USE OF SYMMETRICAL COMPONENTS IN POWER SYSTEM PROTECTION

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ABSTRACT

The report is about the study, performed for the graduation project E.E-400. The subject of the study carried out is the use of the symmetrical components which has been found very useful in solving unbalanced polyphase circuits,and for calculation of currents resulting from unbalanced faults. Most of the faults that occur on power system are unsymmetrical faults. The unsymmetrical faults which may occur quite oftenly are like single line to ground faults, line to line faults or double line to ground faults. In order to detect such faults it is essential that the fault currents and voltages should be known. Such topics were discussed and necessary equations were derived.

We discussed faults at the terminals of an unloaded generator. Then we consider faults on a power sustem applying thevenin's theorem, which allows us to find the current in the fault by replacing the entire system by a single generator and series impedance. Faults can be very destructive to power system, different devices and protection schemes are present to prevent damages to transmission lines equipments and interruption in generator that follow the occurence of a fault. We construct a voltage filter, which is responsive to negative sequence component, so that as the power system undergoes short circuit or it starts operating abnormally. The filter circuit will indicate the presence of a negative sequence components enabling us to do necessary steps to avoid it.

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CHAPTER 1

SYMMETRICAL COMPONENTS ALGEBRA

Introduction. In case of three phase balanced currents the phase voltages and currents are of equal magnitude and they are displaced from each other by 120 degrees, or are said to be symmetrical the analysis of such systems (for calculation of line or phase voltages) is much simplier and can be carried out on per phase basis; but when the load becomes unbalanced, the analysis by usual techniques become very difficult.

To overcome this problem the method of symmetrical components was proposed by C. L. **Fortesue** and has been found very useful in solving unbalanced polyphased circuits for analytical determination of performance of the polyphase electrical circuits when operated from a system of unbalanced voltages and for calculation of currents resulting from unbalanced faults.

According to Fortesu's theorem in an unbalanced three phase system, the unbalanced phasors can be resolved into three balanced systems of Phasors.The balanced sets of component can be given as:

1. **Positive sequence component**
2. **Negative sequence component**
3. **Zero sequence component.**

1-2. **OPERATORS:** As the symmetrical components of the voltages and currents in a three phase system are displaced from each other it is convenient to have a shorthand method of indicating the rotation of a phasor through 120°.

A Complex number of unit magnitude and associated angle THETA is an operator that rotates the phasor on which it operates through the angle THETA.

The letter a is commonly used to designete the operator that causes a rotation of 120° degree in the counterclock wise direction such an operator is a complex number of unit magnitude with an angle of 120° degrees and is defined by

$$a = 1 \angle 120^\circ = e^{j2\pi/3} = -0.5 + j0.866$$

if the operator a is applied to a phasor twice in succession, the phasor is related through 240° degrees. Three sussesive applications of a rotate the phasor through 360° degrees.

Thus,

$$a^2 = 1 \angle 240^\circ = -0.5 - j\ 0.866$$

and

$$a^3 = 1 \angle 360^\circ = 1 \angle 0^\circ = 1$$

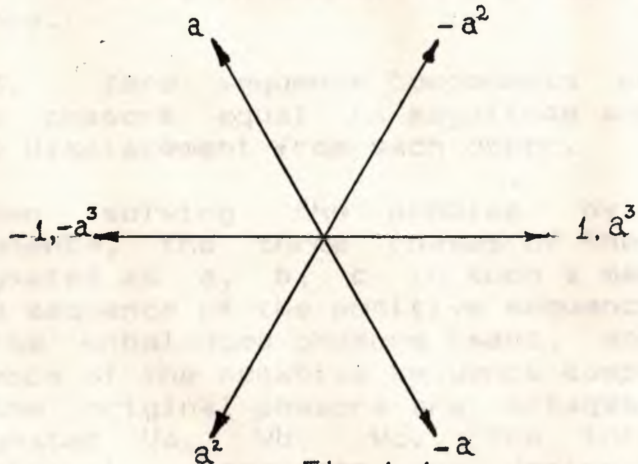

Fig 1.1

Phasors representation of various power of operator a

1-3. NOTATIONS AND MEANING OF POSITIVE NEGATIVE AND ZERO PHASE SEQUENCE.

An unbalanced system of n related phasors can be resolved into n systems of phasors called the symmetrical components of the original phasors. The n phasors of each set of components are equal in length and the angles between the adjacent phasors of the set are equal. Although the method is applicable to any unblanced polyphase system, we shall confine our discusion to three phase system

Three unbalanced phasors of a three phase system can be resolved into three balanced system of phasors. The balanced sets of components are:

1. Positive sequence components consisting of three phasors equal in magnitueds, displaced from each other by 120 degrees in phase and having the same phase sequence as the original phasors.

2. Negative sequence components consisting of three phasors equal in magnitued displaced from each other by 120 degrees in phase and having a phase sequence opposite to that of the original phasors.

3. Zero sequence components consisting of three phasors equal in magnitude and with zero phase displacement from each other.

When solving the problem by symmetrical components, the three phases of the system are designated as a, b, c in such a manner that the phase sequence of the positive sequence components of the unbalanced phasors isabc, and the phase sequence of the negative sequence components is acb if the original phasors are voltages they may be designated Va, Vb, Vc. The three sets of symmetrical components are designated by the additional subscript 1 for the positive sequence components, 2 for the negative sequence components and 0 for the zero sequence components. The positive sequence components of Va,Vb, Vc are V_{a1}, V_{b1}, V_{c1} . Fig 1.2 shows three sets of symmetrical components phasors representing currents, will be designated byI with subscript as for voltages.

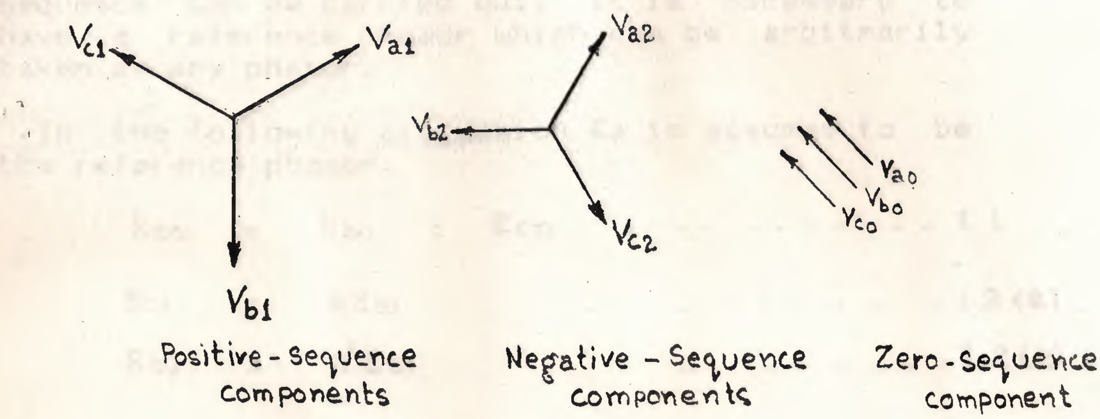

Fig 1.2
Three sets of balanced phasors which are the symmetrical components of three unbalanced phasors.

1-4. SYMMETRICAL COMPONENT EQUATIONS.

Since each of the original unbalanced phasors is the sum of its components, the original phasors expressed interms of their components are:

$$E_a = E_{a1} + E_{a2} + E_{a0}$$

$$E_b = E_{b1} + E_{b2} + E_{b0}$$

$$E_c = E_{c1} + E_{c2} + E_{c0}$$

1-5. RESOLUTION OF UNBALANCED PHASORS INTO THEIR SYMMETRICAL COMPONENTS.

In view of discussion of operator a the components of positive, negative and zero phase sequesce can be carried out, it is necessary to have a reference phasor which can be arbitrarily taken as any phasor.

In the following discussion Ea is assumed to be the reference phasor.

$$E_{ao} = E_{bo} = E_{co} \quad \text{------------ } 1.1$$

$$E_{c1} = aE_{a1} \quad \text{---------- } 1.2\,(a)$$

$$E_{b1} = a^2 E_{a1} \quad \text{---------- } 1.2\,(b)$$

$$E_{b2} = a\,E_{a2} \quad \text{---------- } 1.3\,(a)$$

$$E_{c2} = a^2 E_{a2} \quad \text{---------- } 1.3\,(b)$$

Now, set equations (1.1), (1.2(b)), (1.3(a)) and (1.3(b)) are arranged according to section 1.4.

$$E_a = E_{ao} + E_{a1} + E_{a2} \quad \text{------- } 1.4$$

$$E_b = E_{bo} + a^2 E_{a1} + aE_{a2} \quad \text{------- } 1.5$$

$$E_c = E_{ao} + aE_{a1} + a^2 E_{a2} \quad \text{------- } 1.6$$

In order to find different symmetrical components, three methods can be adopted

1-5(a). MATRIX SOLUTION.

Equations (1.4)(1.5)&(1.6) can be represented in matrix form i.e,

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} \quad \text{----- (1.7)}$$

let the matrix given by equation (1.7) be represented in short form as

$$E = AE_{a12} \quad \text{------- (1.8)}$$

where the subscript 0,1,2 and stand for zero positive and negative components of the reference phasor, the matrix

$$E = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad \text{------- (1.9)}$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{----- (1.10)}$$

and,

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} \quad \text{----- (1.11)}$$

premultiply matrix (1.8) by A

$$A^{-1}E = A^{-1}A\,E_{a12}$$

[As $A^{-1}A$ is unity]

The inverse of matrix A can be obtained by usual techniques and it is easy to write,

$$A^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad \text{---- (1.13)}$$

Rewrite equation (1.12) in view of matrix equation (1.13)

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad \text{---- (1.14)}$$

$$E_{a0} = \frac{1}{3}\left(E_a + E_b + E_c\right) \quad \text{------ (1.15)}$$

$$E_{a1} = \frac{1}{3}\left(E_a + aE_b + a^2E_c\right) \quad \text{----- (1.16)}$$

$$E_{a2} = \frac{1}{3}\left(E_a + a^2E_b + aE_c\right) \quad \text{------ (1.17)}$$

1-5(b). SIMULTANIOUS ALGEBRIC SOLUTION OF EQUATIONS

Add equation (1.4), (1.5), and (1.6) and keeping in view that $(1+a+a^2)$ is zero

$$E_a + E_b + E_c = 3E_{a0} + (1+a+a^2)E_{a1} + (1+a+a^2)E_{a2}$$

$$\text{----- (1.18)}$$

$$E_{a1} = 1/3 \; (E_a + E_b + E_c) \quad ----(1.19)$$

Now multiply equation (1.5) by a and equation (1.6) by **a** and add equation (1.4) keeping in view that a^3 is unity and a^4 is same a.

$$(E_a + aE_b + E_c) = (1 + a + a^2)E_{a1} + (1 + a^3 + a^4)E_{a1} + (1 + a^2 + a^4)E_{a2}$$

$$E_{a1} = 1/3 \; (E_a + aE_b + a^2 E_c) \quad ------(1.20)$$

Similarly it can be shown that if equation (1.5) is multiplied by $\mathbf{a}^2$ and equation (1.6) by a and their results are added to equation (1.4) E_{a2} can be represented by equation (1.17).

Thus the different components can be obtained by equation (1.15), (1.16), (1.17).

CHAPTER 2

ASYMMETRICAL FAULT CURRENTS.

2.1 INTRODUCTION

In power systems faults may occur mainly due to following two reasons:

1. Insulation failure

It may be caused by over - voltage applied to the system produced by the switching surge or by a lighting stroke. However, the insulation failure in case of line insulators may be caused by stress and strain of severe hot and cold weather.

2. MECHANICAL INJURY

In case of transmission lines it may be caused by high velocity winds or by falling trees etc.

The determination of short circuit current in power system has great importance from protection or view. For adequate protection , it is necessary to determine the capacity of the power system to supply short circuit current.

2.2 TYPES OF SHORT CIRCUITS.

The fault in power system may occur:

1. Between one phase and earth
2. Between phase and phase
3. Between two phases and earth
4. Between two phases and at the same time there may be a falt betyween third phase and earth
5. Between all the three phases
6. Between all the three phases and ground

The first four types of faults produce asymmetrical fault currents, while the later two types produce symmetrical short circuit currents.
The possibility of symmetrical fault in a power system is quite rare.The actual fault may occur on one line and ground or two lines or there may occur fault between two lines and ground. In this chapter we will deal with these types of faults only which are asymmetrical faults producing asymmetrical fault currents and voltages.

2.3 ASYMMETRICAL SERIES IMPEDANCE

In this section we shall be concerned with system that are normally balanced. The short circuit faults cause unbalancing of the system. Fig 2.1 shows the asymmetrical part of a system in which Z_1, Z_2, Z_3 and Z_n are the impedances in each phase and in the neutral respectively. Let there be no mutual impedence between them.

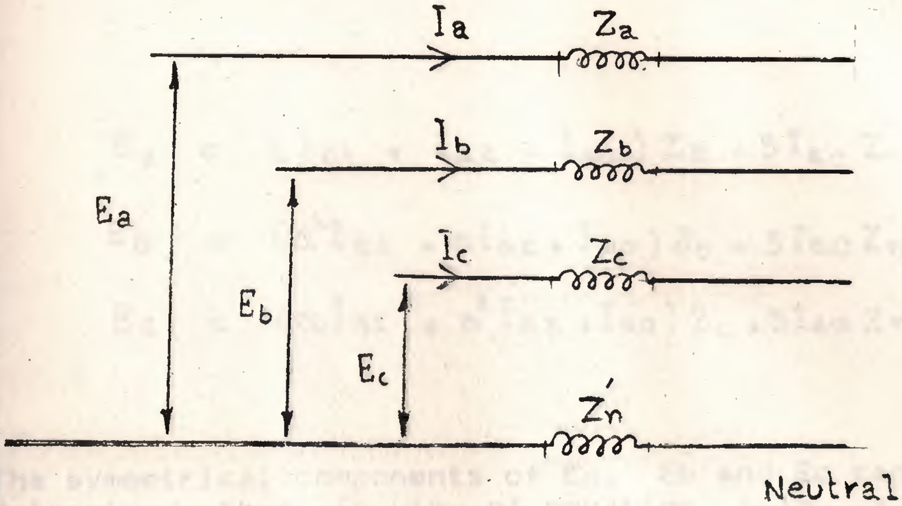

Fig 2.1
Unbalance system of self-impedances

In view of Kirchhoff's law,

$$E_a = I_a Z_a + I_n Z_n' \quad \text{------} \quad (2\text{-}1)$$

$$E_b = I_b Z_b + I_n Z_n' \quad \text{-----} \quad (2\text{-}2)$$

$$E_c = I_c Z_c + I_n Z_n' \quad \text{-----} \quad (2\text{-}3)$$

when,

$$I_n = I_a + I_b + I_c \quad \text{------} \quad (2\text{-}4)$$

In view of equation (1-15)

$$I_n = 3 I_{ao} \quad \text{------} \quad (2\text{-}5)$$

In view of equation 2-5 , and using equation 1.4, 1.5, 1.6 which are rewritte below equation 2.1 to 2.3 can be written as equation 2.6 to 2.8.

$$E_a = E_{a1} + E_{a2} + E_{ao} \quad \text{--------} \quad (1.4)$$

$$E_b = a^2 E_{a1} + a E_{a2} + E_{ao} \quad \text{------} \quad (1\text{-}5)$$

$$E_c = a E_{a1} + a^2 E_{a2} + E_{ao} \quad \text{-----} \quad (1\text{-}6)$$

$$E_a = (I_{a1} + I_{a2} + I_{ao}) Z_a + 3 I_{ao} Z_n' \quad \ldots (2.6)$$

$$E_b = (a^2 I_{a1} + a I_{a2} + I_{ao}) Z_b + 3 I_{ao} Z_n' \quad \ldots (2.8)$$

$$E_c = (a I_{a1} + a^2 I_{a2} + I_{ao}) Z_c + 3 I_{ao} Z_n' \quad (2.9)$$

The symmetrical components of Ea, Eb and Ec can be determined thus in view of equation 1.15, 1.16, 1.17 which are rewritten below.

$$E_{ao} = \frac{1}{3}(E_a + E_b + E_c) \quad \text{-------} (1.15)$$

$$E_{a1} = \frac{1}{3}(E_a + aE_b + a^2 E_c) \quad \text{------} (1.16)$$

$$E_{a2} = \frac{1}{3}(E_a + a^2 E_b + a E_c) \quad \text{-------} (1.17)$$

Using equation 1.16 and equation 2.6 to 2.8

$$\begin{aligned} E_{a1} = {} & \frac{1}{3}\left[(I_{a1} + I_{a2} + I_{ao}) Z_a + 3 I_{ao} Z_n'\right] \\ & + \frac{1}{3} a\left[(a^2 I_{a1} + a I_{a2} + I_{ao}) Z_b + 3 I_{ao} Z_n'\right] \\ & + \frac{1}{3} a^2\left[(a I_{a1} + a^2 I_{a2} + I_{ao}) Z_c + 3 I_{ao} Z_n'\right] \end{aligned}$$

$$\begin{aligned} E_{a1} = {} & \frac{1}{3} I_{a1}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3} I_{a2}\left[Z_a + a^2 Z_b + a Z_c\right] \\ & + \frac{1}{3} I_{ao}\left[Z_a + a Z_b + a^2 Z_c + 3 Z_n'(1 + a + a^2)\right] \end{aligned}$$

$$\begin{aligned} E_{a1} = {} & \frac{1}{3} I_{a1}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3} I_{a2}\left[Z_a + a^2 Z_b + a Z_c\right] \\ & + \frac{1}{3} I_{ao}\left[Z_a + a Z_b + a^2 Z_c\right] \text{--------} (2\text{-}9) \end{aligned}$$

Similarly,

$$E_{a2} = \frac{1}{3} I_{a1}\left[Z_a + aZ_b + a^2 Z_c\right] + \frac{1}{3} I_{a2}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3} I_{ao}\left[Z_a + a^2 Z_b + aZ_c\right] \quad \text{------} \quad (2.10)$$

$$E_{ao} = \frac{1}{3} I_{a1}\left[Z_a + a^2 Z_b + aZ_c\right] + \frac{1}{3} I_{a2}\left[Z_a + aZ_b + a^2 Z_c\right] + \frac{1}{3} I_{ao}\left[Z_a + Z_b + Z_c + 9Z_n'\right] \quad \text{----} \quad (2.11)$$

Let Z_m, Z_s, Z_{as} be the zero sequence positive sequence components of impedances given as

$$Z_m = \frac{1}{3}(Z_a + aZ_b + Z_c) \quad \text{------} \quad (2-12)$$

$$Z_s = \frac{1}{3}(Z_a + aZ_b + Z_c) \quad \text{------} \quad (2-13)$$

$$Z_{as} = \frac{1}{3}(Z_a + a^2 Z_b + aZ_c) \quad \text{------} \quad (2.14)$$

Substituting equation (2.12) to (2.14) in equation (2.9) to (2.11)

$$E_{a1} = I_{a1} Z_m + I_{a2} Z_{as} + I_{ao} Z_s$$

$$E_{a2} = I_{a1} Z_s + I_{a2} Z_m + I_{ao} Z_n$$

$$E_{ao} = I_{a1} Z_{as} + I_{a2} Z_s + I_{ao}(Z_m + 9Z_n')$$

Thus it can be observed that current of one sequence can produce voltage of other sequence.

