



UNIT 1: FAULT ANALYSIS

INTRODUCTION

A fault is any abnormal condition in a power system. The steady state operating mode of a power system is balanced 3-phase a.c. .However, due to sudden external or internal changes in the system, this condition is disrupted.

When the insulation of the system fails at one or more points or a conducting object comes into contact with a live point, a short circuit or a fault occurs.

CAUSES OF POWER SYSTEM FAULTS

The causes of faults are numerous, e.g.

- Lightning
- Heavy winds
- Trees falling across lines
- Vehicles colliding with towers or poles
- Birds shorting lines
- Aircraft colliding with lines
- Vandalism
- Small animals entering switchgear
- Line breaks due to excessive loading

COMMON POWER SYSTEM FAULTS

Power system faults may be categorised as one of four types; in order of frequency of occurrence, they are:

- Single line to ground fault
- Line to line fault
- Double line to ground fault
- Balanced three phase fault



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The first three types constitute severe unbalanced operating conditions which involve only one or two phases hence referred to as unsymmetrical faults. In the fourth type, a fault involving all the three phases occurs therefore referred to as symmetrical (balanced) fault.

EFFECTS OF POWER SYSTEM FAULTS

Faults may lead to fire breakout that consequently results into loss of property, loss of life and destruction of a power system network. Faults also lead to cut of supply in areas beyond the fault point in a transmission and distribution network leading to power blackouts; this interferes with industrial and commercial activities that support economic growth, stalls learning activities in institutions, work in offices, domestic applications and creates insecurity at night.

All the above results into retarded development due to low gross domestic product realised.

It is important therefore to determine the values of system voltages and currents during faulted conditions, so that protective devices may be set to detect and minimize the harmful effects of such contingencies

THEVENIN'S EQUIVALENT CIRCUIT

Thevenin's theorem states that any linear network containing any number of voltage sources and impedances can be replaced by a single emf and an impedance.

The emf is the open circuit voltage as seen from the terminals under consideration and the impedance is the network impedance as seen from these terminals.

This circuit consisting of a single emf and impedance is known as Thevenin's equivalent circuit.

The calculation of fault current can then be very easily done by applying this theorem after obtaining the open circuit emf and network impedance as seen from the fault point.



SYMMETRICAL COMPONENTS

The majority of faults in power systems are asymmetrical. To analyse an asymmetrical fault, an unbalanced 3-phase circuit has to be solved. Since the direct solution of such a circuit is very difficult, the solution can be more easily obtained by using symmetrical components since this yields three (fictitious) single phase networks, only one of which contains a driving emf.

Since the system reactances are balanced the three fictitious networks have no mutual coupling between them, a fact that is making this method of analysis quite simple.

General principles

Any set of unbalanced 3-phase voltages (or current) can be transformed into 3 balanced sets. These are:

1. A positive sequence set of three symmetrical voltages (i.e. all numerically equal and all displaced from each other by 120°) having the same phase sequence abc as the original set and denoted by V_{a1}, V_{b1}, V_{c1} as shown in the fig(1a)

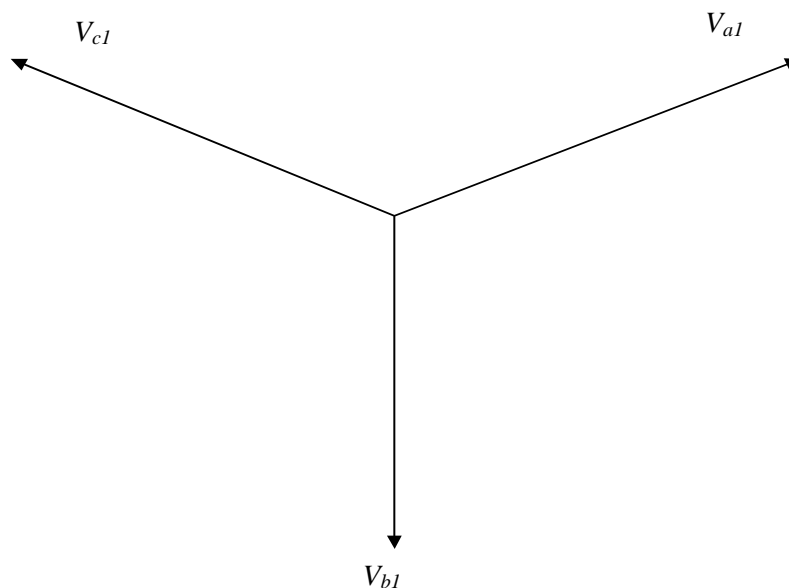


Fig. (a)



2. A negative sequence set of three symmetrical voltages having the phase sequence opposite to that of the original set and denoted by V_{a2} , V_{b2} , V_{c2} as shown in fig(1b)

