Sequence Impedances of Power System Elements:

The concept of impedances of various elements of power system (e.g. generators, transformers, transmission lines etc.) to positive, negative and zero sequence currents is of considerable importance in determining the fault currents in a 3-phase unbalanced system. A complete consideration of this topic does not fall within the scope of this book, but a short preliminary explanation may be of interest here. The following three main pieces of equipment will be considered:

- **Synchronous generators**
- **Transformers**
- **Transmission lines**

(i)Synchronous generators:

The positive, negative and zero sequence impedances of rotating machines are generally different. The positive sequence impedance of a synchronous generator is equal to the synchronous impedance of the machine. The negative sequence impedance is much less than the positive Sequence Impedance of Power System. The zero sequence impedance is a variable item and if its value is not given, it may be assumed to be equal to the positive sequence impedance. In short:

Negative sequence impedance < Positive sequence impedance
Zero sequence impedance = Variable item
= may be taken equal to +ve sequence impedance if its value is not given

It may be worthwhile to mention here that any impedance Z_e in the earth connection of a star-connected system has the effect to introduce an impedance of 3 Z_e per phase. It is because the three equal zero-sequence currents, being in phase, do not sum to zero at the star point, but they flow back along the neutral earth connection.

(ii) Transformers:

Since transformers have the same impedance with reversed phase rotation, their positive and negative sequence impedances are equal; this value being equal to the impedance of the transformer. However, the zero sequence impedance depends upon earth connection. If there is a through circuit for earth current, zero sequence impedance will be equal to positive sequence impedance otherwise it will be infinite. In short,

Positive sequence impedance	=	Negative sequence impedance
	=	Impedance of Transformer
Zero sequence impedance	=	Positive sequence impedance, if there is circuit for earth current
	=	Infinite, if there is no through circuit for earth current.

(iii) Transmission lines:

The positive sequence and negative sequence impedance of a line are the same; this value being equal to the normal impedance of the line. This is expected because the phase rotation of the currents does not make any difference in the constants of the line. However, the zero sequence impedance is usually much greater than the positive or negative Sequence Impedance of Power System. In short:

Positive sequence impedance	=	Negative sequence impedance
	=	Impedance of the line
Zero sequence impedance	=	Variable item
	=	may be taken as three times the +ve sequence impedance if its value is not given

Sequence Impedances and Networks of Synchronous Machines:

An unloaded synchronous machine (generator or motor) grounded through a reactor of impedance Z_n is shown in Fig. E_a, E_b and E_c are the induced emfs in the three phases. When an unsymmetrical fault occurs on the machine terminals, unbalanced currents I_a, I_b and I_c flow in the lines.If the fault involves ground, a current I_n (equal to phasor sum of line currents I_a, I_b and I_c.) flows to neutral from ground via reactor Z_n. Depending on the type of fault one or more of the line currents may be zero. Unbalanced line currents can be resolved into their symmetrical components.

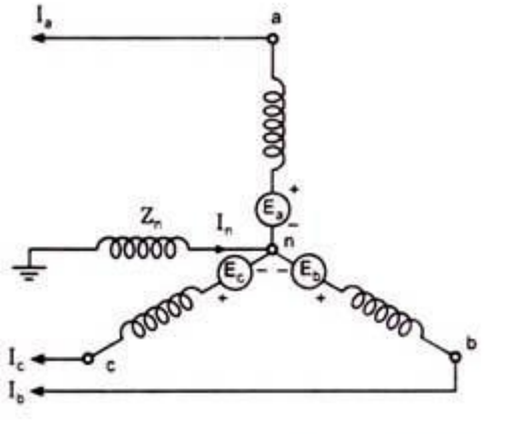
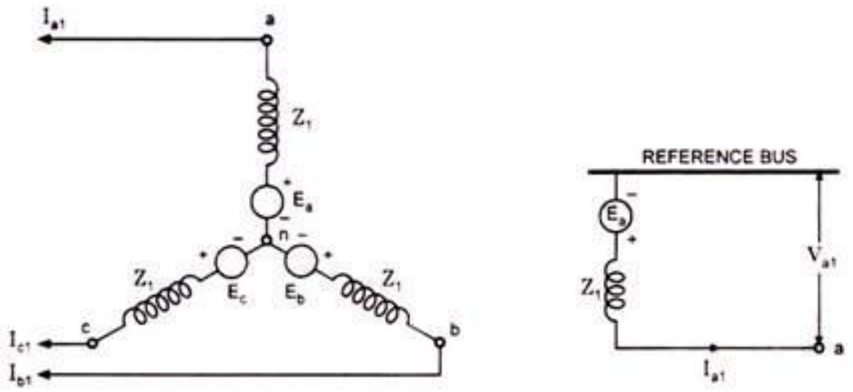