SECOND METHOD BY APPLICATION OF MATRIX EQUATION

The previous results can also be proved by matrix equation. For simplicity it has been assumed that there is no impedance in the neutral as shown in fig 2.2.

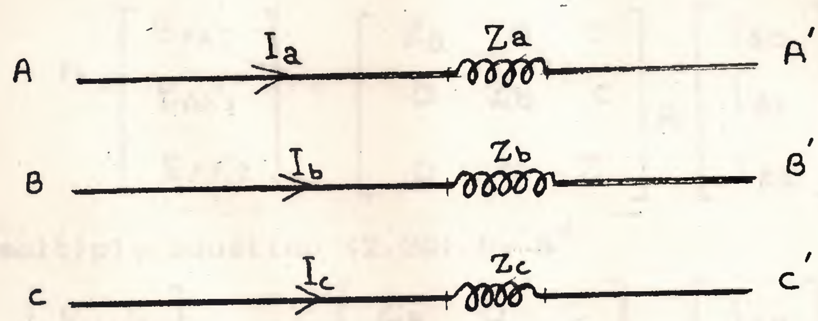

Fig 2.2
Unsymmetrical impedance in the three phases

$$E_{AA'} = I_a Z_a \quad \text{------------ (2.18 (a))}$$

$$E_{BB'} = I_b Z_b \quad \text{------------ (2.18 (b))}$$

and, $$E_{CC'} = I_c Z_c \quad \text{------------ (2.18 (c))}$$

The equation 2.18 can be represented by a matrix form as:

$$\begin{bmatrix} E_{AA'} \\ E_{BB'} \\ E_{CC'} \end{bmatrix} = \begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad \text{---- (2.19)}$$

$$A^{-1}\begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} A = \frac{1}{3}\begin{bmatrix} Z_a & Z_b & Z_c \\ Z_a & aZ_b & a^2Z_c \\ Z_a & a^2Z_b & aZ_c \end{bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

$$= \frac{1}{3}\begin{bmatrix} Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c \\ Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ \\ Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c \end{bmatrix}$$

----(2.23)

Set equation (2.23) in equation (3.20)

$$\begin{bmatrix} E_{AA'0} \\ E_{AA'1} \\ E_{AA'2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c \\ Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c \\ Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z & Z_a + Z_b + Z_c \end{bmatrix}\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{ac} \end{bmatrix}$$

or,

----(2.24)

$$E_{AA'0} = \tfrac{1}{3}(Z_a + Z_b + Z_c)I_{a0} + \tfrac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a1} + \tfrac{1}{3}(Z_a + aZ_b + a^2Z_c)I_{a2}$$

----(2.25)

$$E_{AA'1} = \tfrac{1}{3}(Z_a + aZ_b + a^2Z_c)I_{a0} + \tfrac{1}{3}(Z_a + Z_b + Z_c)I_{a1} + \tfrac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a2}$$

----(2.26)

$$E_{AA'2} = \tfrac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a0} + \tfrac{1}{3}(Z_a + aZ_b + a^2Z_c) + \tfrac{1}{3}(Z_a + Z_b + Z_c)I_{a2}$$

----(2.27)

The equation (2.25, 2.26 and 2.27) can be simplified to a great extent if the impedance Z_a, Z_b and Z_c all are equal to Z, so rewritting equation 2.25, 2.26, 2.27 we get,

$$E_{AA'0} = Z I_{a0} \qquad ------ (2.28)$$

$$E_{AA'1} = Z I_{a1} \qquad ------ (2.29)$$

$$E_{AA'2} = Z I_{a2} \qquad ------ (2.30)$$

Thus, from equation 2.28, 2.29 and 2.30 it can be observed that if unbalanced current flow in symmetrical (equal) series impedances the symmetrical components of voltage drops is of like sequence only, provided no coupling exists between phases, if the impedances are unequal, Equations 2.25, 2.26, 2.27 show that the voltage drop of any one sequence is dependent on the currents of all three sequences.

2.4 SEQUENCE NETWORKS.

This is the most important concept of symmetrical components. The sequence network is an equivalent network which is supposed to be balanced system operating under one of the sequence component of voltages and currents.

Thus the impedance of the network offered to the flow of positive sequence currents is called the positive impedance similarly if only negative sequence currents flow the impedence of the network offered to this current is called negative sequence impedence, also the impedance offered to zero sequence impedance of the network.

Hence the sequence network in reference to any particular sequence currents consist of a single phase network having impedance offered to one particular sequence components of current.

IMPEDENCES WHICH ARE INDEPENDENT OF THE PHASE ORDER OF CURRENTS ARE CALLED INDEPENDENT IMPEDENCES, THOSE DEPENDANT ON THE PHASE SEQUENCE ORDER OF THE CURRENTS ARE CALLED DEPENDANT IMPEDENCES. *

Z_m, Z_s, Z_{as} REPRESENT DEPENDANT IMPEDANCES OPPOSED TO I_o, I_1 AND I_2.

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* As defined by Prof. Haldun Gurmen

2.5 SETTING UP OF THE SEQUENCE NETWORK.

As the sequence network is to be set up seperately for each sequence. This will help us for the analysis under asymmetrical faults. In order to develop set network it is viewed from the fault point assuming that a particular sequence current flows in the circuit. The method consists of assuming that a certain voltage is impressed across the terminals of networks which is followed for the current flow to fault point. However, for zero phase sequence networks one must view the network from fault point because zero phase sequence current may not be flowing through out the circuit.

For example consider unloaded generator which is grounded through reactance X_n , let an assymetrical fault occur (which also involves the ground fault) causing unbalanced currents I_a, I_b and I_c flows through the lines as illustrated in fig 2.3.

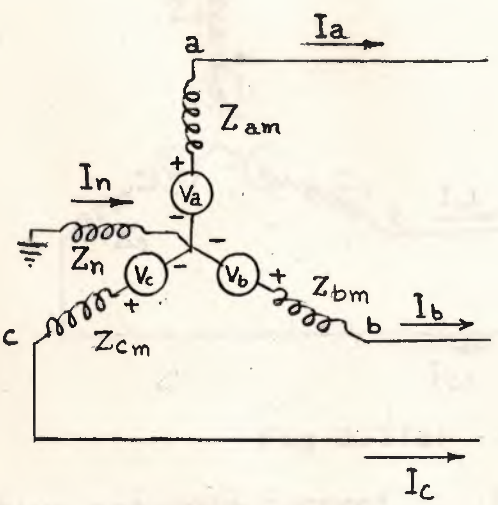

Fig 2.3. Representatiion of unsymmetrical fault on an unbalanced generator.

Since, there is also a ground fault current I_n will flow into the ground reactance X_n . The positive phase sequence component of currents are I_{a1}, I_{b1} and I_{c1} while the negative sequence components are I_{a2}, I_{b2} and I and zero pahse sequence currents are I , I I_{c2} . The generator are always designed to generate balanced voltages so, the generated voltages are positive sequence only. Let V_a , V_b and V_c be the generated phase voltages also assume Z_s , Z_{as} and Z_m be the positive, negative and zero sequence impedance of the generator. Let E_a, E_b and E_c be the potential between the terminal of the generator.

The paths for currents of each sequence in a generator and the corresponding sequence networks are shown in fig 3.3

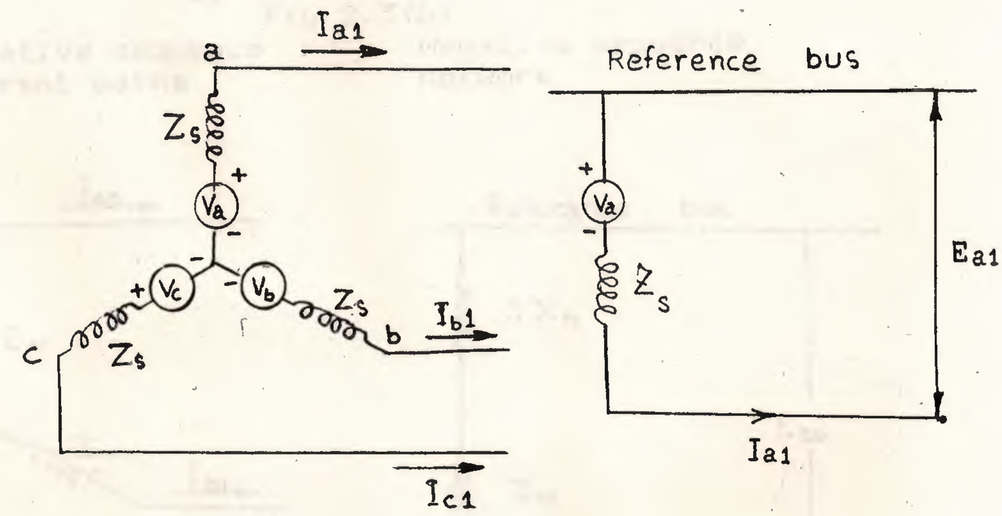

Fig 2.3(a)

Positive sequence current paths.

Positive sequence network

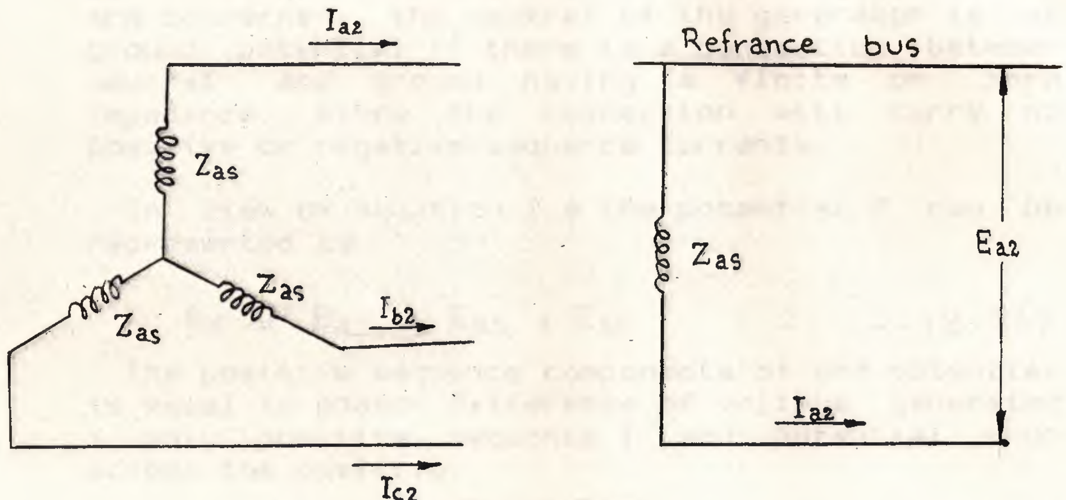

Fig 2.3(b)

Negative sequence current paths

Negative sequence network

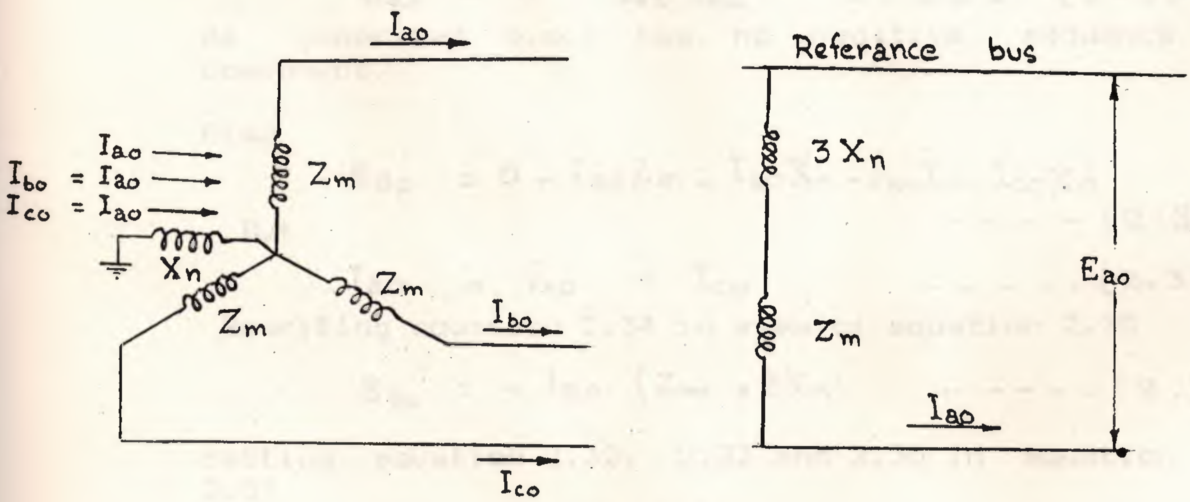

Fig 2.3(c)

Zero sequence current paths

Zero sequence network.

The reference bus for the positive and negative sequence networks is the neutral of the generator. So far as positive and negative sequence components are concerned, the neutral of the generator is at ground potential if there is a connection between neutral and ground having a finite or zero impedance since the connection will carry no positive or negative sequence currents.

In view of equation 1.4 the potential E can be represented as

$$E_a = E_{a1} + E_{a2} + E_{a0} \qquad ----- (2.31)$$

The positive sequence components of the potential is equal to phasor difference of voltage generated (only positive sequence) and potential drop across the positive.

$$E_{a1} = V_a - I_{a1} Z_s \qquad ----- (2.32)$$

Similarly

$$E_{a2} = 0 - I_{a2} Z_{as} \qquad ------ (2.33)$$

As generated e.m.f has no negative sequence component.

Also

$$E_{a0} = 0 - I_{a0} Z_m - I_{a0} X_n - I_{b0} X_n - I_{c0} X_n \qquad ---- (2.34)$$

But

$$I_{a0} = I_{b0} = I_{c0} \qquad ----- (2.35)$$

Rewriting equation 2.34 in view of equation 2.35

$$E_{a0} = - I_{a0} (Z_m + 3X_n) \qquad ----- (2.36)$$

Setting equation 2.32, 2.33 and 2.35 in equation 2.31

$$E_a = (V_a - I_{a1} Z_s) - I_{a1} Z_{as} - I_{a0} (Z_m + 3X_n)$$

similarly

$$E_b = (V_b - I_{b1} Z_s) - I_{b2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

and

$$E_c = (V_c - I_{c1} Z_s) - I_{c2} Z_{as} - I_{ao}(Z_{as} + 3X_n)$$

Rewriting equations 2.38 and 2.39 in view of equation 1.2 and 1.3

$$E_b = (a^2 V_a - a^2 I_{a1} Z_s) - a I_{a2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

and

$$E_c = (a V_a - a I_{a1} Z_s) - a^2 I_{a2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

Now considering equations 2.37, 2.40 and 2.41 the first component within the paranthesis of these equation represents the generated e.m.f and only positive impedance, or these three components can be combined together to form a positive sequence network as shown in fig 2.4 similarly, if the second components of these equations are combined together they will represent negative sequence as shown in fig 2.5 . Also, the third components of these equations are combined together to a zero phase sequence network and are shown in fig 2.6.

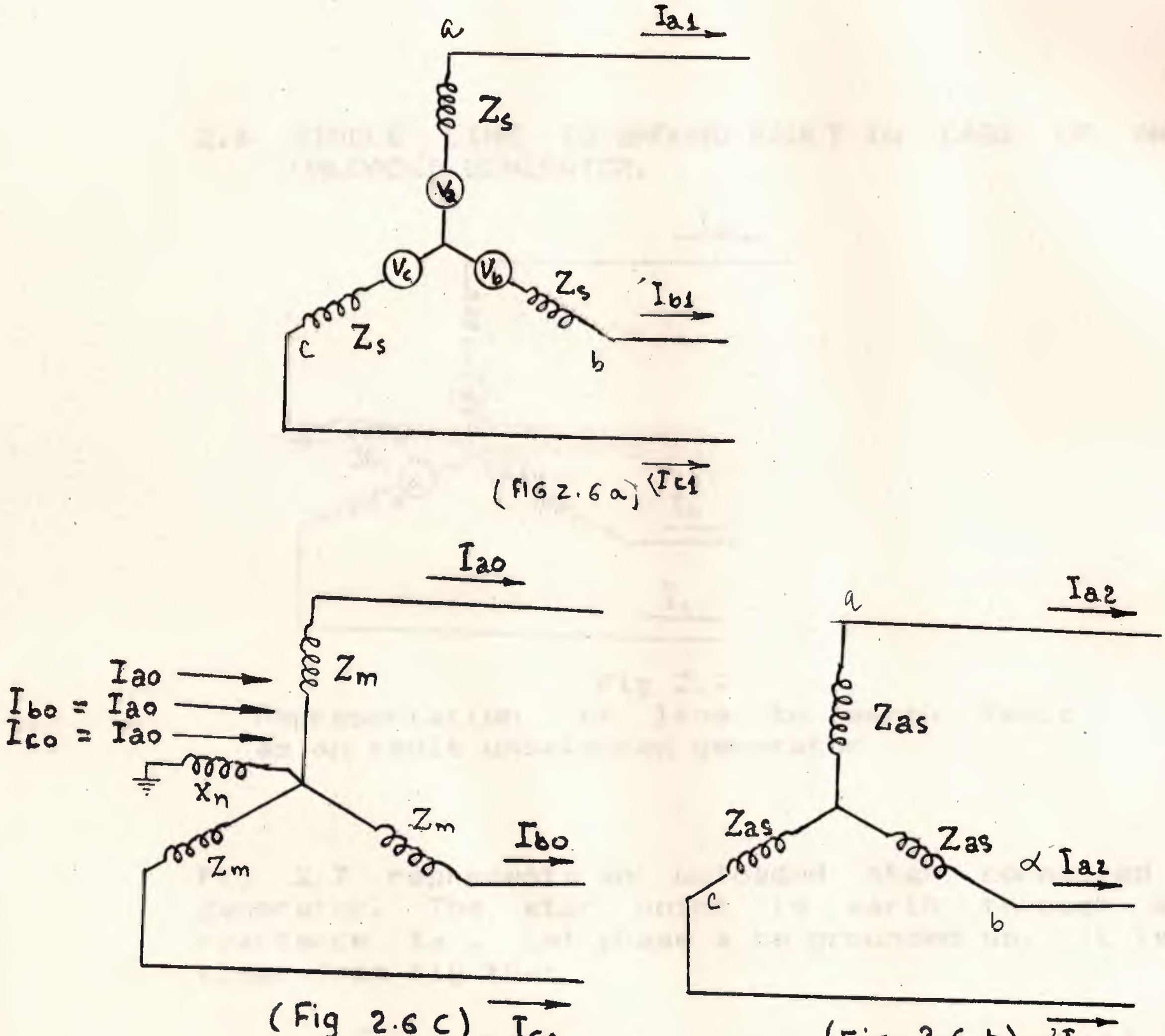

Fig 2.6

(a) The three components $(V_a - I_{a1}Z_s)$, $(a^2 V_a - a^2 I_{a1} Z_s)$ and $(aV_a - aI_{a1} Z_s)$ are combined together to form a positive sequence network.