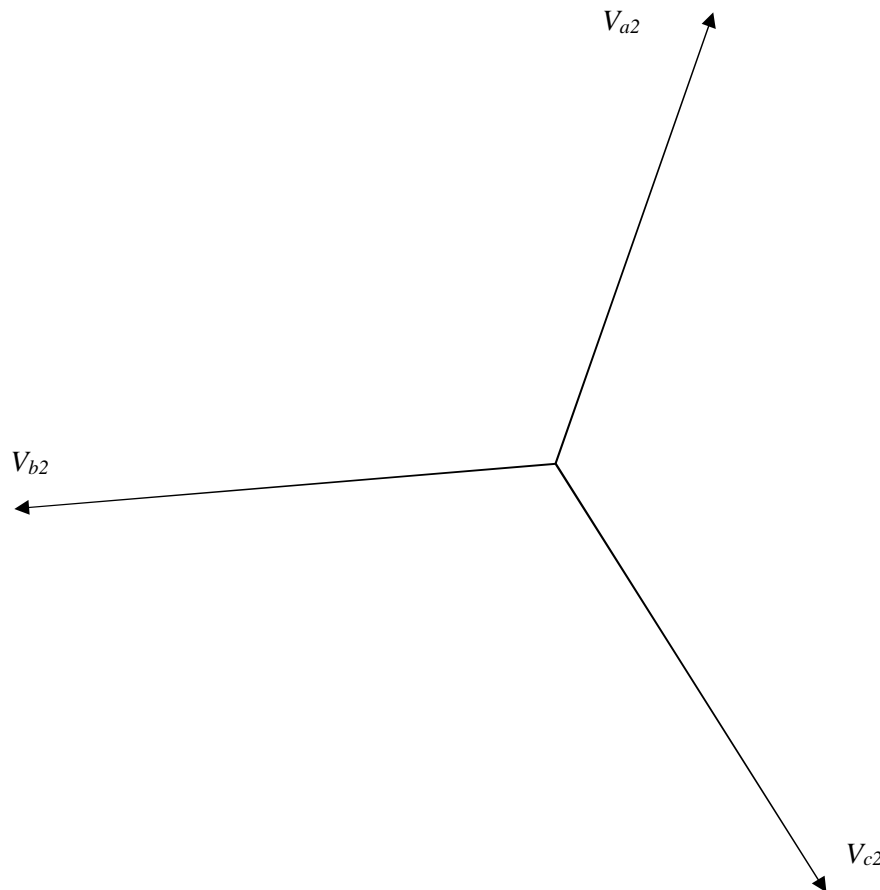


Fig. 1 (b)



3. A zero sequence set of three voltages, all equal in magnitude and in phase with each other and denoted by V_{a0} , V_{b0} , V_{c0} as shown in fig (1c) below:

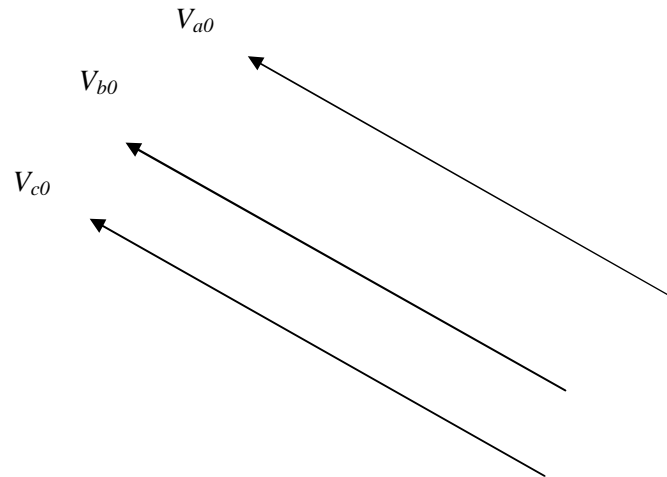


Fig. 1 (c)

The positive, negative and zero sequence sets above are known as symmetrical components.

Thus we have,

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

$$V_b = V_{b1} + V_{b2} + V_{b0}$$

$$V_c = V_{c1} + V_{c2} + V_{c0}$$

The symmetrical components application to power system analysis is of fundamental importance since it can be used to transform arbitrarily unbalanced condition into symmetrical components, compute the system response by straightforward circuit analysis on simple circuit models and transform the results back to the original phase variables.

Generally the subscripts 1, 2 and 0 are used to indicate positive sequence, negative sequence and zero sequence respectively.

The symmetrical components do not have separate existence; they are just mathematical components of unbalanced currents (or voltages) which actually flow in the system.



The “a” operator

The operator “a” as used in symmetrical components is one in which when multiplied to a vector, rotates the vector through 120° in a positive (anticlockwise) direction without changing the magnitude.

The operator “a” is defined as $1 \angle 120^\circ$

THREE-SEQUENCE IMPEDANCES AND SEQUENCE NETWORKS

Positive sequence currents give rise to only positive sequence voltages, the negative sequence currents give rise to only negative sequence voltages and zero sequence currents give rise to only zero sequence voltages, hence each network can be regarded as flowing within in its own network through impedances of its own sequence only.

In any part of the circuit, the voltage drop caused by current of a certain sequence depends on the impedance of that part of the circuit to current of that sequence.

The impedance of any section of a balanced network to current of one sequence may be different from impedance to current of another sequence.

The impedance of a circuit when positive sequence currents are flowing is called impedance,

When only negative sequence currents are flowing the impedance is termed as negative sequence impedance.

With only zero sequence currents flowing the impedance is termed as zero sequence impedance.

The analysis of unsymmetrical faults in power systems is carried out by finding the symmetrical components of the unbalanced currents. Since each sequence current causes a voltage drop of that sequence only, each sequence current can be considered to flow in an independent network composed of impedances to current of that sequence only.

The single phase equivalent circuit composed of the impedances to current of any one sequence only is called the sequence network of that particular sequence.



The sequence networks contain the generated emfs and impedances of like sequence.

Therefore for every power system we can form three- sequence network s. These sequence networks, carrying current I_{a1} , I_{a2} and I_{a0} are then inter-connected to represent the different fault conditions.

PHYSICAL SIGNIFICANCE OF SEQUENCE COMPONENTS

This is achieved by considering the fields which results when these sequence voltages are applied to the stator of a 3-phase machine e.g. an induction motor.

If a positive sequence set of voltages is applied to the terminals a, b, c of the machine, a magnetic field revolving in a certain direction will be set up. If now the voltages to the terminals b and c are changed by interchanging the leads to terminals b and c, it is known from induction motor theory that the direction of magnetic field would be reversed.

It is noted that for this condition, the relative phase positions of the voltages applied to the motor are the same as for the negative sequence set.

Hence, a negative sequence set of voltages produces a rotating field rotating in an opposite direction to that of positive sequence.