Fig. 3.9. Three-Phase Unloaded Synchronous Generator With Grounded Neutral Through Impedance Z_n

1. Positive-Sequence Impedance and Network:

Since a synchronous machine is designed with symmetrical windings, it has induced emfs of positive sequence only, i.e., no negative-or zero-sequence voltages are induced in it. The armature reaction field set up by positive-sequence currents rotates at synchronous speed in the same direction as the rotor, i.e., it is stationary with respect to field excitation.The machine equivalently offers a direct-axis reactance whose value increases from subtransient reactance X''_d to transient reactance X'_d and finally to steady- state (synchronous) reactance X_d as the short circuit transient progresses in time. Subtransient reactance is used in a circuit where a sudden value of current under switching of fault condition is to be obtained. Where current after a few cycles (3 or 4) is desired, transient reactances are used, and for steady-state condition, the steady-state or synchronous reactances are used. Positive-sequence reactances together with the negligible resistance make up the positive sequence subtransient, transient or steady-state positive sequence impedances, respectively.

The positive-sequence network for a synchronous machine can be represented by the source emf on no load and the positive sequence impedance Z_1 in series with it, as shown in Fig. The neutral impedance Zn 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 it is a balanced network, it can be drawn on single phase basis, as shown in Fig.for purpose of analysis.



(a) Three Phase Model (b) Single Phase Model

Fig. 3.10. ***Positive-Sequence Network of a Synchronous Machine***

The reference bus for a positive-sequence network is at neutral potential. Further, since no current flows from ground to neutral, the neutral is at ground potential. The positive-sequence voltage of terminal a with respect to the reference bus, as is obvious from Fig,

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

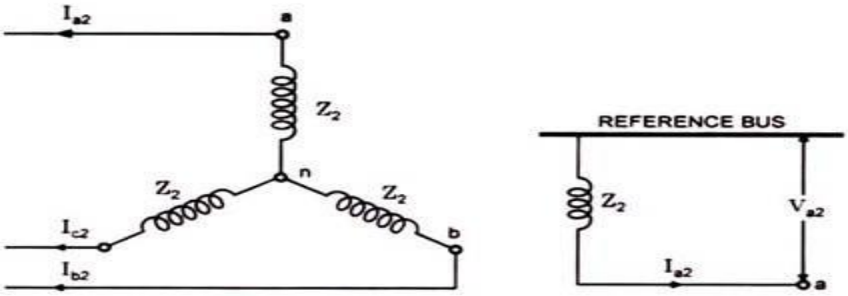
2. Negative-Sequence Impedance and Network:

The synchronous machine does not generate any negative-sequence voltage. Flow of negative sequence currents in the stator winding produces an mmf rotating synchronously in a direction opposite to that of the rotor. Thus the negative sequence field rotates at a speed twice the synchronous speed with respect to rotor. Currents at double the stator frequency are, therefore, induced in rotor field and damper winding.In sweeping over the rotor surface, the negative sequence mmf is alternately presented with reluctances of direct and quadrature axes. Thus the negative-sequence reactance X_2 is found to oscillate between X_d'' and X_q'' and the value taken is usually the average. Thus the negative-sequence reactance

$$X_2 = X_d'' + X_q''/2$$

The negative-sequence networks of a synchronous machine, on a three-phase and single phase basis are shown in Figs respectively. The reference bus for the negative- sequence network is also the neutral of the machine. The negative-sequence voltage of terminal a with respect to reference bus is given as