(b) The three components $(I_{a2} Z_{as})$ $(a^2 I_{a2} Z_{as})$ and $(aI_{a2}\ Z_{as})$ are combined together to form a negative sequence network

(c) The three components $I_{a0} (Z_m + 3X_n)$ are combined together to form zero sequence network.

2.6 SINGLE LINE TO GROUND FAULT IN CASE OF AN UNLOADED GENERATOR.

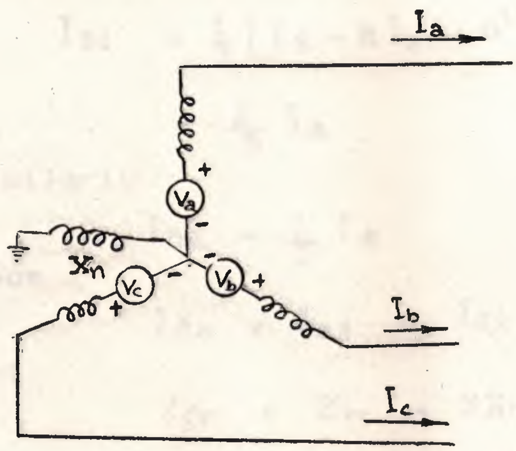

Fig 2.7
Representation of line to earth fault as an fault unbalanced generator

Fig 2.7 represents an unloaded star connected generator. The star point is earth through a reactance X_n. Let phase a be grounded so, it is clear from fig that

$$E_a = 0 \qquad ----(2.45)$$

and

$$I_b = I_c = 0 \qquad ----(2.46)$$

In view of equation 1.15, the zero phase sequence current is given as:

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

$$= \frac{1}{3} I_a \qquad ----(2.47)$$

The positive phase sequence current is given as

$$I_{a1} = \frac{1}{3}\left[I_a + aI_b + a^2 I_c\right]$$

$$= \frac{1}{3} I_a \qquad \text{------ (2.48)}$$

Similarly

$$I_{a2} = \frac{1}{3} I_a \qquad \text{------ (2.49)}$$

Thus

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3} I_a \qquad \text{---- (2.50)}$$

Let

$$Z_{gm} = Z_m + 3X_n \qquad \text{----- (2.42)}$$

Where Z_{gm} is the generator zero sequence impedance

Equations 2.32, 2.33 and 2.36 can also be represented in matrix form in view of equation 2.42

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_g \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \qquad \text{--- (2.43)}$$

In equation 2.43 the impedance matrix can be defined as

$$Z = \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \qquad \text{---- (2.44)}$$

In view of equation 2.32, 2.33, 2.36

$$E_{a1} = V_a - I_{a1} Z_s \qquad ----(2.51)$$

$$E_{a2} = 0 - I_{a2} Z_{as} \qquad ----(2.52)$$

$$E_{ao} = - I_{ao} (Z_m + 3X_n) \qquad ----(2.53)$$

Let

$$Z_m + 3X_n = Z_{gm}$$

where Z_{gm} is the generator zero sequence inpedence.

Adding equations 2.51, 2.52, 2.53

$$E_{a1} + E_{a2} + E_{ao} = V_1 - I_{a1} - I_{a2} Z_{as} - I_{ao} Z_{gm} \qquad -----(2.54)$$

But

$$E_a = E_{a1} + E_{a2} + E_{ao} = 0 \qquad ---(2.55)$$

Rewrite equation 2.54 in view of equations 2.50 and 2.55

$$V_a = (I_{a1} Z_s + I_{a1} Z_{as} + I_{a2} Z_{gm})$$

$$I_{a1} = 3 \frac{V_a}{Z_s + Z_{as} + Z_{gm}} \qquad ----(2.56)$$

$$I_a = 3 \frac{V_a}{Z_s + Z_{as} + Z_{gm}} \qquad -----(2.57)$$

In view of equations 2.50 and 2.51 the sequence network can be constructed as illustrated in fig 2.8.

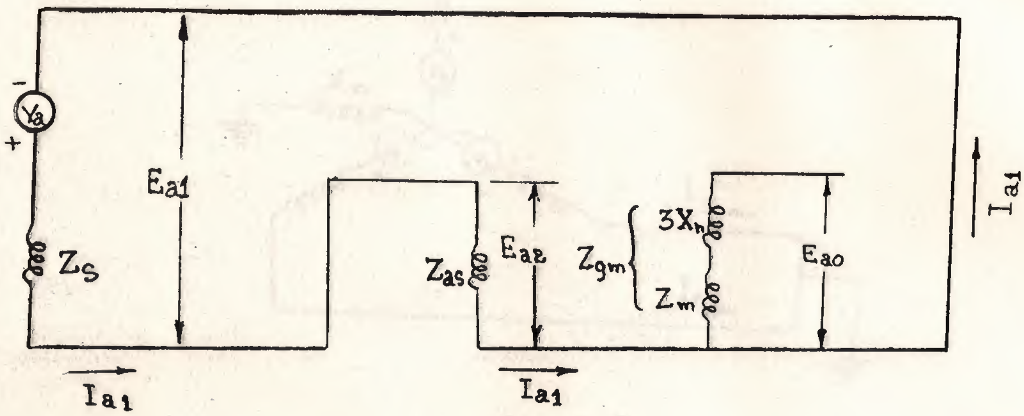

Fig 2.8
Sequence network representing single line to ground fault.

2.7 DOUBLE LINE TO GROUND FAULT ON AN UNLOADED GENERATOR.

Fig 2.9 represents the current distribution when there is a double line to ground faults which occurs between phases b and c and in view of fig 2.9

$$E_b = E_c = 0 \qquad ---- \quad (2.58)$$

and $$I_a = 0 \qquad ---- \quad (2.59)$$

Also $$E_{a1} = \frac{1}{3}(E_a + aE_b + a^2E_c) = \frac{1}{3}E_a$$

$$E_{a2} = \frac{1}{3}(E_a + a^2E_b + aE_c) = \frac{1}{3}E_a$$

and $$E_{ao} = \frac{1}{3}(E_a + E_b + E_c) = \frac{1}{3}E_a$$

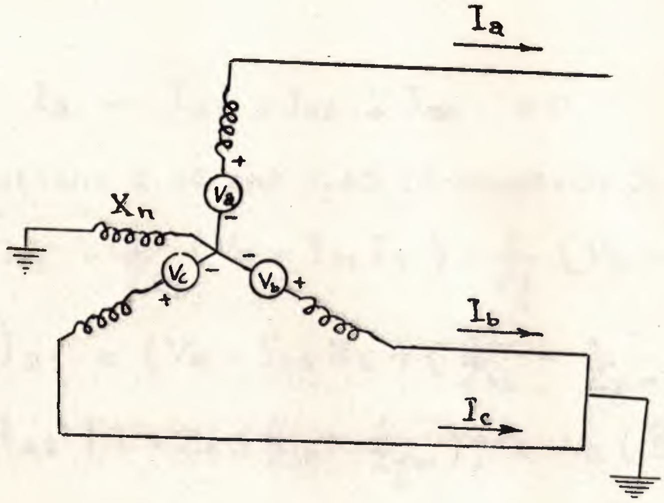

Fig 2.9
Double line to ground fault

So
$$E_{a1} = E_{a2} = E_{ao} = \frac{E_a}{3} \qquad \text{---} (2.60)$$

But
$$E_{a1} = V_a - I_{a1} Z_s \qquad \text{----}(2.61)$$

$$E_{a2} = - I_{a2} Z_{as} \qquad \text{----}(2.62)$$

$$E_{ao} = - I_{ao} Z_{gm} \qquad \text{----}(2.63)$$

In view of equation 2.60 and 3.63

$$I_{a2} = -\frac{1}{Z_{as}} (V_a - I_{a1} Z_s) \qquad \text{---} (2.64)$$

Similarly from equation 2.60 and 2.63

$$I_{ao} = \frac{-1}{Z_{gm}} (V_a - I_{a1} Z_s) \qquad \text{---} (2.65)$$

Again $I_a = I_{a1} + I_{a2} + I_{ao} = 0$ ----(2.66)

Set equations 2.64 and 2.65 in equation 2.66

$$I_{a1} - \frac{1}{Z_{as}}(V_a - I_{a1}Z_s) - \frac{1}{Z_g}(V_a - I_{a1}Z_s) = 0$$

$$I_{a1} = (V_a - I_{a1}Z_s)\left(\frac{1}{Z_{as}} + \frac{1}{Z_{gm}}\right)$$

or

$$I_{a1}\left[1 + Z_s\left(\frac{1}{Z_{as}} + \frac{1}{Z_{gm}}\right)\right] = V_a\left(\frac{Z_{as} + Z_{gm}}{Z_{as}Z_m}\right)$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{gm}Z_{as}}$$

$$I_{a1} = \frac{V_a}{Z_s + (Z_{gm}Z_{as}/(Z_{gm}+Z_{as}))} \quad \text{----(2.67)}$$

Simplify equation 2.62 and set equation 2.67

$$I_{a2} = -\frac{I_{a1}}{Z_{as}}\left(\frac{V_a}{I_{a1}} - Z_s\right)$$

$$I_{a2} = -\frac{I_{a1}}{Z_{as}}\left(\frac{V_a}{}\left(Z_s + \frac{Z_{gm}Z_{as}}{Z_{gm}Z_{as}}\right) - Z_s\right)$$

$$I_{a2} = -\frac{I_{a1}Z_{gm}}{Z_{gm}+Z_{as}}$$

Similarly simpligy equation 2.65 and set equation 2.67 in it.

$$I_{ao} = -\frac{I_{a1}}{Z_{gm}}\left(\frac{V_a}{I_{a1}} - Z_{gm}\right)$$

$$= -\frac{I_{a1}}{Z_{gm}} \frac{Z_{as}Z_{gm}}{}$$

$$= -I_{a1} \frac{Z_{as}}{Z_{gm}+Z_{as}}$$

Thus, from above equation I_{a1}, I_{a2}, I_{ao} can be obtained. E_{a1}, E_{a2}, E_{ao} an be determined once we known these currents.

The sequence network is illustrated in fig 2.11

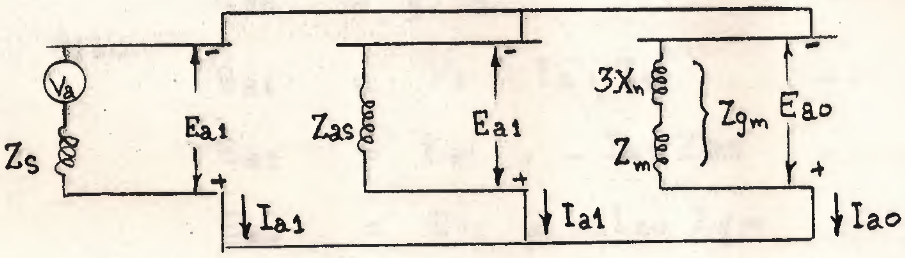

Fig 2.10
Representation of sequence network.

2.7(b) ALTERNATIVE METHOD.

To illustrate the use of the matrix the above results can be proved as follows

In view of equations 1.7 and 2.58

$$\begin{bmatrix} E_{ao} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \frac{1}{3} A \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix}$$

$$= \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix} \quad \text{----(2.68)}$$

From equation 2.68 it can be concluded that

$$E_{a1} = \frac{1}{3} E_a \quad \text{-------(2.69)}$$

$$E_{a2} = \frac{1}{3} E_a \quad \text{-------(2.70)}$$

$$E_{ao} = \frac{1}{3} E_a \quad \text{-------(2.71)}$$

Also

$$E_{a1} = V_a - I_{a1} Z_s \quad \text{-------(2.72)}$$

$$E_{a2} = E_{a1} = -I_{a1} Z_{as} \quad \text{-------(2.73)}$$

$$E_{ao} = E_{a1} = -I_{ao} Z_{gm} \quad \text{-------(2.74)}$$

so in view of above equations and equation 2.43.

$$\begin{bmatrix} V_a - I_{a1} Z_s \\ V_a - I_{a1} Z_s \\ V_a - I_{a1} Z_s \end{bmatrix} = \begin{bmatrix} 0 \\ V_1 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{---(2-75)}$$

In order to determine the values of I , I and I premultiply equation 2.75 by Z given as.

$$Z^{-1} = \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix}^{-1} = \begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \quad \text{-----(2.76)}$$

$$\begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \begin{bmatrix} V_1 - I_{a1} Z_s \\ V_1 - I_{a1} Z_s \\ V_1 - I_{a1} Z_s \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \begin{bmatrix} 0 \\ V \\ 0 \end{bmatrix} - \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

$$\text{-----(2.77)}$$

$$\text{or}\quad \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_a/Z_s \\ 0 \end{bmatrix} - \begin{bmatrix} 1/Z_{gm}\,(V_a - I_{a1} Z_s) \\ 1/Z_s\,(V_a - I_{a1} Z_s) \\ 1/Z_{as}\,(V_a - I_{a1} Z_s) \end{bmatrix}$$

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} -1/Z_{gm}\,(V_a - I_{a1} Z_s) \\ V_a/Z_s - 1/Z_s(V_a - I_{a1} Z_s) \\ -1/Z_{as}\,(V_a - Z_{a1} Z_s \end{bmatrix} \quad ----(2.78)$$

from equation 2.78 I_{ao}, I_{a1} and I_{a2} can be determined and in view of equation 2.66 the value of I_{a1} can be determined as represented by equation 3.67.

2.8. LINE TO LINE FAULT.

Fig 2.11 represents the condition and current distribution when there is a fault between two lines from cinfiguration it will be clear that

$$E_b = E_c \quad ----(2.79)$$

$$I_b = -I_c \quad ------(2.80)$$

$$I_a = 0 \quad ------(2.81)$$

But in view of equation 1.16

$$\begin{aligned} I_{a1} &= 1/3\,(I_a + aI_b + a^2 I_c) \\ &= 1/3\,(aI_b + a^2 I_c) \\ &= 1/3\, I_b\,(a - a^2) = \frac{j}{\sqrt{3}} I_b \end{aligned}$$

$$\begin{aligned} I_{a2} &= 1/3\,(I_a + a^2 I_b + aI_c) \\ &= 1/3\,(a^2 - a)\, I_b = \frac{-j}{\sqrt{3}} I_b \end{aligned}$$

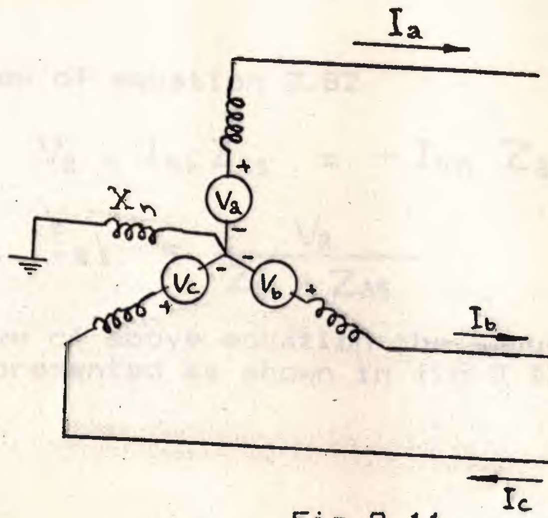

Fig 2.11
Line to line fault

$$I_{a2} = 1/3 \; (I_a + a^2 I_b + a I_c) \qquad \text{----(2.82)}$$

Also

$$I_{ao} = 1/3 \; (I_a + I_b + I_c)$$

In view of equation 2.79

$$E_{ao} + a^2 E_{a1} + a E_{a2} = E_{ao} + a E_{a1} + a^2 E_{a2}$$

$$E_{a1} (a^2 - a) = E_{a2} (a^2 - a)$$

$$E_{a1} = E_{a2}$$

SO

$$V_a - I_{a1} Z_s = - I_{a2} Z_{as}$$

In view of equation 2.82

$$V_a - I_{a1} Z_{as} = - I_{an} \; Z_{a2} Z_{as}$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{as}}$$

In view of above equation the sequence network can be represented as shown in fig 3.12.

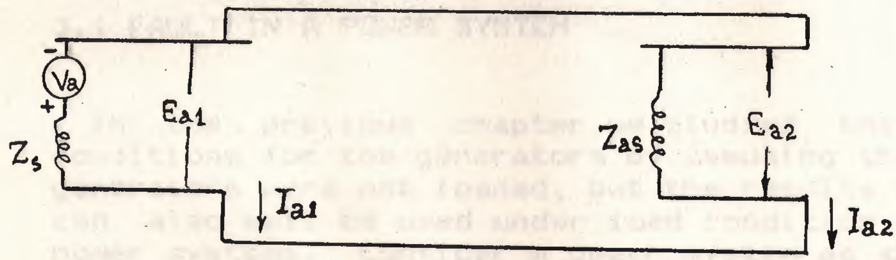

Fig 2.12
Representation of sequence network for line to line fault.

CHAPTER 3

APPLICATIONS OF SYMMETRICAL COMPONENTS IN POWER SYSTEM PROTECTION

3.1 FAULT IN A POWER SYSTEM

In the previous chapter we studied the fault conditions for the generators by assuming that the generators were not loaded, but the results derived can also well be used under load condition i.e to power systems. Consider a power system as shown in fig 3.1

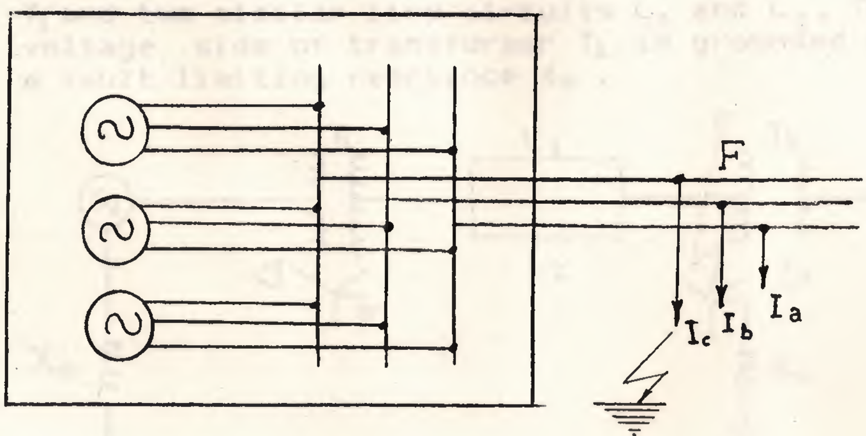

Fig 3.1
Representation of power system under load conditions

USE OF SYMMETRICAL COMPONENTS IN POWER SYSTEM PROTECTION

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ABSTRACT

The report is about the study, performed for the graduation project E.E-400. The subject of the study carried out is the use of the symmetrical components which has been found very useful in solving unbalanced polyphase circuits,and for calculation of currents resulting from unbalanced faults. Most of the faults that occur on power system are unsymmetrical faults. The unsymmetrical faults which may occur quite oftenly are like single line to ground faults, line to line faults or double line to ground faults. In order to detect such faults it is essential that the fault currents and voltages should be known. Such topics were discussed and necessary equations were derived.