For both positive and negative sequence components, the standard convention of counter clockwise rotation is followed.

The application of zero sequence voltages does not produce any field because these voltages are in phase and the three -phase windings are displaced by 120° . The positive and the negative sequence set are the balanced one. Thus, if only positive and negative sequence currents are flowing, the phasor sum of each will be zero and there will be no residual current. However, the zero sequence components of currents in the three phases are in phase and the residual current will be three times the zero sequence current of one phase. In the case of a fault involving ground, the positive and negative sequence currents are in equilibrium while the zero sequence currents flow through the ground and overhead ground wires.



SEQUENCE NETWORKS OF SYNCHRONOUS MACHINES

An unloaded synchronous machine having its neutral earthed through impedance, Z_n , is shown in fig. 2(a) below.

A fault at its terminals causes currents I_a , I_b and I_c to flow in the lines. If fault involves earth, a current I_n flows into the neutral from the earth. This current flows through the neutral impedance Z_n .

Thus depending on the type of fault, one or more of the line currents may be zero.

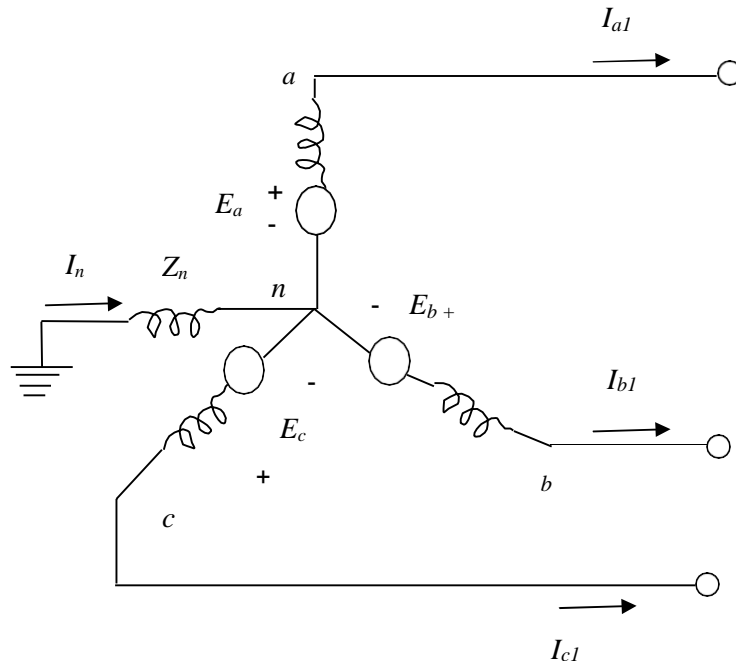


Fig.2 (a)



Positive sequence network

The generated voltages of a synchronous machine are of positive sequence only since the windings of a synchronous machine are symmetrical.

The positive sequence network consists of an emf equal to no load terminal voltages and is in series with the positive sequence impedance Z_1 of the machine. Fig.2 (b) and fig.2(c) shows the paths for positive sequence currents and positive sequence network respectively on a single phase basis in the synchronous machine. The neutral impedance Z_n does not appear in the circuit because the phasor sum of I_{a1} , I_{b1} and I_{c1} is zero and no positive sequence current can flow through Z_n . Since its a balanced circuit, the positive sequence N

The reference bus for the positive sequence network is the neutral of the generator.

The positive sequence impedance Z_1 consists of winding resistance and direct axis reactance. The reactance is the sub-transient reactance X''_d or transient reactance X'_d or synchronous reactance X_d depending on whether sub-transient, transient or steady state conditions are being studied.

From fig.2 (b) , the positive sequence voltage of terminal a with respect to the reference bus is given by:

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

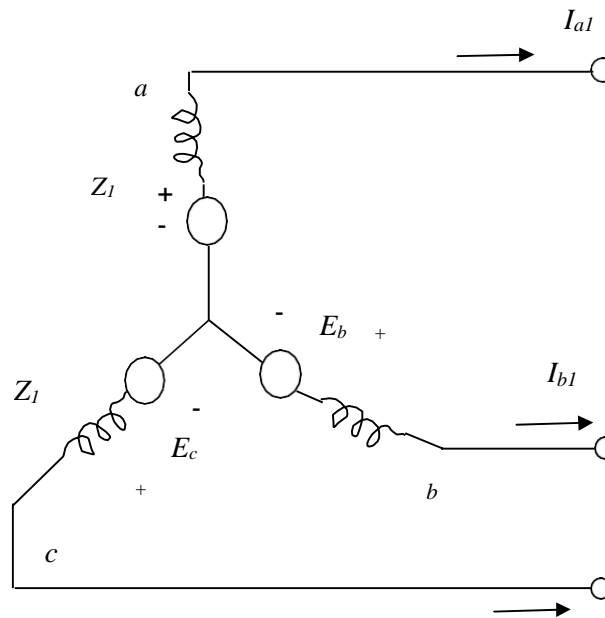


Fig.2 (b)

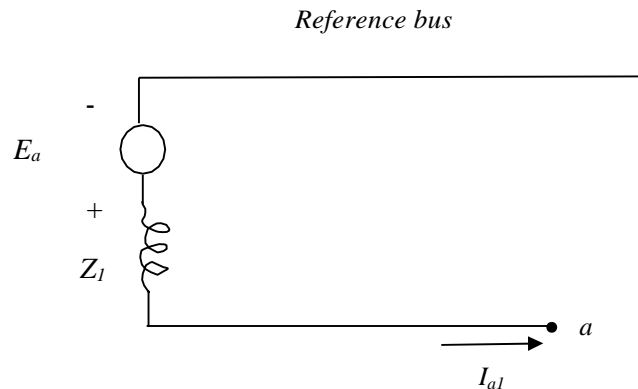


Fig.2(c)

Negative sequence network

A synchronous machine does not generate any negative sequence voltage. The flow of negative sequence currents in the stator windings creates an mmf which rotates at synchronous speed in a direction opposite to the direction of rotor, i.e., at twice the synchronous speed with respect to rotor.