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

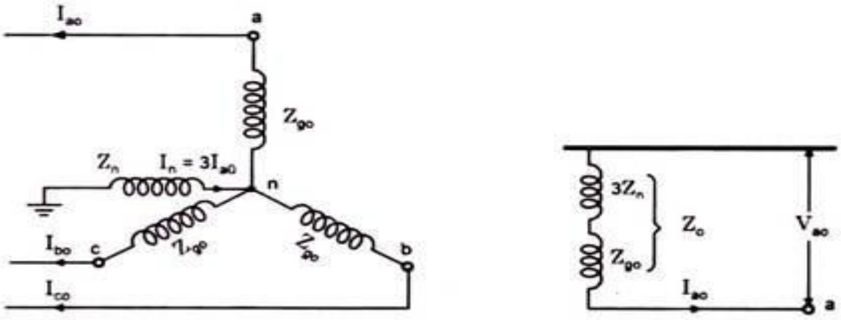


(a) Three Phase Model *(b) Single Phase Model*

Fig. 3.11. ***Negative-Sequence Network of a Synchronous Machine***

3. Zero-Sequence Impedance and Network:

No zero-sequence voltage is induced in synchronous machine. The flow of zero-sequence currents in the stator windings produces three mmfs which are in time phase but are distributed in space by 120°. The resultant air gap field produced by zero-sequence currents is therefore zero. Hence, the rotor windings present leakage reactance only to the flow of zero-sequence currents.



(a) Three Phase Model *(b) Single Phase Model*

Fig. 3.12. ***Zero-Sequence Network of a Synchronous Machine***

As the current flowing in the reactor impedance Z_n is the sum of the zero sequence currents in all the three phases, hence voltage drop caused by it will be 3 $I_{a0} Z_n$. Now voltage drop of zero sequence from terminal a of the synchronous machine to ground is $3 I_{a0} Z_n + I_{a0} Z_{g0}$ where Z_{g0} is the zero-sequence impedance of the generator. Hence total zero-sequence impedance, through which zero-sequence current I_{a0} flows is

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

The zero-sequence voltage of terminal an of the synchronous machine with respect to ground is, therefore, given as

$$V_{a0} = -I_{a0} Z_0 = -I_{a0} (Z_{g0} + 3Z_n)$$

Sequence Impedances of Induction Machines:

In rotating machines, the impedances of the three phase sequences will generally be different. For example in case of induction machines, the positive-sequence impedance is represented by the normal equivalent circuit of the machine. Negative-sequence stator currents produce a magnetic field rotating at the same speed as under normal conditions but in opposite direction (against the rotor).As a result the field rotates relative to rotor at nearly twice its speed relative to the stator and many times its speed relative to the rotor under normal conditions. The currents induced in the rotor also go up considerably. By Lenz's law, they tend to reduce the magnetic field in a greater measure that under normal conditions, thereby bringing about a reduction in the emfs induced by the magnetic field in the stator windings. Thus the stator currents increase and as a consequence, the motor offers a low impedance to the negative-sequence than to positive-sequence currents (i.e., $Z_2 > Z_1$) for the same applied positive- and negative- sequence voltages and the same speed and direction of rotation. Because the zero-sequence stator currents do not produce a rotating field the equivalent circuit may be considered of magnetizing and leakage impedances only. However, in practice, the presence of third- harmonic currents and fluxes is an important consideration in the zero-sequence analysis of induction machines.

Sequence Impedances of Transmission Lines:

A fully transposed three-phase line is completely symmetrical and, therefore, the positive-and negative-sequence impedances of a transmission line are independent of phase sequence and are equal. The expression for inductive reactance, of "Elements of Power Systems" is valid for both positive and negative sequences. When only zero-sequence currents flow in a transmission line, the currents in each phase are identical in both magnitude and phase. Such currents return partly through ground and the rest through overhead ground wires. The magnetic field due to flow of zero-sequence currents through the transmission lines, ground wires and ground is very different from the magnetic field set up by the flow of positive- or negative-sequence currents. The zero-sequence impedance (particularly the reactance) is about 2 to 4 times the positive sequence impedance.

Sequence Impedances and Networks of Transformers:

The positive-sequence series impedance of a transformer is equal to its leakage reactance (the resistance of the winding is usually small in comparison to the leakage reactance). Transformer being a static device, the positive and negative-sequence impedances is identical, because the impedance is independent of phase order, provided the applied voltages are balanced. Thus, for a transformer

$Z_1 = Z_2 = Z_{leakage}$

The situation with 3-phase transformer is more complex with regard to zero-sequence impedance because of the possibility of variety of connections. Assuming such transformer connections that zero- sequence currents can flow on both sides, a transformer offers zero-sequence impedance slightly different from positive-sequence impedance but the difference is so small that zero-sequence impedance can be assumed equal to positive- or negative- sequence impedance.