We discussed faults at the terminals of an unloaded generator. Then we consider faults on a power sustem applying thevenin's theorem, which allows us to find the current in the fault by replacing the entire system by a single generator and series impedance. Faults can be very destructive to power system, different devices and protection schemes are present to prevent damages to transmission lines equipments and interruption in generator that follow the occurence of a fault. We construct a voltage filter, which is responsive to negative sequence component, so that as the power system undergoes short circuit or it starts operating abnormally. The filter circuit will indicate the presence of a negative sequence components enabling us to do necessary steps to avoid it.

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CHAPTER 1

SYMMETRICAL COMPONENTS ALGEBRA

Introduction. In case of three phase balanced currents the phase voltages and currents are of equal magnitude and they are displaced from each other by 120 degrees, or are said to be symmetrical the analysis of such systems (for calculation of line or phase voltages) is much simplier and can be carried out on per phase basis; but when the load becomes unbalanced, the analysis by usual techniques become very difficult.

To overcome this problem the method of symmetrical components was proposed by C. L. **Fortesue** and has been found very useful in solving unbalanced polyphased circuits for analytical determination of performance of the polyphase electrical circuits when operated from a system of unbalanced voltages and for calculation of currents resulting from unbalanced faults.

According to Fortesu's theorem in an unbalanced three phase system, the unbalanced phasors can be resolved into three balanced systems of Phasors.The balanced sets of component can be given as:

1. **Positive sequence component**

2. **Negative sequence component**

3. **Zero sequence component.**

1-2. **OPERATORS:** As the symmetrical components of the voltagesand currents in a three phase system are displaced from each other it is convenient to have a shorthand method of indicating the rotation of a phasor through 120°.

A Complex number of unit magnitude and associated angle THETA is an operator that rotates the phasor on which it operates through the angle THETA.

The letter a is commonly used to designete the operator that causes a rotation of 120° degree in the counterclock wise direction such an operator is a complex number of unit magnitude with an angle of 120° degrees and is defined by

$$a = 1 \angle 120^\circ = e^{j2\pi/3} = -0.5 + j0.866$$

if the operator a is applied to a phasor twice in succession, the phasor is related through 240° degrees. Three sussesive applications of a rotate the phasor through 360° degrees.

Thus,

$$a^2 = 1 \angle 240^\circ = -0.5 - j\ 0.866$$

and $$a^3 = 1 \angle 360^\circ = 1 \angle 0^\circ = 1$$

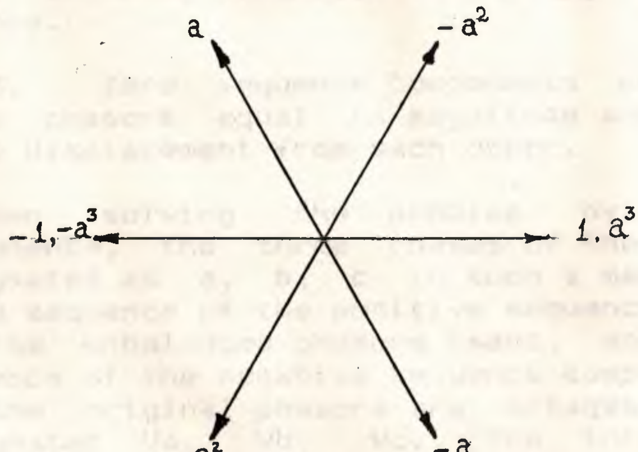


Fig 1.1

Phasors representation of various power of operator a

1-3. NOTATIONS AND MEANING OF POSITIVE NEGATIVE AND ZERO PHASE SEQUENCE.

An unbalanced system of n related phasors can be resolved into n systems of phasors called the symmetrical components of the original phasors. The n phasors of each set of components are equal in length and the angles between the adjacent phasors of the set are equal. Although the method is applicable to any unblanced polyphase system, we shall confine our discusion to three phase system

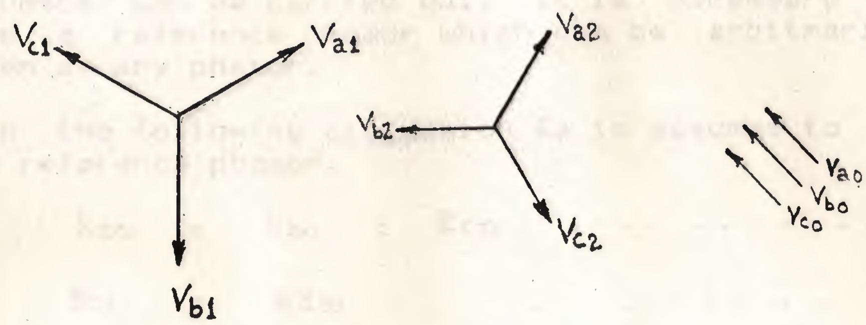
Three unbalanced phasors of a three phase system can be resolved into three balanced system of phasors. The balanced sets of components are:

1. Positive sequence components consisting of three phasors equal in magnitueds, displaced from each other by 120 degrees in phase and having the same phase sequence as the original phasors.

2. Negative sequence components consisting of three phasors equal in magnitued displaced from each other by 120 degrees in phase and having a phase sequence opposite to that of the original phasors.

3. Zero sequence components consisting of three phasors equal in magnitude and with zero phase displacement from each other.

When solving the problem by symmetrical components, the three phases of the system are designated as a, b, c in such a manner that the phase sequence of the positive sequence components of the unbalanced phasors isabc, and the phase sequence of the negative sequence components is acb if the original phasors are voltages they may be designated Va, Vb, Vc. The three sets of symmetrical components are designated by the additional subscript 1 for the positive sequence components, 2 for the negative sequence components and 0 for the zero sequence components. The positive sequence components of Va,Vb, Vc are V_{a1}, V_{b1}, V_{c1} . Fig 1.2 shows three sets of symmetrical components phasors representing currents, will be designated byI with subscript as for voltages.



Positive-Sequence components   Negative - Sequence components   Zero-Sequence component

Fig 1.2
Three sets of balanced phasors which are the symmetrical components of three unbalanced phasors.

1-4. SYMMETRICAL COMPONENT EQUATIONS.

Since each of the original unbalanced phasors is the sum of its components, the original phasors expressed interms of their components are:

$$E_a = E_{a1} + E_{a2} + E_{a0}$$

$$E_b = E_{b1} + E_{b2} + E_{b0}$$

$$E_c = E_{c1} + E_{c2} + E_{c0}$$

1-5. RESOLUTION OF UNBALANCED PHASORS INTO THEIR SYMMETRICAL COMPONENTS.

In view of discussion of operator a the components of positive, negative and zero phase sequesce can be carried out, it is necessary to have a reference phasor which can be arbitrarily taken as any phasor.

In the following discussion Ea is assumed to be the reference phasor.

$$E_{ao} = E_{bo} = E_{co} \qquad \text{------------ 1.1}$$

$$E_{c1} = aE_{a1} \qquad \text{---------- 1.2 (a)}$$

$$E_{b1} = a^2 E_{a1} \qquad \text{--------- 1.2 (b)}$$

$$E_{b2} = a\,E_{a2} \qquad \text{--------- 1.3 (a)}$$

$$E_{c2} = a^2 E_{a2} \qquad \text{--------- 1.3 (b)}$$

Now, set equations (1.1), (1.2(b)), (1.3(a)) and (1.3(b)) are arranged according to section 1.4.

$$E_a = E_{ao} + E_{a1} + E_{a2} \qquad \text{------ 1.4}$$

$$E_b = E_{bo} + a^2E_{a1} + aE_{a2} \qquad \text{------- 1.5}$$

$$E_c = E_{ao} + aE_{a1} + a^2E_{a2} \qquad \text{------- 1.6}$$

In order to find different symmetrical components, three methods can be adopted

1-5(a). MATRIX SOLUTION.

Equations (1.4)(1.5)&(1.6) can be represented in matrix form i.e,

$$\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} \quad \text{----- (1.7)}$$

let the matrix given by equation (1.7) be represented in short form as

$$E = AE_{a12} \quad \text{-------- (1.8)}$$

where the subscript 0,1,2 and stand for zero positive and negative components of the reference phasor, the matrix

$$E = \begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad \text{-------- (1.9)}$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \quad \text{----- (1.10)}$$

and,

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} \quad \text{----- (1.11)}$$

premultiply matrix (1.8) by A

$$A^{-1}E = A^{-1}A\,E_{a12}$$

[As $A^{-1}A$ is unity]

The inverse of matrix A can be obtained by usual techniques and it is easy to write,

$$A^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \quad \text{----} \quad (1.13)$$

Rewrite equation (1.12) in view of matrix equation (1.13)

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} E_a \\ E_b \\ E_c \end{bmatrix} \quad \text{----} \quad (1.14)$$

$$E_{a0} = \frac{1}{3}\left(E_a + E_b + E_c \right) \quad \text{------} \quad (1.15)$$

$$E_{a1} = \frac{1}{3}\left(E_a + aE_b + a^2E_c \right) \quad \text{-----} \quad (1.16)$$

$$E_{a2} = \frac{1}{3}\left(E_a + a^2E_b + aE_c \right) \quad \text{------} \quad (1.17)$$

1-5(b). SIMULTANIOUS ALGEBRIC SOLUTION OF EQUATIONS

Add equation (1.4), (1.5), and (1.6) and keeping in view that $(1+a+a^2)$ is zero

$$E_a + E_b + E_c = 3\,E_{a0} + (1+a+a^2)E_{a1} + (1+a+a^2)E_{a2}$$

$$\text{-----} \quad (1.18)$$

$$E_{a1} = 1/3 \; (E_a + E_b + E_c) \quad ----(1.19)$$

Now multiply equation (1.5) by a and equation (1.6) by **a** and add equation (1.4) keeping in view that a^3 is unity and a^4 is same a.

$$(E_a + aE_b + E_c) = (1 + a + a^2) E_{a1} + (1 + a^3 + a^4) E_{a1} + (1 + a^2 + a^4) E_{a2}$$

$$E_{a1} = 1/3 \; (E_a + aE_b + a^2 E_c) \quad ------(1.20)$$

Similarly it can be shown that if equation (1.5) is multiplied by a^2 and equation (1.6) by a and their results are added to equation (1.4) E_{a2} can be represented by equation (1.17).

Thus the different components can be obtained by equation (1.15), (1.16), (1.17).

CHAPTER 2

ASYMMETRICAL FAULT CURRENTS.

2.1 INTRODUCTION

In power systems faults may occur mainly due to following two reasons:

1. Insulation failure

It may be caused by over - voltage applied to the system produced by the switching surge or by a lighting stroke. However, the insulation failure in case of line insulators may be caused by stress and strain of severe hot and cold weather.

2. MECHANICAL INJURY

In case of transmission lines it may be caused by high velocity winds or by falling trees etc.

The determination of short circuit current in power system has great importance from protection or view. For adequate protection , it is necessary to determine the capacity of the power system to supply short circuit current.

2.2 TYPES OF SHORT CIRCUITS.

The fault in power system may occur:

1. Between one phase and earth
2. Between phase and phase
3. Between two phases and earth
4. Between two phases and at the same time there may be a falt betyween third phase and earth
5. Between all the three phases
6. Between all the three phases and ground

The first four types of faults produce asymmetrical fault currents, while the later two types produce symmetrical short circuit currents.
The possibility of symmetrical fault in a power system is quite rare.The actual fault may occur on one line and ground or two lines or there may occur fault between two lines and ground. In this chapter we will deal with these types of faults only which are asymmetrical faults producing asymmetrical fault currents and voltages.

2.3 ASYMMETRICAL SERIES IMPEDANCE

In this section we shall be concerned with system that are normally balanced. The short circuit faults cause unbalancing of the system. Fig 2.1 shows the asymmetrical part of a system in which Z_1, Z_2, Z_3 and Z_n are the impedances in each phase and in the neutral respectively. Let there be no mutual impedence between them.

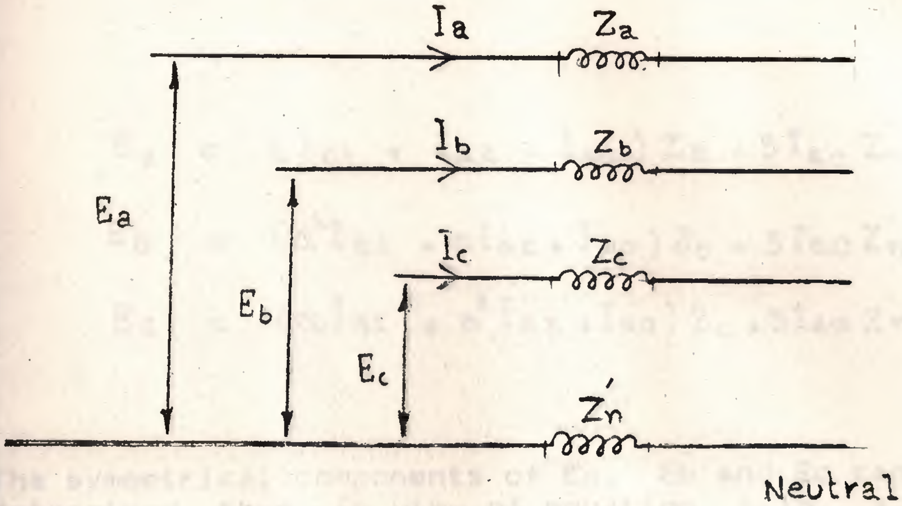


Fig 2.1
Unbalance system of self-impedances

In view of Kirchhoff's law,

$$E_a = I_a Z_a + I_n Z_n' \qquad \text{------} \quad (2.1)$$

$$E_b = I_b Z_b + I_n Z_n' \qquad \text{-----} \quad (2.2)$$

$$E_c = I_c Z_c + I_n Z_n' \qquad \text{-----} \quad (2.3)$$

when,
$$I_n = I_a + I_b + I_c \qquad \text{------} \quad (2.4)$$

In view of equation (1-15)

$$I_n = 3 I_{ao} \qquad \text{------} \quad (2.5)$$

In view of equation 2-5 , and using equation 1.4, 1.5, 1.6 which are rewritte below equation 2.1 to 2.3 can be written as equation 2.6 to 2.8.

$$E_a = E_{a1} + E_{a2} + E_{ao} \qquad \text{--------} (1.4)$$

$$E_b = a^2 E_{a1} + a E_{a2} + E_{ao} \qquad \text{------} (1.5)$$

$$E_c = a E_{a1} + a^2 E_{a2} + E_{ao} \qquad \text{-----} (1.6)$$

$$E_a = (I_{a1} + I_{a2} + I_{ao})Z_a + 3I_{ao}Z_n' \quad \ldots(2.6)$$

$$E_b = (a^2 I_{a1} + aI_{a2} + I_{ao})Z_b + 3I_{ao}Z_n' \quad \ldots(2.8)$$

$$E_c = (aI_{a1} + a^2 I_{a2} + I_{ao})Z_c + 3I_{ao}Z_n' \quad (2.9)$$

The symmetrical components of Ea, Eb and Ec can be determined thus in view of equation 1.15, 1.16, 1.17 which are rewritten below.

$$E_{ao} = \frac{1}{3}(E_a + E_b + E_c) \quad \text{--------} (1.15)$$

$$E_{a1} = \frac{1}{3}(E_a + aE_b + a^2 E_c) \quad \text{--------} (1.16)$$

$$E_{a2} = \frac{1}{3}(E_a + a^2 E_b + aE_c) \quad \text{--------} (1.17)$$

Using equation 1.16 and equation 2.6 to 2.8

$$E_{a1} = \frac{1}{3}\left[(I_{a1} + I_{a2} + I_{ao})Z_a + 3I_{ao}Z_n'\right] + \frac{1}{3}a\left[(a^2 I_{a1} + aI_{a2} + I_{ao})Z_b + 3I_{ao}Z_n'\right] + \frac{1}{3}a^2\left[(aI_{a1} + a^2 I_{a2} + I_{ao})Z_c + 3I_{ao}Z_n'\right]$$

$$E_{a1} = \frac{1}{3}I_{a1}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3}I_{a2}\left[Z_a + a^2 Z_b + aZ_c\right] + \frac{1}{3}I_{ao}\left[Z_a + aZ_b + a^2 Z_c + 3Z_n'(1 + a + a^2)\right]$$

$$E_{a1} = \frac{1}{3}I_{a1}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3}I_{a2}\left[Z_a + a^2 Z_b + aZ_c\right] + \frac{1}{3}I_{ao}\left[Z_a + aZ_b + a^2 Z_c\right] \quad \text{--------} (2\text{-}9)$$

Similarly,

$$E_{a2} = \frac{1}{3} I_{a1}\left[Z_a + aZ_b + a^2 Z_c\right] + \frac{1}{3} I_{a2}\left[Z_a + Z_b + Z_c\right] + \frac{1}{3} I_{ao}\left[Z_a + a^2 Z_b + a Z_c\right] \quad \text{-----} (2.10)$$

$$E_{ao} = \frac{1}{3} I_{a1}\left[Z_a + a^2 Z_b + aZ_c\right] + \frac{1}{3} I_{a2}\left[Z_a + aZ_b + a^2 Z_c\right] + \frac{1}{3} I_{ao}\left[Z_a + Z_b + Z_c + 9 Z_n'\right] \quad \text{----} (2.11)$$

Let Z_m, Z_s, Z_{as} be the zero sequence positive sequence components of impedances given as

$$Z_m = \frac{1}{3}(Z_a + aZ_b + Z_c) \quad \text{------} (2-12)$$

$$Z_s = \frac{1}{3}(Z_a + aZ_b + Z_c) \quad \text{-----} (2-13)$$

$$Z_{as} = \frac{1}{3}(Z_a + a^2 Z_b + aZ_c) \quad \text{------} (2.14)$$

Substituting equation (2.12) to (2.14) in equation (2.9) to (2.11)

$$E_{a1} = I_{a1} Z_m + I_{a2} Z_{as} + I_{ao} Z_s$$

$$E_{a2} = I_{a1} Z_s + I_{a2} Z_m + I_{ao} Z_n$$

$$E_{ao} = I_{a1} Z_{as} + I_{a2} Z_s + I_{ao}(Z_m + 9 Z_n')$$

Thus it can be observed that current of one sequence can produce voltage of other sequence.