Thus the negative sequence mmf alternates past the direct and quadrature axis and sets up a varying armature reaction effect. Thus, the negative sequence reactance is taken as the average of direct axis and quadrature axis sub-transient reactance, i.e.,

$$X_2 = 0.5 (X''_d + X''_q).$$

It not necessary to consider any time variation of X_2 during transient conditions because there is no normal constant armature reaction to be effected. For more accurate calculations, the negative sequence resistance should be considered to account for power dissipated in the rotor poles or damper winding by double supply frequency induced currents.

The fig.2 (d) and fig.2 (e) shows the negative sequence currents paths and the negative sequence network respectively on a single phase basis of a synchronous machine.

The reference bus for the negative sequence network is the neutral of the machine. Thus, the negative sequence voltage of terminal a with respect to the reference bus is given by:



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

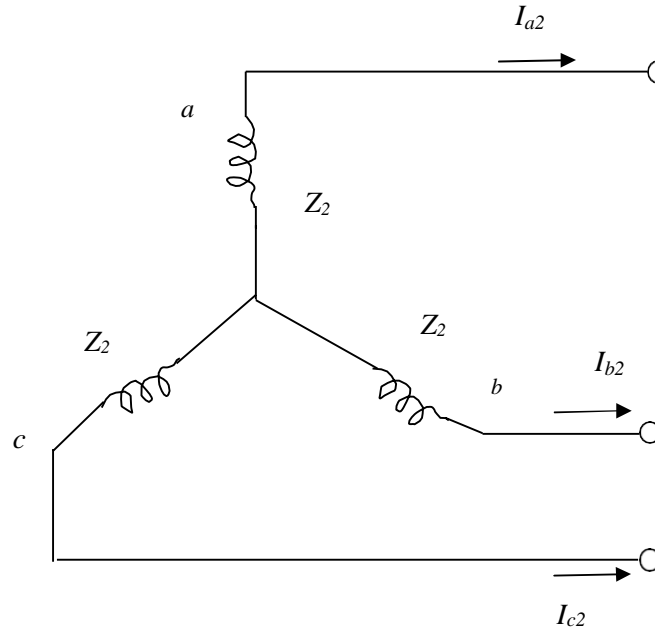


Fig.2 (d)

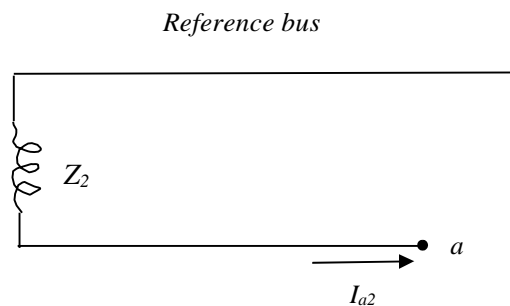


Fig.2 (e)



Zero sequence network

No zero sequence voltage is induced in a synchronous machine. The flow of zero sequence currents in the stator windings produces three mmf which are in time phase. If each phase winding produced a sinusoidal space mmf, then with the rotor removed, the flux at a point on the axis of the stator due to zero sequence current would be zero at every instant.

When the flux in the air gap or the leakage flux around slots or end connections is considered, no point in these regions is equidistant from all the three ϕ -phase windings of the stator.

The mmf produced by a phase winding departs from a sine wave, by amounts which depend upon the arrangement of the winding.

The zero sequence currents flow through the neutral impedance Z_n and the current flowing through this impedance is $3I_{a0}$.

Fig.2(f) and fig.2(g) shows the zero sequence current paths and zero sequence network respectively, and as can be seen, the zero sequence voltage drop from point a to ground is - $3I_{a0}Z_n - I_{a0}Z_{g0}$ where Z_{g0} is the zero sequence impedance per phase of the generator.

Since the current in the zero sequence network is I_{a0} this network must have an impedance of $3Z_n + Z_{g0}$. Thus,

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

The zero sequence voltage of terminal a with respect to the reference bus is thus:

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

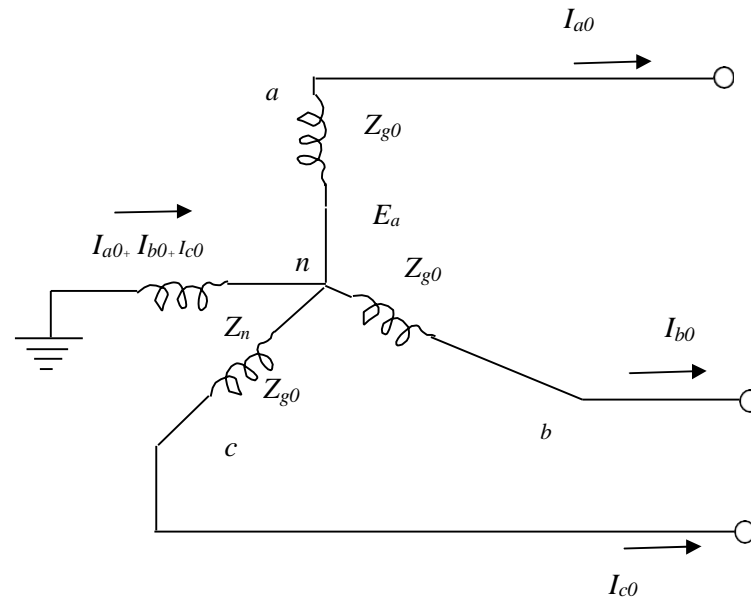


Fig.2 (f)

