnection of sequence networks:

The sequence networks are connected as shown in fig 5.44 to represent LG fault.

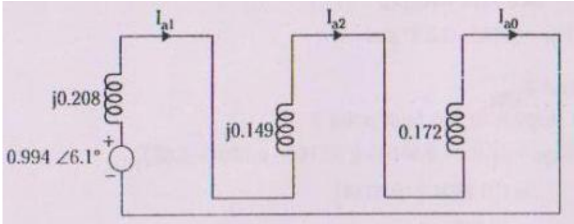

Fig. 5.44

Here,
$I_{a1}=I_{a2}=I_{a0}= (0.994\angle 6.1°) / j(0.208+0.149+0.172)$
$=1.88\angle -83.9°$ p.u

Hence fault current:
$|I_f|=3.|I_{a0}|$

$=3(1.88)$

$=5.64$ p.u

Fault current in amperes is:
$=|I_f|_{p.u} \times (I_{TL})_B$

$=5.64\times((1000\times 20) / (\sqrt{3}\times 33))$

$=1973.49$ A

5.5 Series type of faults:

We have so far discussed the various shunt type of faults that occur in a power system. But unsymmetrical faults in the form of open conductors (series type) also do take place in power system. It is required to determine the sequence components of line currents and the voltages across the broken ends of the conductors.

Fig 5.56 shows a system wherein an open conductor fault takes place.

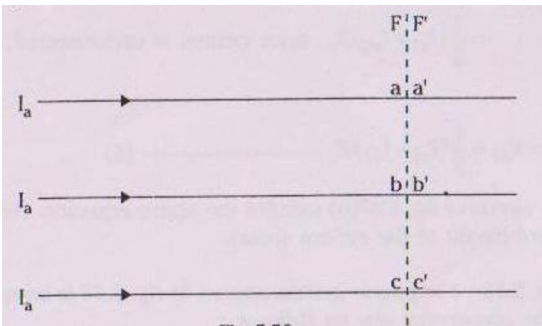

Fig. 5.56

The ends of the system on the sides of the fault are identified as F, F', while the conductor ends are denoted by aa', bb' and cc'. The voltage across the conductors are denoted by V_{aa}', V_{bb}' and V_{cc}'. The symmetrical components of these voltages are $(V_{aa}')_1$, $(V_{aa}')_2$,$(V_{aa}')_0$. The sequence networks as seen from the two ends FF' of the system are schematically shown in fig 5.57.

These are suitably interconnected depending on the type of fault (one or two conductors open).

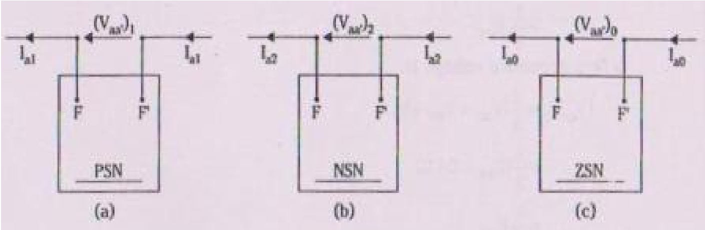

Fig. 5.57

i) One conductor open fault:

Let us assume that the conductor 'a' of a system gets opened as shown in fig 5.58.

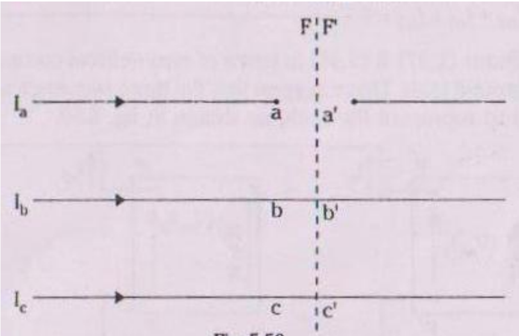

Fig. 5.58

Terminal conditions:

As seen from the two ends F and F'. The terminal conditions that are applicable are:

$I_a=0$ 5.94

$V_{bb}'=0$ 5.95

$V_{cc}'=0$ 5.96

Symmetrical components relations:

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

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

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

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

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

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

$(V_{aa'})_0=(1/3)(V_{aa'}+V_{bb'}+V_{cc'})$

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

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

Thus,

$(V_{aa'})_1=(V_{aa'})_2=(V_{aa'})_0=(1/3)V_{aa'}$ 5.97

The condition $I_a=0$ gives the result

$I_{a0}+I_{a1}+I_{a0}=0$ 5.98

Condition 5.97 and 5.98 in terms of symmetrical components are similar to a double line to ground fault. These suggest that the three sequence networks should be connected in parallel to represent the fault, as shown in fig 5.59.

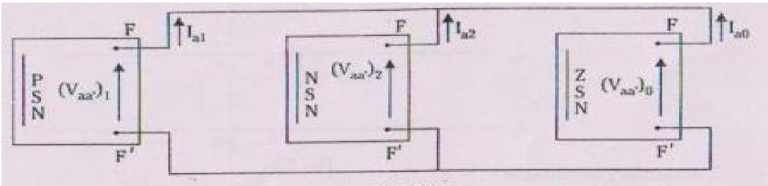

Fig. 5.59

ii)Two conductors open fault:

Let us assume that the two conductors b and c get open at the points F, F' as shown in fig 5.60.

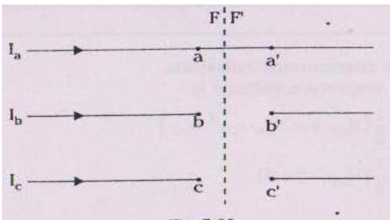

Fig. 5.60

Terminal conditions:

As seen from the points F and F', the terminal conditions that are applicable to this fault are:

$I_b=0$ 5.99

$I_c=0$ 5.100

$V_{aa'}=0$ 5.101

Symmetrical components relations:

consider,

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

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

$I_{a2}=(1/3)(I_a+a^2.I_b+a.I_c)=(1/3)(I_a+0+0)=(1/3).I_a$

so $I_{a1}=I_{a2}=I_{a0}=(1/3).I_a$ 5.102

The terminal conditions $V_{aa'}=0$ gives the result,

$(V_{aa'})_0+(V_{aa'})_1+(V_{aa'})_2=0$ 5.103

These conditions are similar to those of line to ground fault and suggest that the three sequence networks be connected in series and shorted as shown in fig5.61.

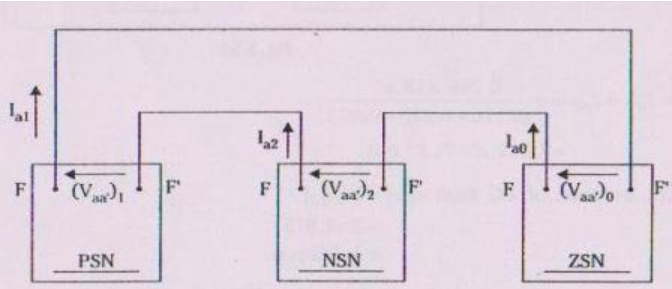

Fig. 5.61

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