SECOND METHOD BY APPLICATION OF MATRIX EQUATION

The previous results can also be proved by matrix equation. For simplicity it has been assumed that there is no impedance in the neutral as shown in fig 2.2.

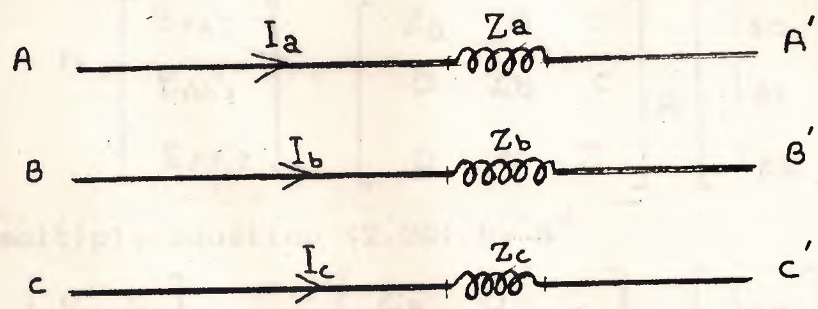


Fig 2.2
Unsymmetrical impedance in the three phases

$$E_{AA'} = I_a Z_a \quad \text{-----------} \quad (2.18(a))$$

$$E_{BB'} = I_b Z_b \quad \text{-----------} \quad (2.18(b))$$

and, $$E_{CC'} = I_c Z_c \quad \text{-----------} \quad (2.18(c))$$

The equation 2.18 can be represented by a matrix form as:

$$\begin{bmatrix} E_{AA'} \\ E_{BB'} \\ E_{CC'} \end{bmatrix} = \begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad \text{----} \quad (2.19)$$

$$A^{-1}\begin{bmatrix} Z_a & 0 & 0 \\ 0 & Z_b & 0 \\ 0 & 0 & Z_c \end{bmatrix} A = \frac{1}{3}\begin{bmatrix} Z_a & Z_b & Z_c \\ Z_a & aZ_b & a^2Z_c \\ Z_a & a^2Z_b & aZ_c \end{bmatrix}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix}$$

$$= \frac{1}{3}\begin{bmatrix} Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c \\ Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ \\ Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c \end{bmatrix}$$

----(2.23)

Set equation (2.23) in equation (3.20)

$$\begin{bmatrix} E_{AA'0} \\ E_{AA'1} \\ E_{AA'2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z_c \\ Z_a + aZ_b + a^2Z_c & Z_a + Z_b + Z_c & Z_a + a^2Z_b + aZ_c \\ Z_a + a^2Z_b + aZ_c & Z_a + aZ_b + a^2Z & Z_a + Z_b + Z_c \end{bmatrix}\begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{ac} \end{bmatrix}$$

or,

----(2.24)

$$E_{AA'0} = \frac{1}{3}(Z_a + Z_b + Z_c)I_{a0} + \frac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a1} + \frac{1}{3}(Z_a + aZ_b + a^2Z_c)I_{a2}$$

----(2.25)

$$E_{AA'1} = \frac{1}{3}(Z_a + aZ_b + a^2Z_c)I_{a0} + \frac{1}{3}(Z_a + Z_b + Z_c)I_{a1} + \frac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a2}$$

----(2.26)

$$E_{AA'2} = \frac{1}{3}(Z_a + a^2Z_b + aZ_c)I_{a0} + \frac{1}{3}(Z_a + aZ_b + a^2Z_c) + \frac{1}{3}(Z_a + Z_b + Z_c)I_{a2}$$

----(2.27)

The equation (2.25, 2.26 and 2.27) can be simplified to a great extent if the impedance Z_a, Z_b and Z_c all are equal to Z, so rewritting equation 2.25, 2.26, 2.27 we get,

$$E_{AA'0} = Z I_{a0} \qquad \text{------} \qquad (2.28)$$

$$E_{AA'1} = Z I_{a1} \qquad \text{------} \qquad (2.29)$$

$$E_{AA'2} = Z I_{a2} \qquad \text{------} \qquad (2.30)$$

Thus, from equation 2.28, 2.29 and 2.30 it can be observed that if unbalanced current flow in symmetrical (equal) series impedances the symmetrical components of voltage drops is of like sequence only, provided no coupling exists between phases, if the impedances are unequal, Equations 2.25, 2.26, 2.27 show that the voltage drop of any one sequence is dependent on the currents of all three sequences.

2.4 SEQUENCE NETWORKS.

This is the most important concept of symmetrical components. The sequence network is an equivalent network which is supposed to be balanced system operating under one of the sequence component of voltages and currents.

Thus the impedance of the network offered to the flow of positive sequence currents is called the positive impedance similarly if only negative sequence currents flow the impedence of the network offered to this current is called negative sequence impedence, also the impedance offered to zero sequence impedance of the network.

Hence the sequence network in reference to any particular sequence currents consist of a single phase network having impedance offered to one particular sequence components of current.

IMPEDENCES WHICH ARE INDEPENDENT OF THE PHASE ORDER OF CURRENTS ARE CALLED INDEPENDENT IMPEDENCES, THOSE DEPENDANT ON THE PHASE SEQUENCE ORDER OF THE CURRENTS ARE CALLED DEPENDANT IMPEDENCES. *

Z_m, Z_s, Z_{as} REPRESENT DEPENDANT IMPEDANCES OPPOSED TO I_o, I_1 AND I_2.

---

* As defined by Prof. Haldun Gurmen

2.5 SETTING UP OF THE SEQUENCE NETWORK.

As the sequence network is to be set up seperately for each sequence. This will help us for the analysis under asymmetrical faults. In order to develop set network it is viewed from the fault point assuming that a particular sequence current flows in the circuit. The method consists of assuming that a certain voltage is impressed across the terminals of networks which is followed for the current flow to fault point. However, for zero phase sequence networks one must view the network from fault point because zero phase sequence current may not be flowing through out the circuit.

For example consider unloaded generator which is grounded through reactance X_n, let an assymetrical fault occur (which also involves the ground fault) causing unbalanced currents I_a, I_b and I_c flows through the lines as illustrated in fig 2.3.

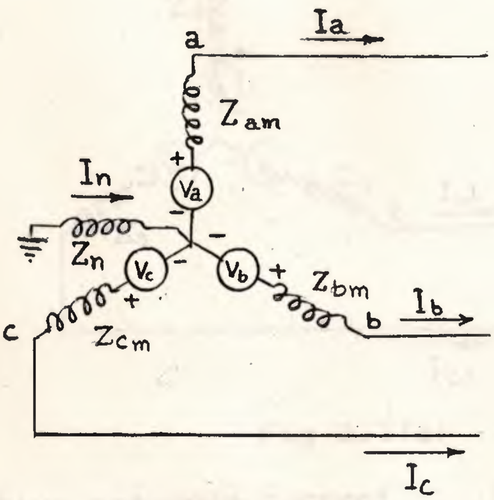


Fig 2.3. Represențatiion of unsymmetrical fault on an unbalanced generator.

Since, there is also a ground fault current I_n will flow into the ground reactance X_n . The positive phase sequence component of currents are I_{a1}, I_{b1} and I_{c1} while the negative sequence components are I_{a2}, I_{b2} and I and zero pahse sequence currents are I , I I_{c2} . The generator are always designed to generate balanced voltages so, the generated voltages are positive sequence only. Let V_a , V_b and V_c be the generated phase voltages also assume Z_s , Z_{as} and Z_m be the positive, negative and zero sequence impedance of the generator. Let E_a, E_b and E_c be the potential between the terminal of the generator.

The paths for currents of each sequence in a generator and the corresponding sequence networks are shown in fig 3.3

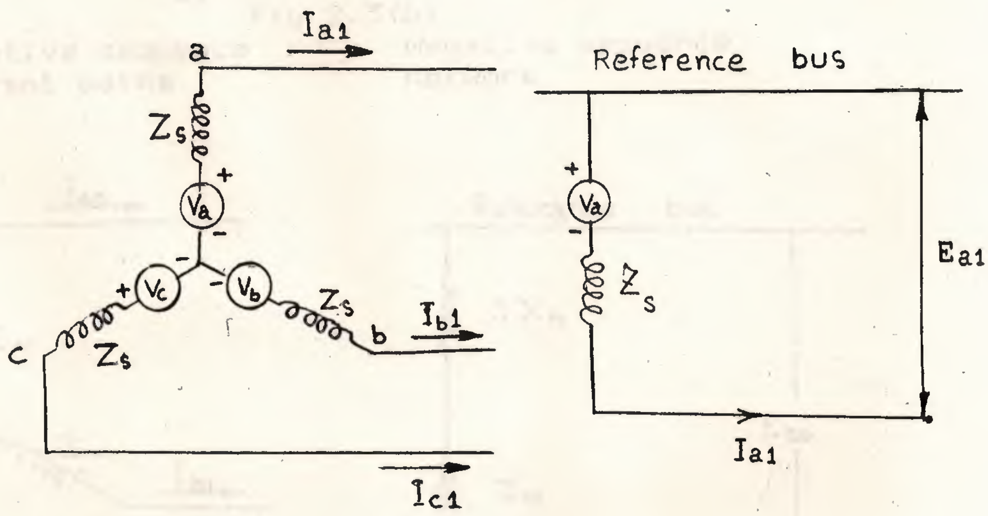


Fig 2.3(a)

Positive sequence current paths.

Positive sequence network

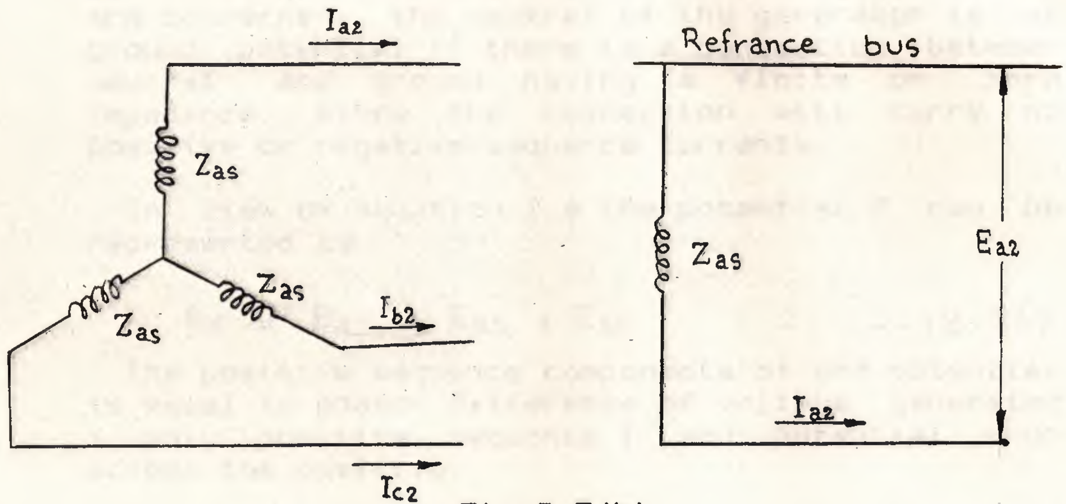


Fig 2.3(b)

Negative sequence current paths

Negative sequence network

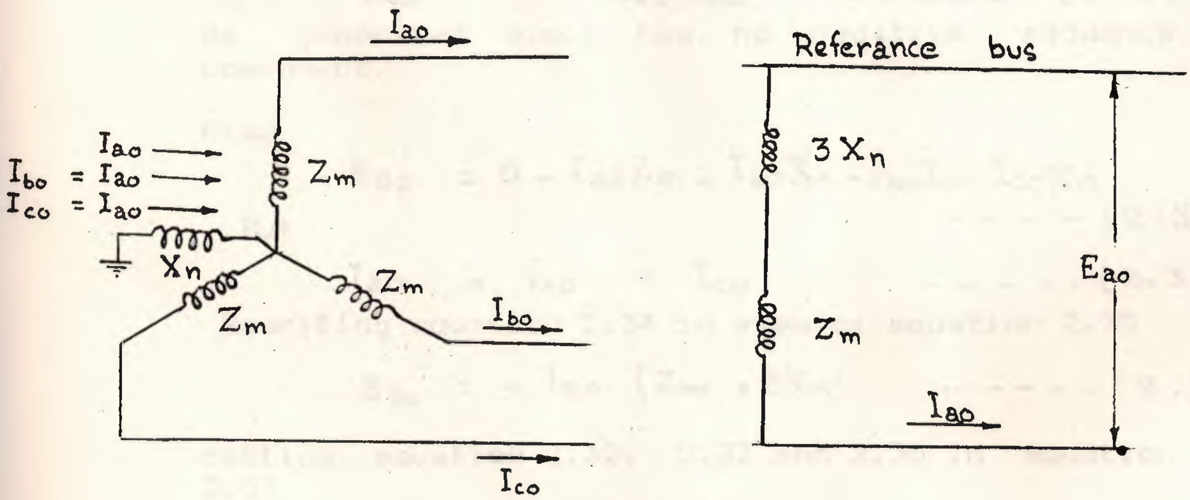


Fig 2.3(c)

Zero sequence current paths

Zero sequence network.

The reference bus for the positive and negative sequence networks is the neutral of the generator. So far as positive and negative sequence components are concerned, the neutral of the generator is at ground potential if there is a connection between neutral and ground having a finite or zero impedance since the connection will carry no positive or negative sequence currents.

In view of equation 1.4 the potential E can be represented as

$$E_a = E_{a1} + E_{a2} + E_{a0} \qquad ----- (2.31)$$

The positive sequence components of the potential is equal to phasor difference of voltage generated (only positive sequence) and potential drop across the positive.

$$E_{a1} = V_a - I_{a1} Z_s \qquad ----- (2.32)$$

Similarly

$$E_{a2} = 0 - I_{a2} Z_{as} \qquad ------- (2.33)$$

As generated e.m.f has no negative sequence component.

Also

$$E_{a0} = 0 - I_{a0} Z_m - I_{a0} X_n - I_{b0} X_n - I_{c0} X_n \qquad ---- (2.34)$$

But

$$I_{a0} = I_{b0} = I_{c0} \qquad ----- (2.35)$$

Rewriting equation 2.34 in view of equation 2.35

$$E_{a0} = - I_{a0} \ (Z_m + 3X_n) \qquad ----- (2.36)$$

Setting equation 2.32, 2.33 and 2.35 in equation 2.31

$$E_a = (V_a - I_{a1} Z_s) - I_{a1} Z_{as} - I_{a0} (Z_m + 3X_n)$$

similarly

$$E_b = (V_b - I_{b1} Z_s) - I_{b2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

and

$$E_c = (V_c - I_{c1} Z_s) - I_{c2} Z_{as} - I_{ao}(Z_{as} + 3X_n)$$

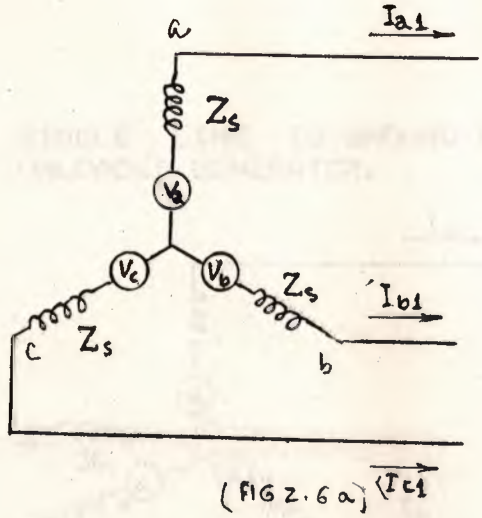
Rewriting equations 2.38 and 2.39 in view of equation 1.2 and 1.3

$$E_b = (a^2 V_a - a^2 I_{a1} Z_s) - a I_{a2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

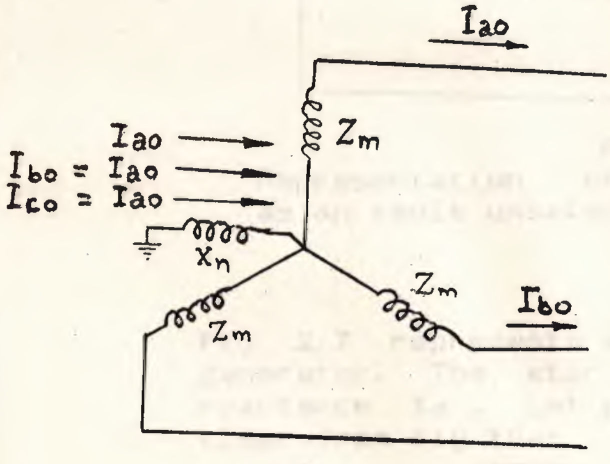
and

$$E_c = (a V_a - a I_{a1} Z_s) - a^2 I_{a2} Z_{as} - I_{ao}(Z_m + 3X_n)$$

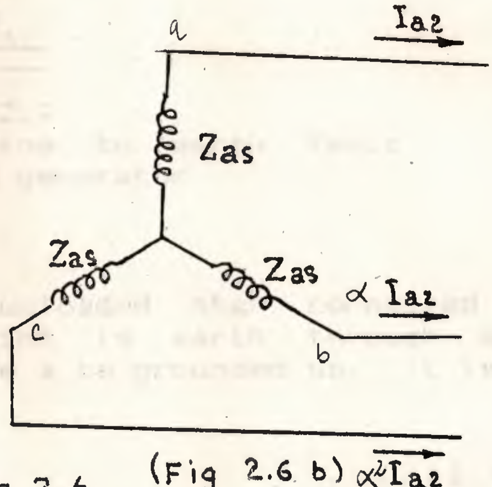
Now considering equations 2.37, 2.40 and 2.41 the first component within the paranthesis of these equation represents the generated e.m.f and only positive impedance, or these three components can be combined together to form a positive sequence network as shown in fig 2.4 similarly, if the second components of these equations are combined together they will represent negative sequence as shown in fig 2.5 . Also, the third components of these equations are combined together to a zero phase sequence network and are shown in fig 2.6.



(FIG 2.6 a)



(Fig 2.6 c)



(Fig 2.6 b)

Fig 2.6

(a) The three components $(V_a - I_{a1}Z_s)$, $(a^2 V_a - a^2 I_{a1} Z_s)$ and $(aV_a - aI_{a1}Z_s)$ are combined together to form a positive sequence network.