However, the zero- sequence currents can flow through the winding connected in star only if the star point is grounded. Moreover, the zero- sequence currents cannot flow in the windings if the star point is isolated. No zero-sequence currents can flow in the lines connected to a delta-connected winding as no return path is available for these zero-sequence currents. Zero-sequence currents can, however, flow through the delta-connected windings themselves if any zero sequence voltages are induced in delta. These various conditions can be taken into account by the use of general circuit shown in Fig. Z_0 is the zero-sequence impedance of windings of the transformer. There are two series and two shunt switches-one series and one shunt switch for each side. The series switch of a particular side is closed if it is star grounded and the shunt switch is closed if that side is delta connected, otherwise they remain left open.

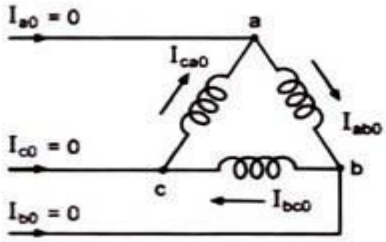


Fig. 3.13. ***Flow of Zero-Sequence Current in Delta-Connected Windings***

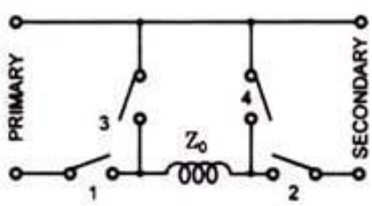
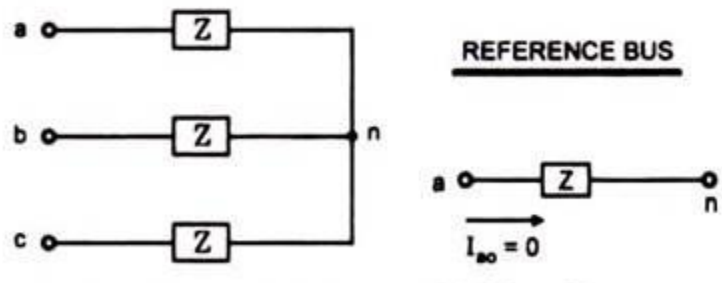


Fig. 3.14. ***General Circuit For Determination of Zero-Sequence Network of a Transformer***

The switches need not be shown in the final network.

Sequence Impedance and Networks of Load:

For a star-connected load with isolated neutral, there is no path for the flow of zero-sequence currents and the star point of the load will not be connected to the reference bus, as shown in Fig. Thus the zero- sequence impedance is infinite beyond the neutral point (i.e., $Z_n = \infty$). This fact is indicated by an open circuit in the zero-sequence network between the neutral of the star-connected load and the reference bus in Fig.



(a) Star-Connected Load With Isolated Neutral *(b) Zero-Sequence Network*

Fig. 3.15

When the star point of the load is grounded, there will be continuity of the load circuit to ground and the star point of the load n will be connected to the reference bus. The current flowing through the neutral under unbalanced condition of system is zero-sequence current. If the neutral point of load is grounded through a reactor of impedance Z_n, the zero-sequence voltage drop caused by flow of current 3 I_{a0} through Z_n will be the same as if current I_{a0} flows through 3 Z_n. Thus impedance 3 Z_n is introduced between neutral point n and the reference bus, when representing on the zero-sequence network.

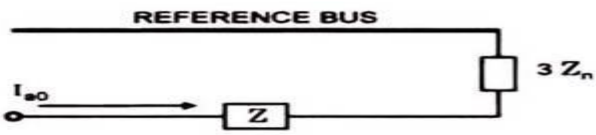


Fig. 3.16. ***Zero-Sequence Network For Star-Connected Load With Neutral Grounded Through Impedance Z_n***

The zero-sequence impedance of the load is equal to its positive- or negative-sequence impedance if the load is balanced. The positive-sequence network is composed of positive-sequence impedances only and since positive-sequence currents do not flow to ground, therefore, neutral point n and the ground are at the same potential. Thus impedance inserted between neutral and ground has no effect on positive- sequence currents. The negative-sequence impedance of a static load is the same as positive- sequence impedance and so the negative-sequence network is the same as the positive- sequence network.

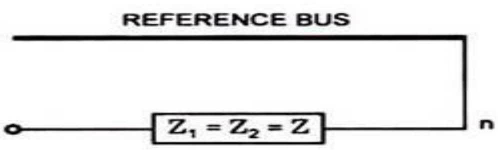


Fig. 3.17. ***Positive/Negative-Sequence Network For Star-Connected Load***