Reference bus

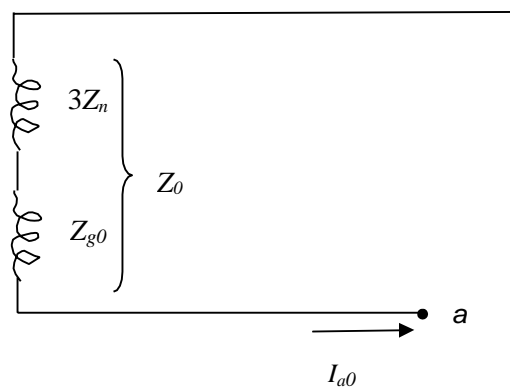


Fig.2 (g)



SEQUENCE IMPEDANCES OF TRANSMISSION LINE

The positive and negative sequence impedances of linear symmetrical static circuits do not depend on the phase sequence and are, therefore equal. When only zero sequence currents flow in the lines, the currents in all the phases are identical. These currents return partly through the ground and partly through overhead ground wires.

The magnetic field due to the flow of zero sequence currents through line, ground and round wires is very different from the magnetic field due to positive sequence currents. The zero sequence reactance of lines is about 2 to 4 times the positive sequence reactance.

SEQUENCE IMPEDANCES OF TRANSFORMERS

A power system network has a number of transformers for stepping up and stepping down the voltage levels.

A transformer for a 3-phase circuit may consist of three single phase transformers with windings suitably connected in star or delta or it may be a 3-phase unit.

Modern transformers are invariably three-phase units because of their lower cost, lesser space requirements and higher efficiency. The positive sequence impedance of a transformer equals its leakage impedance. The resistance of the windings is usually small as compared to leakage reactance.

For transformers above 1 MVA rating, the reactance and impedance are almost equal. Since the transformer is a static device, the negative sequence impedance is equal to the positive sequence impedance.

The zero sequence impedance of 3-phase units is slightly different from positive sequence impedance. However the difference is very slight and the zero sequence impedance is also assumed to be the same as the positive sequence impedance.

The flow of zero sequence currents through a transformer and hence in the system depends greatly on the winding connections. The zero sequence currents can flow through the winding



connected in star only if the star point is grounded. If the star point is isolated zero sequence currents cannot flow in the winding.

The zero sequence currents cannot flow in the lines connected to a delta connected winding because no return path is available for these zero sequence currents. However, the zero sequence currents caused by the presence of zero sequence voltages can circulate through the delta connected windings.

FORMATION OF SEQUENCE NETWORKS

A power system network consists of synchronous machines, transmission lines and transformers.

The positive sequence network is the same as the single line reactance diagram used for the calculation of symmetrical fault current. The reference bus for positive sequence network is the system neutral.

The negative sequence network is similar to the positive sequence network except that the negative sequence network does not contain any voltage source. The negative sequence impedances for transmission line and transformers are the same as the positive sequence impedances. But the negative sequence impedance of a synchronous machine may be different from its positive sequence impedance.

Any impedance connected between a neutral and ground is not included in the positive and negative sequence networks because the positive and the negative sequence currents cannot flow through such impedance.

The zero sequence network also does not contain any voltage source. Any impedance included between neutral and ground becomes three times its value in a zero sequence network.

The following are the summary of the rules for the formation of sequence networks:-



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- The positive sequence network is the same as single line impedance or reactance diagram used in symmetrical fault analysis. The reference bus for this network is the system neutral.
- The generators in power system produce balanced voltages. Therefore only positive sequence network has voltage source. There are no voltage sources in negative and zero sequence networks.
- The positive sequence current can cause only positive sequence voltage drop. Similarly negative sequence current can cause only negative sequence voltage drop and zero sequence current can cause only zero sequence voltage drop.
- The reference for negative sequence network is the system neutral. However, the reference for zero sequence network is the ground. Zero sequence current can flow only if the neutral is grounded.
- The neutral grounding impedance Z_n appears as $3Z_n$ in the zero sequence network.
- The three sequence networks are independent and are interconnected suitably depending on the type of fault.



UNSYMMETRICAL FAULTS

The basic approach to the analysis of unsymmetrical faults is to consider the general situation shown in the fig.3.0 which shows the three lines of the three- phase power system at the point of fault.

The general terminals brought out are for purposes of external connections which simulate the fault. Appropriate connections of the three stubs represent the different faults, e.g., connecting stub 'a' to ground produces a single line to ground fault, through zero impedance, on phase 'a'. The currents in stubs *b* and *c* are then zero and I_a is the fault current.

Similarly, the connection of stubs *b* and *c* produces a line to line fault, through zero impedance, between phases *b* and *c*, the current in stub *a* is then zero and I_b is equal to I_c . The positive assignment of phase quantities is important. It is seen that the currents flow out of the system.

The three general sequence circuits are shown in fig.3.1 (a). The ports indicated correspond to the general 3- phase entry port of fig.3.1. A suitable inter- connection of the three- sequence networks depending on the type fault yields the solution to the problem.