(b) The three components $(I_{a2} Z_{as})$ $(a^2 I_{a2} Z_{as})$ and $(aI_{a2}\ Z_{as})$ are combined together to form a negative sequence network

(c) The three components $I_{a0}(Z_m + 3X_n)$ are combined together to form zero sequence network.

2.6 SINGLE LINE TO GROUND FAULT IN CASE OF AN UNLOADED GENERATOR.

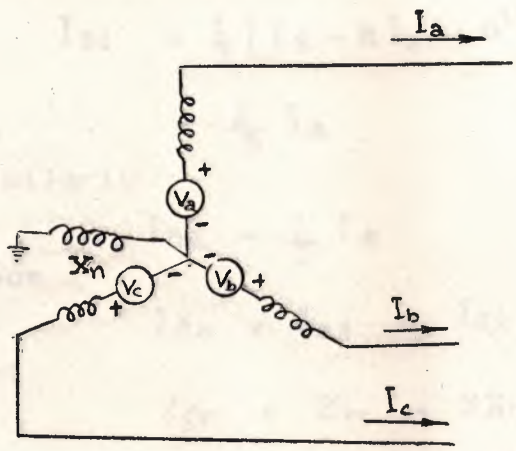


Fig 2.7
Representation of line to earth fault as an fault unbalanced generator

Fig 2.7 represents an unloaded star connected generator. The star point is earth through a reactance X_n. Let phase a be grounded so, it is clear from fig that

$$E_a = 0 \qquad \text{----}(2.45)$$

and

$$I_b = I_c = 0 \qquad \text{----}(2.46)$$

In view of equation 1.15, the zero phase sequence current is given as:

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

$$= \frac{1}{3} I_a \qquad \text{----}(2.47)$$

The positive phase sequence current is given as

$$I_{a1} = \frac{1}{3}\left[I_a + aI_b + a^2 I_c\right]$$

$$= \frac{1}{3} I_a \qquad \text{------ (2.48)}$$

Similarly

$$I_{a2} = \frac{1}{3} I_a \qquad \text{------ (2.49)}$$

Thus

$$I_{a0} = I_{a1} = I_{a2} = \frac{1}{3} I_a \qquad \text{---- (2.50)}$$

Let

$$Z_{gm} = Z_m + 3X_n \qquad \text{----- (2.42)}$$

Where Z_{gm} is the generator zero sequence impedance

Equations 2.32, 2.33 and 2.36 can also be represented in matrix form in view of equation 2.42

$$\begin{bmatrix} E_{a0} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_g \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \begin{bmatrix} I_{a0} \\ I_{a1} \\ I_{a2} \end{bmatrix} \qquad \text{--- (2.43)}$$

In equation 2.43 the impedance matrix can be defined as

$$Z = \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \qquad \text{---- (2.44)}$$

In view of equation 2.32, 2.33, 2.36

$$E_{a1} = V_a - I_{a1} Z_s \quad ----(2.51)$$

$$E_{a2} = 0 - I_{a2} Z_{as} \quad ----(2.52)$$

$$E_{ao} = - I_{ao} (Z_m + 3X_n) \quad ----(2.53)$$

Let

$$Z_m + 3X_n = Z_{gm}$$

where Z_{gm} is the generator zero sequence inpedence.

Adding equations 2.51, 2.52, 2.53

$$E_{a1} + E_{a2} + E_{ao} = V_1 - I_{a1} - I_{a2} Z_{as} - I_{ao} Z_{gm}$$

But ----(2.54)

$$E_a = E_{a1} + E_{a2} + E_{ao} = 0 \quad ---(2.55)$$

Rewrite equation 2.54 in view of equations 2.50 and 2.55

$$V_a = (I_{a1} Z_s + I_{a1} Z_{as} + I_{a2} Z_{gm})$$

$$I_{a1} = 3 \frac{V_a}{Z_s + Z_{as} + Z_{gm}} \quad ----(2.56)$$

$$I_a = 3 \frac{V_a}{Z_s + Z_{as} + Z_{gm}} \quad -----(2.57)$$

In view of equations 2.50 and 2.51 the sequence network can be constructed as illustrated in fig 2.8.

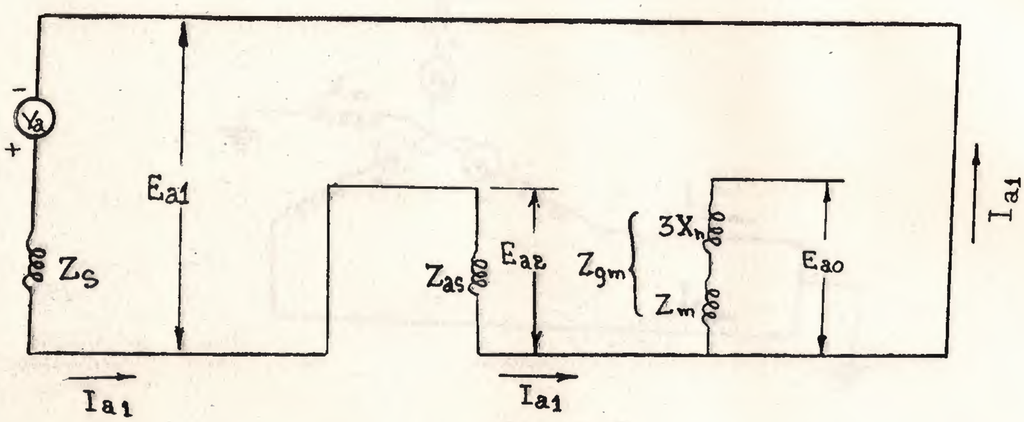


Fig 2.8
Sequence network representing single line to ground fault.

2.7 DOUBLE LINE TO GROUND FAULT ON AN UNLOADED GENERATOR.

Fig 2.9 represents the current distribution when there is a double line to ground faults which occurs between phases b and c and in view of fig 2.9

$$E_b = E_c = 0 \quad \text{----} \quad (2.58)$$

and

$$I_a = 0 \quad \text{----} \quad (2.59)$$

Also

$$E_{a1} = \frac{1}{3}(E_a + aE_b + a^2E_c) = \frac{1}{3}E_a$$

$$E_{a2} = \frac{1}{3}(E_a + a^2E_b + aE_c) = \frac{1}{3}E_a$$

and

$$E_{ao} = \frac{1}{3}(E_a + E_b + E_c) = \frac{1}{3}E_a$$

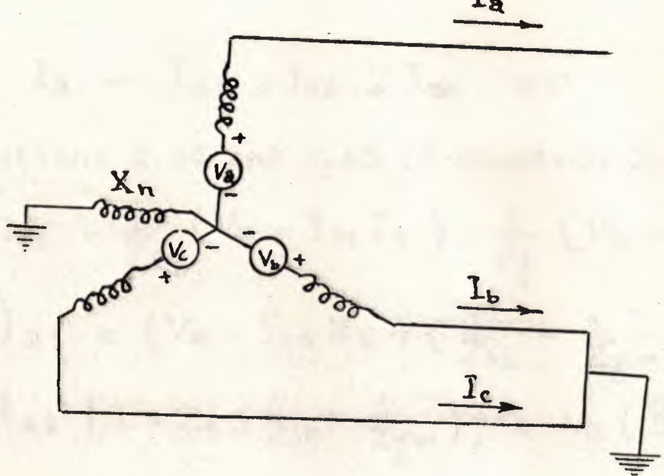


Fig 2.9
Double line to ground fault

So $$E_{a1} = E_{a2} = E_{ao} = \frac{E_a}{3} \quad \text{---} (2.60)$$

But
$$E_{a1} = V_a - I_{a1} Z_s \quad \text{----}(2.61)$$

$$E_{a2} = - I_{a2} Z_{as} \quad \text{----}(2.62)$$

$$E_{ao} = -I_{ao} Z_{gm} \quad \text{----}(2.63)$$

In view of equation 2.60 and 3.63

$$I_{a2} = -\frac{1}{Z_{as}} (V_a - I_{a1} Z_s) \quad \text{---} (2.64)$$

Similarly from equation 2.60 and 2.63

$$I_{ao} = \frac{-1}{Z_{gm}} (V_a - I_{a1} Z_s) \quad \text{---} (2.65)$$

Again $I_a = I_{a1} + I_{a2} + I_{ao} = 0$ ----(2.66)

Set equations 2.64 and 2.65 in equation 2.66

$$I_{a1} - \frac{1}{Z_{as}}(V_a - I_{a1}Z_s) - \frac{1}{Z_g}(V_a - I_{a1}Z_s) = 0$$

$$I_{a1} = (V_a - I_{a1}Z_s)\left(\frac{1}{Z_{as}} + \frac{1}{Z_{gm}}\right)$$

or $$I_{a1}\left[1 + Z_s\left(\frac{1}{Z_{as}} + \frac{1}{Z_{gm}}\right)\right] = V_a\left(\frac{Z_{as} + Z_{gm}}{Z_{as}Z_m}\right)$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{gm}Z_{as}}$$

$$I_{a1} = \frac{V_a}{Z_s + (Z_{gm}Z_{as}/(Z_{gm}+Z_{as}))} \quad \text{----(2.67)}$$

Simplify equation 2.62 and set equation 2.67

$$I_{a2} = -\frac{I_{a1}}{Z_{as}}\left(\frac{V_a}{I_{a1}} - Z_s\right)$$

$$I_{a2} = -\frac{I_{a1}}{Z_{as}}\left(\frac{V_a}{} \left(Z_s + \frac{Z_{gm}Z_{as}}{Z_{gm}Z_{as}}\right) - Z_s\right)$$

$$I_{a2} = -\frac{I_{a1}\,Z_{gm}}{Z_{gm}+Z_{as}}$$

Similarly simpligy equation 2.65 and set equation 2.67 in it.

$$I_{ao} = -\frac{I_{a1}}{Z_{gm}}\left(\frac{V_a}{I_{a1}} - Z_{gm}\right)$$

$$= -\frac{I_{a1}}{Z_{gm}}\ \frac{Z_{as}\ Z_{gm}}{}$$

$$= -\frac{I_{a1}}{}\ \frac{Z_{as}}{Z_{gm}+Z_{as}}$$

Thus, from above equation I_{a1}, I_{a2}, I_{ao} can be obtained. E_{a1}, E_{a2}, E_{ao} an be determined once we known these currents.

The sequence network is illustrated in fig 2.11

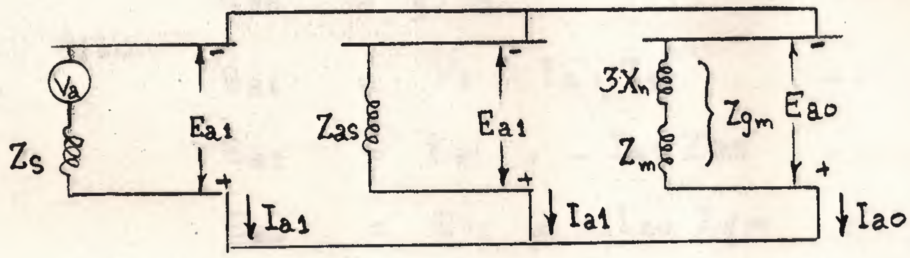


Fig 2.10
Representation of sequence network.

2.7(b) ALTERNATIVE METHOD.

To illustrate the use of the matrix the above results can be proved as follows

In view of equations 1.7 and 2.58

$$\begin{bmatrix} E_{ao} \\ E_{a1} \\ E_{a2} \end{bmatrix} = \frac{1}{3} A \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix}$$

$$= \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} E_1 \\ 0 \\ 0 \end{bmatrix} \quad \text{----(2.68)}$$

From equation 2.68 it can be concluded that

$$E_{a1} = \frac{1}{3} E_a \quad \text{------(2.69)}$$

$$E_{a2} = \frac{1}{3} E_a \quad \text{------(2.70)}$$

$$E_{ao} = \frac{1}{3} E_a \quad \text{------(2.71)}$$

Also

$$E_{a1} = V_a - I_{a1} Z_s \quad \text{------(2.72)}$$

$$E_{a2} = E_{a1} = - I_{a1} Z_{as} \quad \text{------(2.73)}$$

$$E_{ao} = E_{a1} = - I_{ao} Z_{gm} \quad \text{------(2.74)}$$

so in view of above equations and equation 2.43.

$$\begin{bmatrix} V_a - I_{a1} Z_s \\ V_a - I_{a1} Z_s \\ V_a - I_{a1} Z_s \end{bmatrix} = \begin{bmatrix} 0 \\ V_1 \\ 0 \end{bmatrix} - \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix} \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} \quad \text{---(2-75)}$$

In order to determine the values of I , I and I premultiply equation 2.75 by Z given as.

$$Z^{-1} = \begin{bmatrix} Z_{gm} & 0 & 0 \\ 0 & Z_s & 0 \\ 0 & 0 & Z_{as} \end{bmatrix}^{-1} = \begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \quad \text{-----(2.76)}$$

$$\begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \begin{bmatrix} V_1 - I_{a1} Z_s \\ V_1 - I_{a1} Z_s \\ V_1 - I_{a1} Z_s \end{bmatrix} = \begin{bmatrix} \frac{1}{Z_{gm}} & 0 & 0 \\ 0 & \frac{1}{Z_s} & 0 \\ 0 & 0 & \frac{1}{Z_{as}} \end{bmatrix} \begin{bmatrix} 0 \\ V \\ 0 \end{bmatrix} - \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix}$$

$$\text{-----(2.77)}$$

$$\text{or}\quad \begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} 0 \\ V_a/Z_s \\ 0 \end{bmatrix} - \begin{bmatrix} 1/Z_{gm}\,(V_a - I_{a1}Z_s) \\ 1/Z_s\,(V_a - I_{a1}Z_s) \\ 1/Z_{as}\,(V_a - I_{a1}Z_s) \end{bmatrix}$$

$$\begin{bmatrix} I_{ao} \\ I_{a1} \\ I_{a2} \end{bmatrix} = \begin{bmatrix} -1/Z_{gm}\,(V_a - I_{a1}Z_s) \\ V_a/Z_s - 1/Z_s(V_a - I_{a1}Z_s) \\ -1/Z_{as}\,(V_a - Z_{a1}Z_s \end{bmatrix} \quad ----(2.78)$$

from equation 2.78 I_{ao}, I_{a1} and I_{a2} can be determined and in view of equation 2.66 the value of I_{a1} can be determined as represented by equation 3.67.

2.8. LINE TO LINE FAULT.

Fig 2.11 represents the condition and current distribution when there is a fault between two lines from cinfiguration it will be clear that

$$E_b = E_c \quad ----(2.79)$$

$$I_b = -I_c \quad ------(2.80)$$

$$I_a = 0 \quad ------(2.81)$$

But in view of equation 1.16

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

$$= 1/3\,(aI_b + a^2I_c)$$

$$= 1/3\,I_b(a - a^2) = \frac{j}{\sqrt{3}}\,I_b$$

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

$$= 1/3\,(a^2 - a)\,I_b = \frac{-j}{\sqrt{3}}\,I_b$$

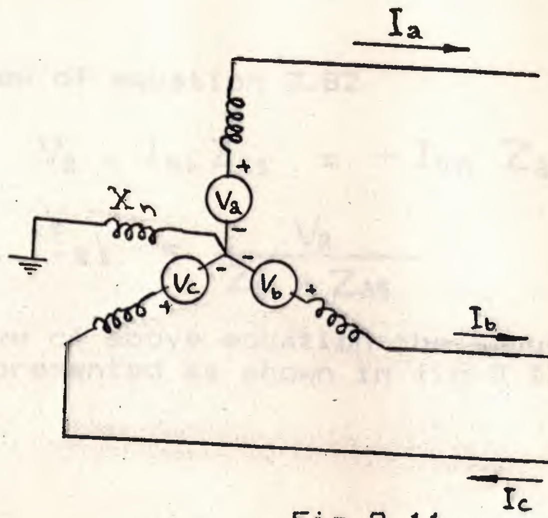


Fig 2.11
Line to line fault

$$I_{a2} = 1/3 \; (I_a + a^2 I_b + a I_c) \qquad ----(2.82)$$

Also

$$I_{ao} = 1/3 \; (I_a + I_b + I_c)$$

In view of equation 2.79

$$E_{ao} + a^2 E_{a1} + a E_{a2} = E_{ao} + a E_{a1} + a^2 E_{a2}$$

$$E_{a1} (a^2 - a) = E_{a2} (a^2 - a)$$

$$E_{a1} = E_{a2}$$

So

$$V_a - I_{a1} Z_s = - I_{a2} Z_{as}$$

In view of equation 2.82

$$V_a - I_{a1} Z_{as} = - I_{an} Z_{a2} Z_{as}$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{as}}$$

In view of above equation the sequence network can be represented as shown in fig 3.12.

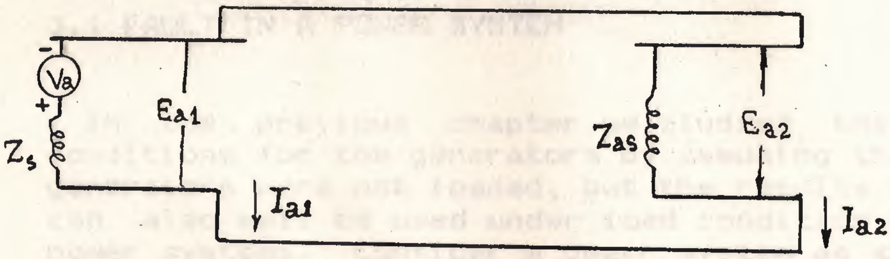


Fig 2.12
Representation of sequence network for line to line fault.

CHAPTER 3

APPLICATIONS OF SYMMETRICAL COMPONENTS IN POWER SYSTEM PROTECTION

3.1 FAULT IN A POWER SYSTEM

In the previous chapter we studied the fault conditions for the generators by assuming that the generators were not loaded, but the results derived can also well be used under load condition i.e to power systems. Consider a power system as shown in fig 3.1

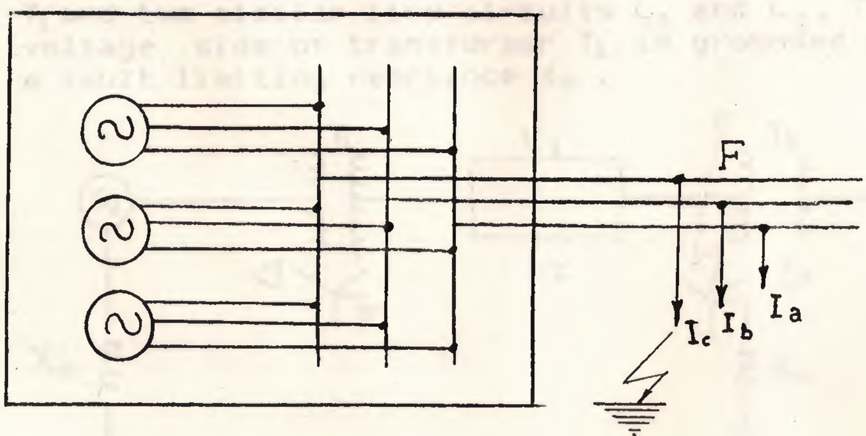


Fig 3.1
Representation of power system under load conditions

Let there be a fault at point F of the feeder. Assume that there is a small off-shoot or stub lines from the feeder at fault point as shown in fig 3.1. Let I_a , I_b and I_c be current in the three phase of the hypothetical stubs. The flow of current from each line into the fault is indecated by arrows on the diagram beside hypothetical stubs connected to each line at the fault location. Appropriate connection of the stubs represent various types of faults. If it is assumed that the power system consist of linear elements the whole system can be reduced to a single generator with an equivalent internal impedance by use of Thevinin's theorem. Let Z_m, Z_s and Z_{as} be the zero, positive and negative sequence impedance respectively. Also let, E_1 , E_2 and E_3 be the zero positive and negative symmetrical components respectively. Let, the open circuit generatied voltage for each phase be V_a , V_b and V_c respectively.

In order to illustrate the technique for fault currnet consider a single power system as show in fig 3.2 having similar generators G_1 and G_2 connected together through two transformers T_1 and T_2 and two similar line circuits L_1 and L_2. The high voltage side of transformer T_2 is grounded through a fault limiting reactance X_n .

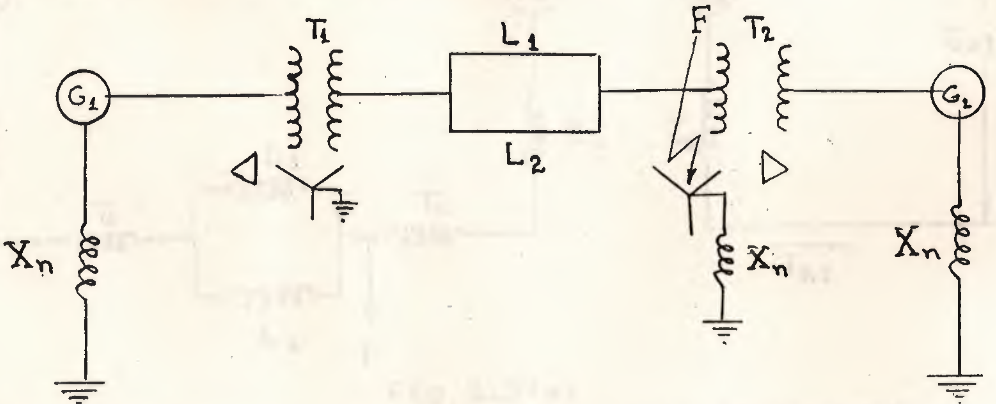


Fig 3.2
One line diagram of balanced three phase system.

The system shown in fig 3.2 is sufficiently general for equations derived in the last chapter therfore to be applicable to any balanced system regardless of the complexity. If a fault occurs at point F as shown in fig 3.2 it will introduce unbalanced conditions into an otherwise balanced system. for analysis the assumptions made are:

1. The impedances are all constant and independent of currents.

2. The generator is producing negligable e.m.f for negative and zero sequence when fault occurs.

3. Thus for all practical purposes it may be assumed that machine be that machine generated only positive phase e.m.f's.

The network under these conditions can be represented by three independent single phase sequence networks as shown in fig 3.3.

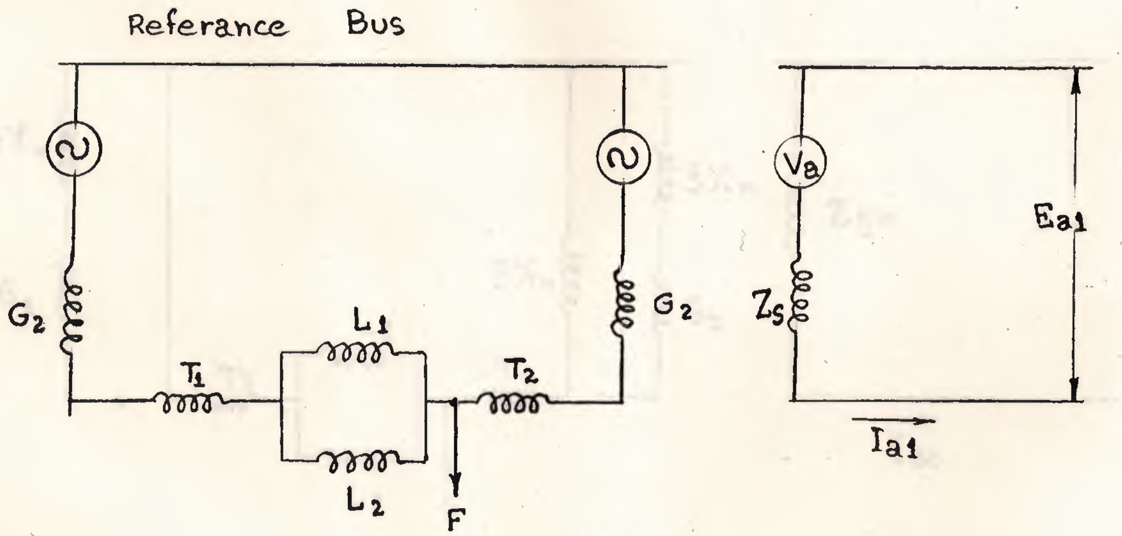


Fig 3.3(a)

Positive sequence network — Thevinin's equivalent positive sequence network

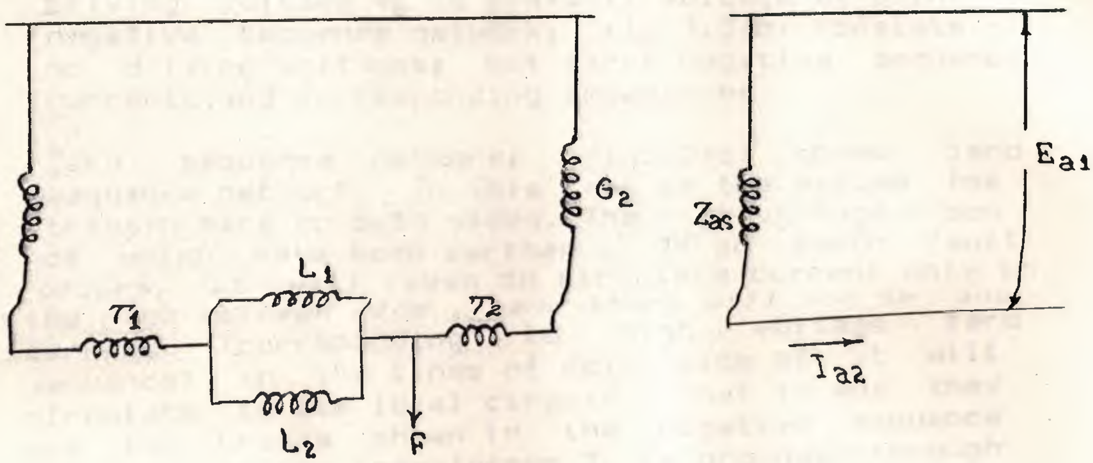


Fig 3.3(b)

Negative sequence net-work

Thevinin's equivalent negative sequence network

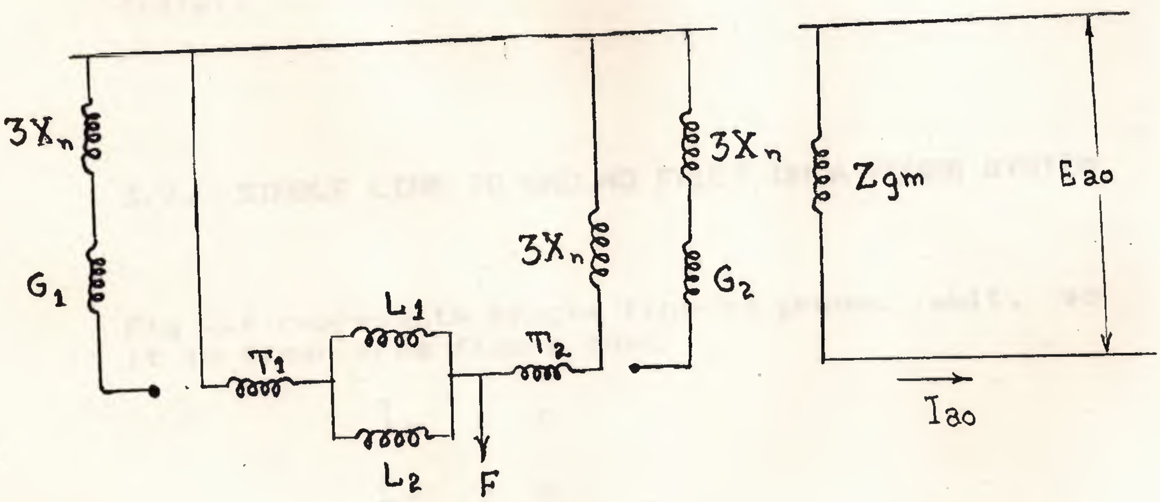


Fig 3.3(c)

Zero sequence network

Thevinin's equivalent zero sequence network

Positive sequence network: fig 3.3(a) consists of positive sequence driving voltages, positive sequence cuttents and correspomding impedances. Driving voltage V_a is prefault voltage at point negative sequence network; fig 3.3(b) consists of no driving voltages; but carry negative sequence currents and corresponding impedances.

Zero sequence network: fig3.3(c) shows zero sequence network. In this case as the system has transformers on both sides. The high voltage sides *of which have been earthed . If an earth fault* occurs, it will cause *to circulate current only in* the high voltage side , and there will not be any current (corrsponding to high voltage zero sequance) in the lines of delta side as it will circulate in its local circuit, that is why they are two breaks shown in the negative sequence network. As the transformer T_2 is grounded through reactance X_n , the zero sequence equivalent circuit for transformer will contain a reactance of $3X_n$ between the reference bus and T_2 as shown in Fig 3.3(c).

3.2. SINGLE LINE TO GROUND FAULT ON A POWER SYSTEM

Fig 3.4 represents single line to ground fault, so it is clear from figure that

$$I_b = 0$$

$$I_c = 0$$

$$E_a = 0$$

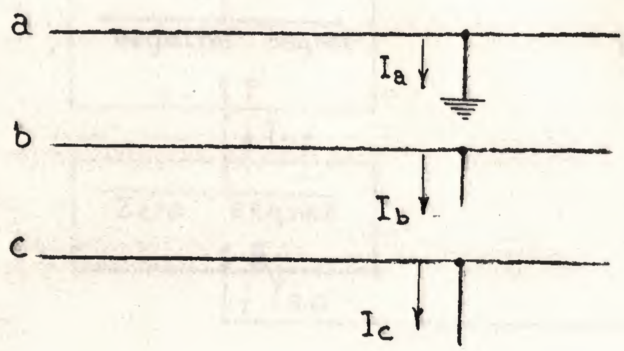


Fig 3.4
Connection diagram of the hypothetical stubs for single line to ground fault.

The above three equation are same as those which apply to a line to ground in case of an unloaded generator. So these equation must have some relation of symmetrical components as found in the case of unloaded generator.

Hence, in case of single line to ground fault on a power system

$$I_{a1} = I_{a2} = I_{ao} \quad \text{------(3.1)}$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{as} + Z_{gm}} \quad \text{------(3.2)}$$

equation 3.1 and 3.2 indecate that the three sequence network should be connected in series through the fault point in order to simulate a single line to ground fault as shown in fig 3.5.

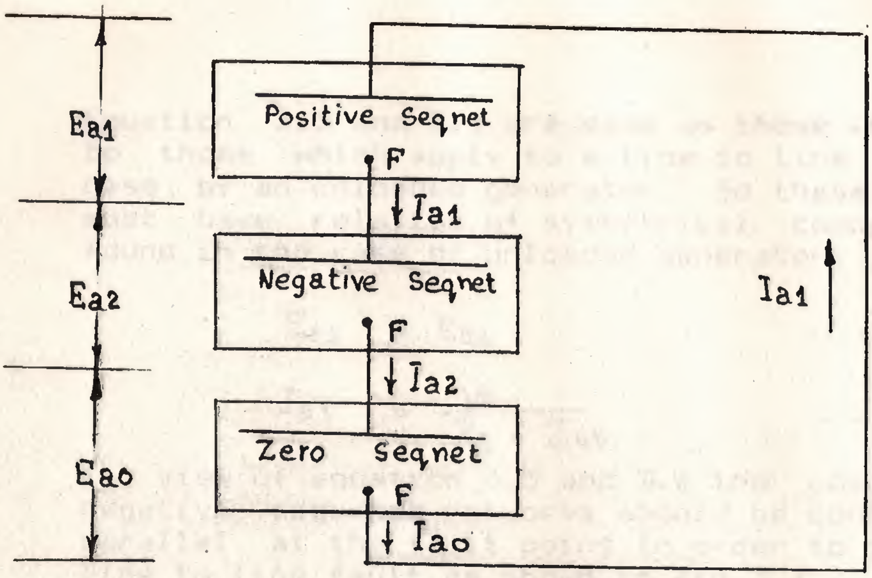


Fig 3.5
Connection of the sequence network to simulate single line to ground fault.

3.3. LINE-TO-LINE FAULT ON A POWER SYSTEM.

Fig 3.6 represents line-to-line fault so it is cleat from figure that

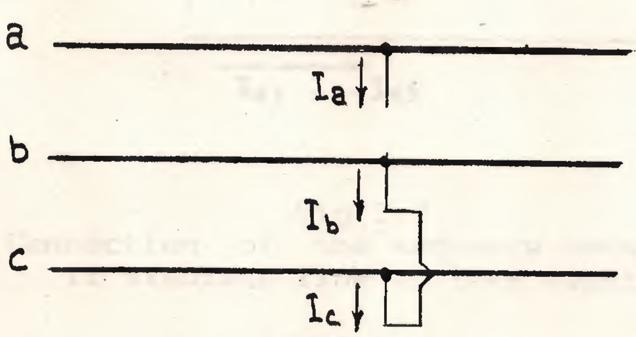


Fig 3.6
Connection diagram of the hypothetical stubs for line to line fualt

$$E_b = E_c \qquad \text{-------------(3.3)}$$

$$I_b = -I_c \qquad \text{-------------(3.4)}$$

Equation 3.3 and 3.4 are same as those which apply to those which apply to a line to line fault in case of an unloaded generator. So these equations must have relation of symmetrical components as found in the case of unloaded generator.

$$E_{a1} = E_{a2} \qquad \text{-----}(3.5)$$

$$I_{a1} = \frac{V_a}{Z_s + Z_{as}} \qquad \text{-----}(3.6)$$

In view of equation 3.5 and 3.6 the positive and negative sequence networks should be connected in parallel at the fault point in order to simulate a line to line fault as shown in fig 3.7

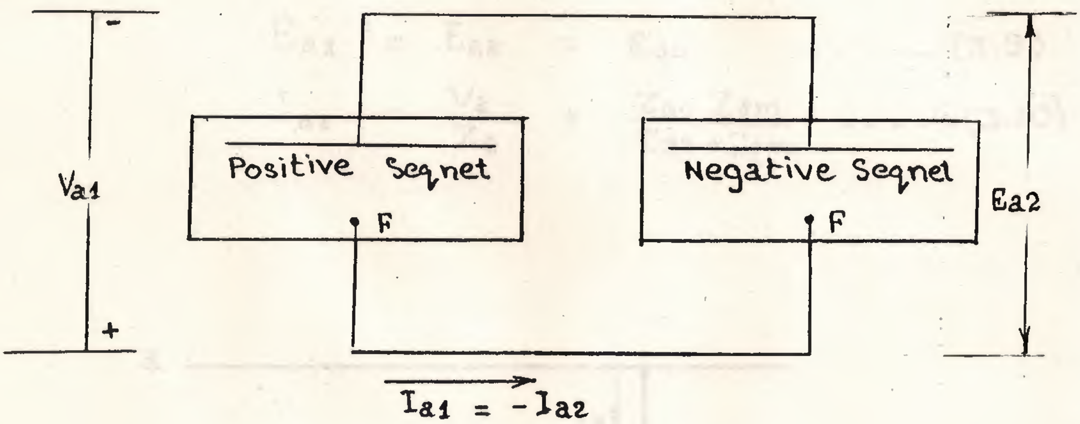


Fig 3.7
Connection of the sequence networks it simulate line to line fault.

3.4 DOUBLE LINE TO GROUND FAULT ON A POWER SYSTEM

Fig 3.8 represents double line to ground, it is clear from figure that;

$$E_b = E_c = 0 \quad \text{-----}(3.7)$$

$$I_a = 0 \quad \text{-----}(3.8)$$

By comparison with equations derived for the case of double line to ground fault in case of unloaded generator we see that they are exactly same. So these equations must have relation of symmetrical components as found in the case of unloaded generator.

$$E_{a1} = E_{a2} = E_{a0} \quad \text{-----}(3.9)$$

$$I_{a1} = \frac{V_a}{Z_s} + \frac{Z_{as}\, Z_{gm}}{Z_{as} + Z_{gm}} \quad \text{-----}(3.10)$$

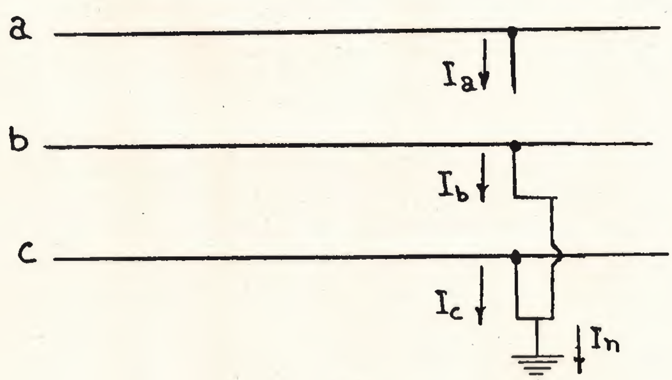


Fig 3.8
Connection diagram of the hypothetical stubs for a double line to ground fault.

Equations 3.9 and 3.10 indecate that the three sequence network should be connected in parallel at the fault point in order to simulate double line to ground fault as is shown in Fig 3.9.