The sequence networks of fig.3.1 (a) can be replaced by equivalent sequence networks of fig.3.1 (b) . Z_0 , Z_1 and Z_2 indicate the sequence impedances of the network looking into the fault

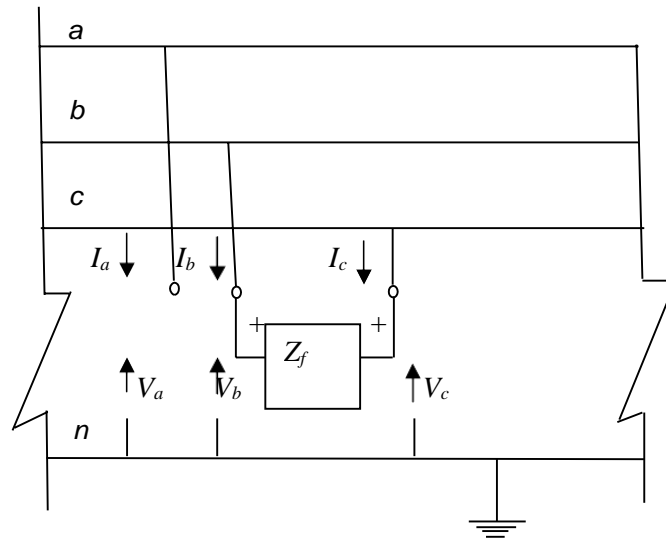


Fig.3.0 General 3- phase access port



General sequence networks

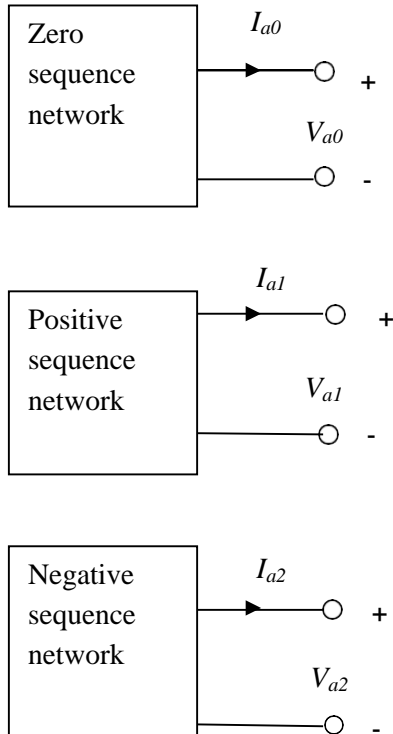


Fig.3.1 (a)

Equivalent sequence networks

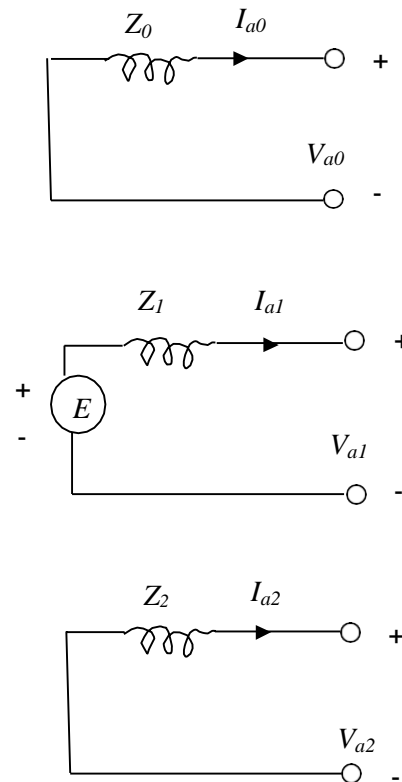


Fig.3.1 (b)



SINGLE LINE TO GROUND FAULT

Typically Z_f is set to zero in all fault studies. I include Z_f in the analysis for the sake of generality. The terminal conditions at the fault point give the following equations:

$$I_b = 0$$

$$I_c = 0$$

$$V_a = I_a Z_f$$

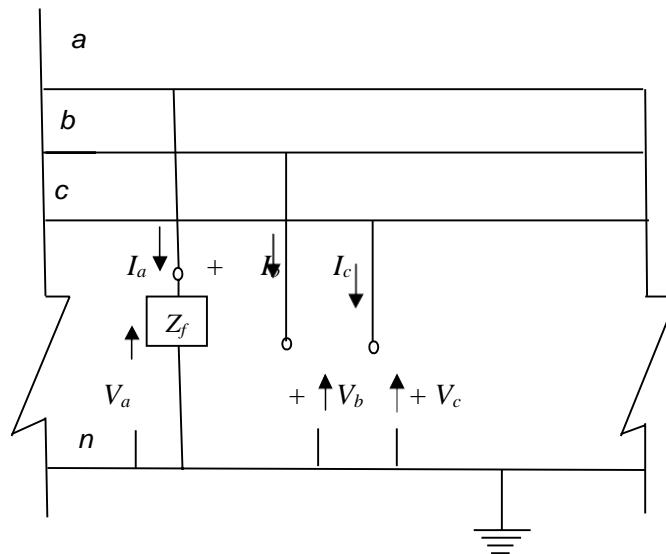


Fig. 3.2

Connections of sequence networks for a single line to ground fault and its simplified equivalent circuit are shown in the fig. 3.3(a) and fig. 3.3 (b) below:



General sequence networks

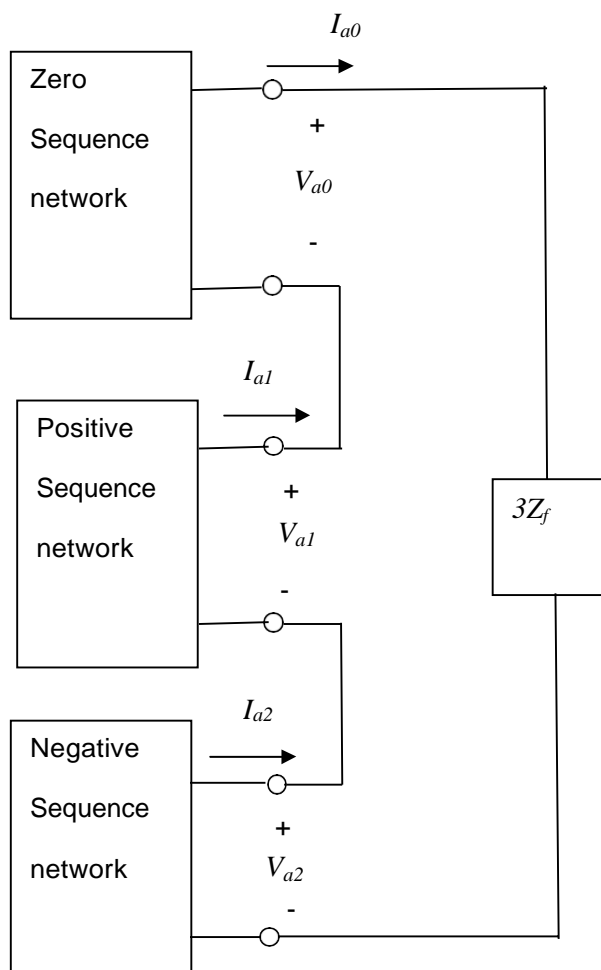


Fig.3.3 (a)

Equivalent sequence networks

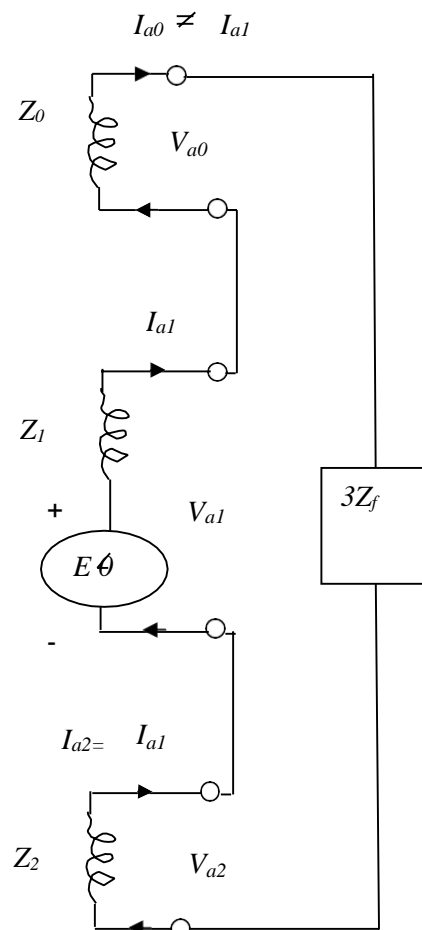


Fig.3.3
(b)



LINE TO LINE FAULT

The termination of the three- phase access port as in the fig.3.4 below simulates a line to line fault through a fault impedance Z_f .

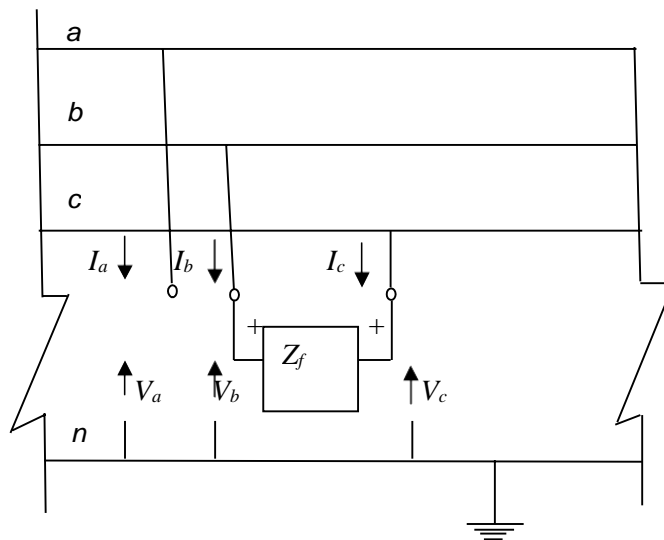


Fig. 3.4

The terminal conditions at the fault point give the following equations,

$$I_a = 0$$

$$I_b = -I_c$$

$$V_b = V_c + Z_f I_b$$

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

Connection of sequence networks for a line to line fault and its simplified equivalent circuit are shown in the fig.3.5 (a) and fig.(b) below.



Equivalent sequence networks

General sequence networks

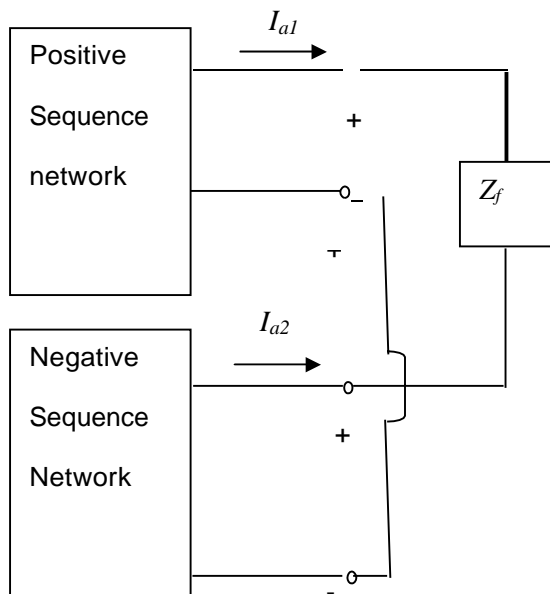
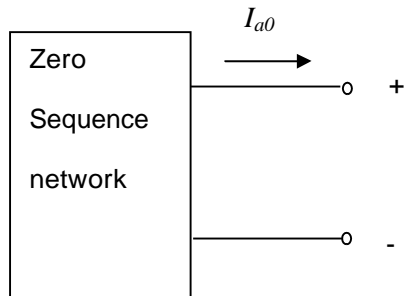


Fig. 3.5 (a)

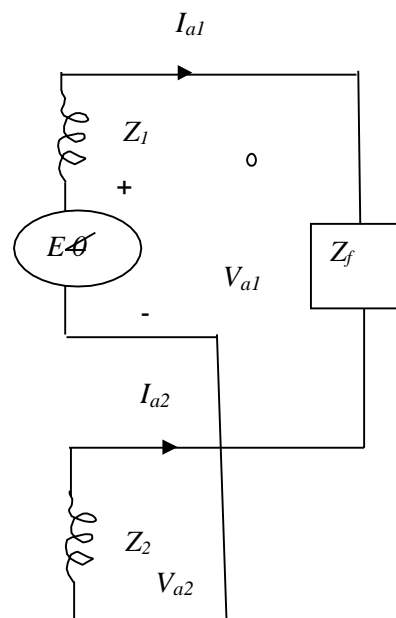


Fig.3.5 (b)

DOUBLE LINE TO GROUND FAULT

The termination of the three- phase access port as shown in fig.3.6 simulates a double line to ground fault through fault impedance Z_f .