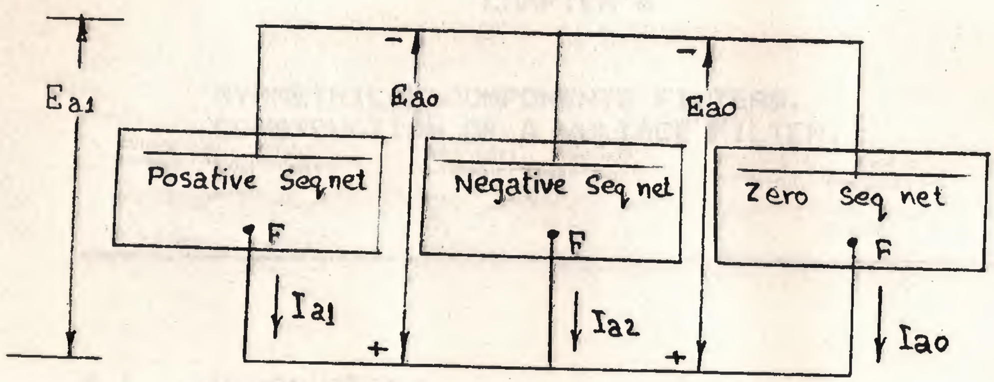


Fig 3.9
Connections of sequence networks to simulate double line to ground fault.

CHAPTER 4

SYMMETRICAL COMPONENTS FILTERS.
CONSTRUCTION OF A VOLTAGE FILTER.

4.1 INTRODUCTION

In the previous chapters much has been discussed about various types of fault and the techniques for fault current calculations. The protection of power system is as important as its generation and transmission. To avoid heavy loss to equipment and industry we always require to have a normal operation of the power system without failures. In this chapter the protection techniques will dealt for the safe guard of the power system.

4.2. FUSES. Fuse is being considered as the weakest link in the electrical circuit. It is taken as the simplest protective device as in used as circuit interrupting device under short circuit conditions. It prevents over heating of the electrical appliances.

A fuse is essentially a small piece of metal terminals mounted between two terminals mounted on insulated base which forms a series path of the circuit.

The duity of the fuse wire is to carry the normal working current safely without heating but when the normal working current is exceeded it should rapidly heat up to the melting point.

4.3 CIRCUIT BREAKER.

For low voltage circuit fuses may be used to isolate the faulty circuit, but for higher voltage isolation is achieved by circuit breaker. The difference between the fuse and the circuit breaker is that under fault condition the fuse melts and a new one is to be replaced, while the circuit breaker can close the circuit as break the circuit without any replacement.

The power dealt by the circuit breaker is quite large and serves as an important link between consumers and suppliers. The following are the necessary requirements for a circuit breakers;

1. It must safely interrupt the normal working current as well as the short circuit current

2. After occurance of fault the circuit breaker must isolate the faulty circuit as quikly as possible, keeping the delay to minimum.

3. It must have high sense of discrimination it should isolate only faulty circuit without effecting the healthy one

4. It should not operate when over current flows under healthy conditions.

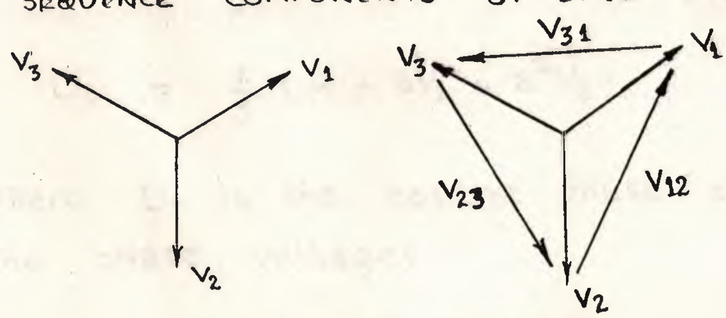
4.4 RELAYS.

The relays are used to cut off the supply promptly to any element of power system which under goes short circuit or it starts operating abnormally.

The relays only give a signal to the circuit breaker for tripping or isolating the faulty system. The circuit breaker used must be of sufficient capacity to carry the fault current momentarily and then interupt it .

The protective equipment (relays) provide a very good indication of the type of fault which has occured.

4. 5 THE POSITIVE , NEGATIVE AND ZERO PHASE SEQUENCE COMPONENTS OF LINE VOLTAGES.



Phase and line to line voltages of a three phase system.

The symmetrical components equations for line to line voltages are.

$$V_{l+} = \frac{1}{3}(V_{12} + a V_{23} + a^2 V_{31})$$

$$V_{l-} = \frac{1}{3}(V_{12} + a^2 V_{23} + a V_{31})$$

$$V_o = \frac{1}{3}(V_{12} + V_{23} + V_{31})$$

The zero sequence of the line voltage is zero.

because, $V_{ab} + V_{bc} + V_{ca} = 0$

$$V_{l+} = \frac{1}{3}\left(V_{12} + a V_{23} + a^2 V_{31} \right)$$

$$V_{l+} = \frac{1}{3}\left[V_{12} + a V_{23} - a^2 (V_{12} + V_{23}) \right] \qquad \text{--- (4.1)}$$

$$= \frac{1-a^2}{3} \left(V_{12} - a^2_{23} \right)$$

$$= \frac{1-a^2}{3} \left(V_1 - V_2 - a^2 (V_2 - V_3 \right)$$

$$= \frac{1-a^2}{3} \left(V_1 + aV_2 + a^2 V_3 \right)$$

$$U_+ = \frac{1}{3} \left(V_1 + aV_2 + a^2 V_3 \right)$$

Where U_+ is the positive phase sequence of the phase voltages.

$$U_{l+} = \frac{1-a^2}{3} U_+ \qquad \text{------ (4.2)}$$

Using 4.1 and 4.2.

$$3U_+ = U_{13} - a^2_{23}$$

Similarly the negative phase sequence of the line voltage is

$$3U_- = U_{12} - a U_{23}$$

4.6 CONSTRUCTION OF VOLTAGE FILTER.

As it has been discussed earlier that when ever there is unbalanced circuit the unbalanced currents will have a negative phase sequence component. To avoid unbalanced currents we have constructed a voltage filter. The filter circuit is responsive only to negative sequence components. When a power system undergoes short circuit or it starts operating abnormally, the fault current will spell into the filter, which will indecate the presence of a negative phase sequence component, enabling us to do necessary steps to avoid it.
Figure 4.2 illustrates the scheme utilized for the negative phase sequence filter.

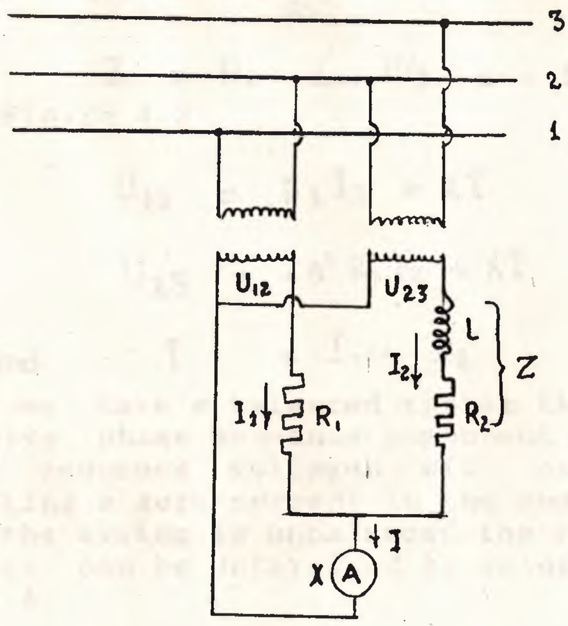


Figure 4.2
A voltage filter

As illustrated in Figure 4.2, U_{12} and U_{23} are the voltages at the secondary side of the transformer from section 4.5 we know that

$$U_{+} = \frac{1}{3}\left(U_{12} - a^2 U_{23}\right) \quad \text{------ } (4.3)$$

$$U_{-} = \frac{1}{3}\left(U_{12} - a U_{23}\right) \quad \text{---- } (4.4)$$

First transformer supplies cirrent I through resistor R to the mearuring device i.e ammeter while the second transformer supplies current I through Z (a series combination of resistance as well as reactance)
R and L are chosen such that

$$Z = \sqrt{R_2^2 + L^2\omega^2} = R_1 \quad \text{----- } (4.5)$$

$$\arctan \frac{L\omega}{R_2} = \pi/3$$

$$Z = R_1 \angle \pi/3 = -a^2 R_1 \quad \text{----} (4.6)$$

from Figure 4.2

$$U_{12} = R_1 I_1 + XI$$

$$U_{23} = -a^2 R_1 I_2 + XI$$

$$\text{and} \quad I = I_1 + I_2$$

when we have a balanced system ther will be no negative phase sequence component and the positive phase sequence voltages will canel each other resulting a zero current in the ammeter.
When the system is unbalanced the negative sequence current can be determined by using equations 4.3 and 4.4.

$$U_{12} - a U_{23} = R_1 (I_1 + I_2) + X(1-a) I$$

$$I_{-} = \frac{U_{12} - a U_{23}}{R_1 + X(1-a)} \quad \text{--- } (4.7)$$

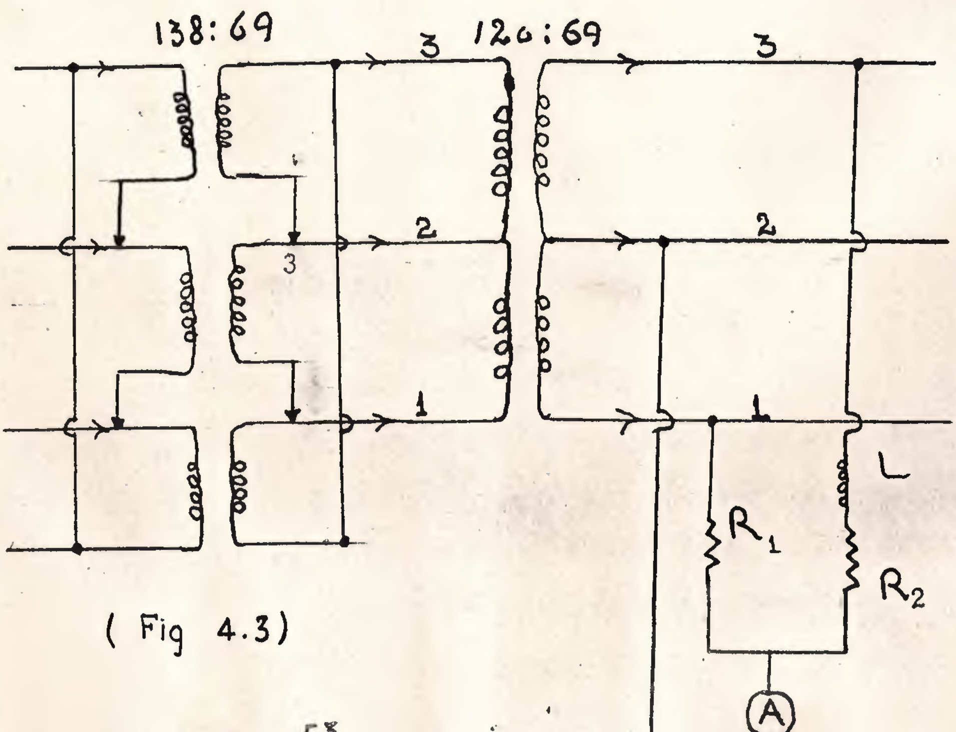
X is the ammeter resistance and can be neglected.

$$I_- = \frac{3U}{R_1} \qquad \ldots (4.8)$$

we can measure the positive phase sequence currents by changing the place of the impedances in the circuit.

4.7 EXPERIMENTAL PORCEDURE FOR THE CONSTRUCTION OF THE VOLTAGE FILTER

To construct a voltage filter as shown in Figure 4.2 we need a three phase transformer to drop the line voltages at the secondary side, since small values of over current can cause dangerous conditions, it becomes essential to have low setting for the filter.
As we couldn't find a transformer having input voltage that of the line voltage we use a three phase variable transformer, to drop the line voltages. After dropping the three phase line voltages to 100 volts with the help of variable transformer we connect theline voltages to the primary side of a delta connected three phase transformer. The line voltages coming out of the delta connected secondary side of the transformer, or connected to another transformer with secondary side was giving us the line voltages U_{12} and U_{23}. The circuit diagram is shown in figure 4.3.
We choosed values of R_1 , L and R_2 such that they satisfy equation 4.5, 4.6 and 4.7. And the values selected were,



(Fig 4.3)

$L = 5\,H$

$R_L = 180\,\Omega$

$R_2 = 720\,\Omega$

$R_1 = 1810.35$

The the circuit was connected according to Figure 4.2

4.8 CALCULATION OF NEGATIVE SEQUENCE CURRENTS INCASE OF BALANCED AND UNBALANCED LINE VOLTAGES

In the first step of the experiment the system was made balanced byselecting 138:69 for each phase of the three phase of the delta connected transformer and 120:60 for the transformer whose secondary side was connected to the filter as we disscus in section 4.6. We should not get any current in the ammeter but in this part we get a current of 6.7 miliampere, the reason for this is as explained in the conclusion. Then we made the system unbalanced by selecting different winding ratios for each of the delta cinnected three phase transformer. All the necessary calculations to calculate negative sequence current are shown on next page.

$U_1 = 100$

$N_1 = 138$

$U_{12} = ?$

U_{12} at $N_2 = 40$

$$U_2 = \frac{N_2}{N_1} U_1$$

$$= 28.9 \quad = U_{12}$$

$$U_{12} = 28.9 \angle 0^\circ \qquad V$$

U_{23} at $N_2 = 50$

$$U_{23} = \frac{50}{138} 100$$

$$= 36.2 \angle -120^\circ \qquad V$$

U_{31} at $N_2 = 69$

$$U_{31} = \frac{69}{138} 100$$

$$= 50 \angle -240^\circ$$

$$= -25 + 43.3j \qquad V$$

$U_1 = 10.5 \angle 30^\circ$ V

$U_2 = 6.5 \angle -90^\circ$ V

$U_3 = 6.5 \angle -150^\circ$ V

$$U- = \frac{1}{3}\left[U_1 + a^2 U_2 + a U_3 \right]$$

$$U- = -0.703 + 1.75$$

$$= 1.8 \angle -68^\circ \quad V$$

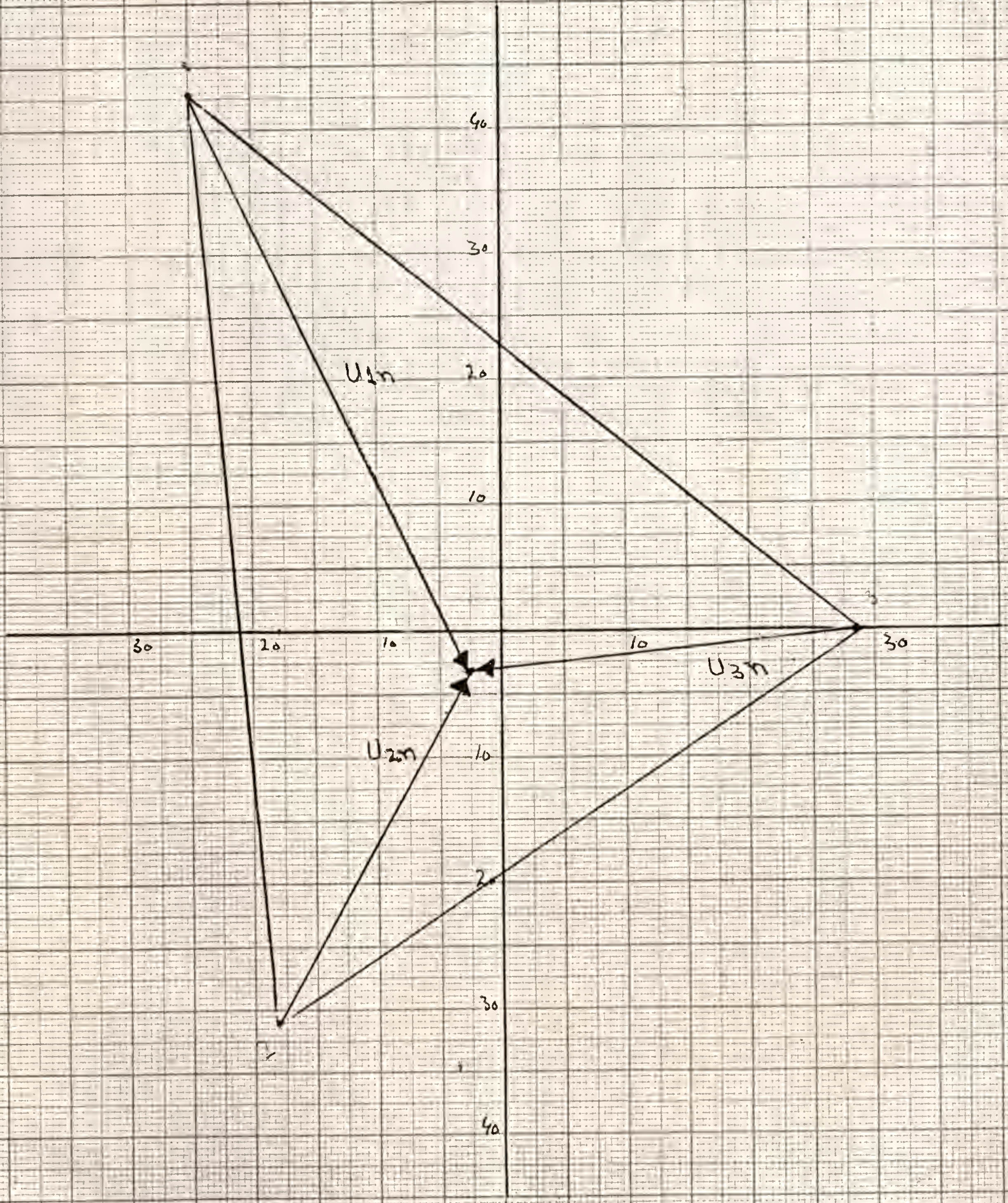
$$U- = 20\,(1.8 \angle -68^\circ)$$

$$U- = 36 \angle -68^\circ$$

$$I- = \frac{U-}{R_1}$$

$$I- = 18\ mA$$

Exprimantally the value of I- found was equal to <u>17 mA</u>


40
30
20
10
30
20
10
10
30
U1n
U2n
U3n
10
20
30
40

4.9 CONCLUSION

In this experiment we should get a zero current when the system was balanced but we were getting a certain amount of current in the ammeter, the reason was that we were unable to produce a balanced system. With the apparatus we were using. First of all, the variable transformer was not producing exactly equal phase and line voltages, Secondly, the three phase transformer was not producing voltages of equal proportion on its secondary side. These errors were always making the system unbalanced and we could'nt get a zero current in case of balanced system.

CONCLUSION

In fact this was a study for the course given, power Sys. Analysis I and power System Analysis II a study was carried out on a particular topic, the use of symmetrical components which is one of the most power tool for dealing with unbalanced polyphased circuits. The method of symmetrical components has great importance and has been subject of many articles, and experimental investigations.
The study and work gave me an apportunity for developing my practical side and it also gave me a chance to use my knowledge achieved during class times of power System Analysis I and System Analysis II.

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