The terminal conditions at the fault point give the following equations,

$$I_a = 0$$

$$V_b = V_c = (I_b + I_c) Z_f$$

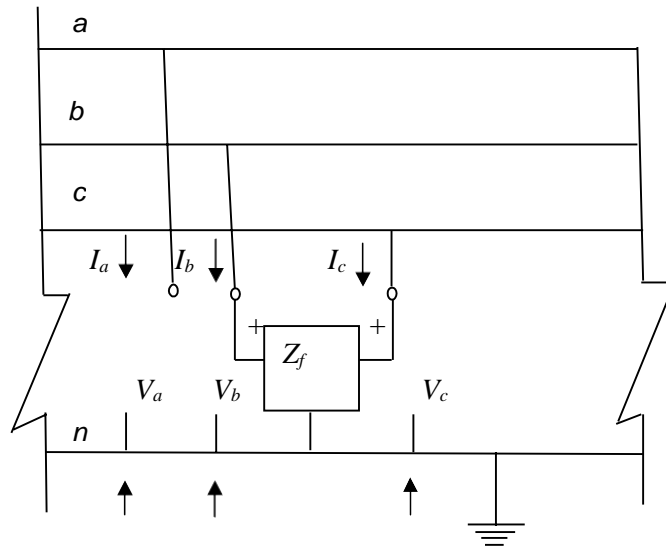


Fig. 3.6

The sequence networks and the equivalent circuit are shown by the Fig.3.7 (a) and Fig. 3.7 (b) below



General sequence networks

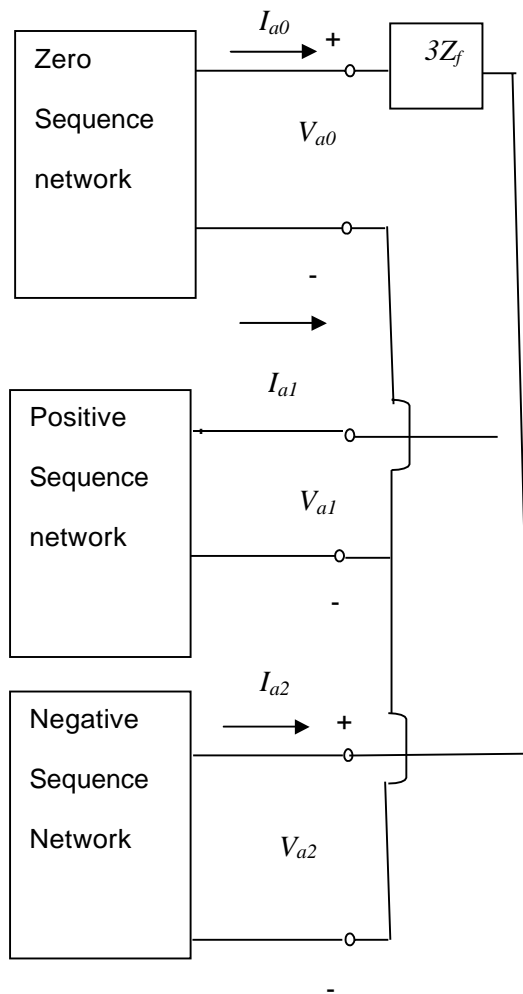


Fig. 3.7(a)

Equivalent sequence networks

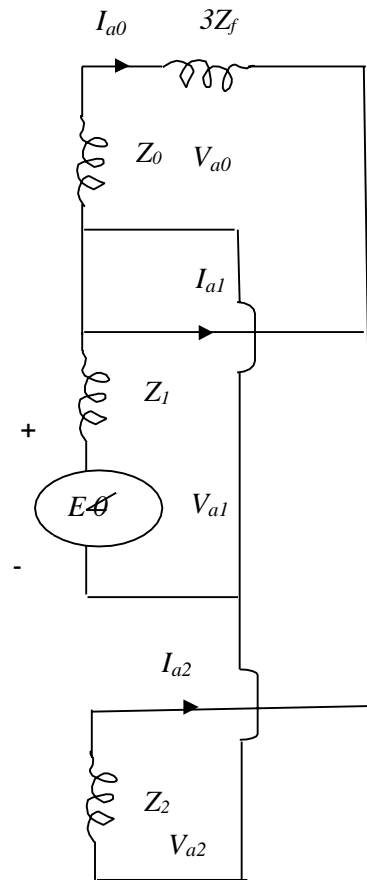


Fig.3.7 (b)



BALANCED THREE PHASE FAULT

This type of fault occurs infrequently, as for example, when a line, which has been made safe for maintenance by clamping all the three phases to earth, is accidentally made alive or when, due to slow fault clearance, an earth fault spreads across to the other two phases or when a mechanical excavator cuts quickly through a whole cable.

It is an important type of fault in that it results in an easy calculation and generally, a pessimistic answer.

The circuit breaker rated MVA breaking capacity is based on 3- phase fault MVA. Since circuit breakers are manufactured in preferred standard sizes e.g. 250, 500, 750 MVA high precision is not necessary when calculating the 3- phase fault level at a point in a power system.

The system impedances are also never known accurately in three phase faults.