6- Sequence Impedances and Sequence Networks

Each element of power system will offer impedance to different phase sequence components of current which may not be the same. For example, the impedance which any piece of equipment offers to positive sequence current will not necessarily be the same as offered to negative sequence current or zero sequence current. Therefore, in unsymmetrical fault calculations, each piece of equipment will have three values of impedance—one corresponding to each sequence current.

(***i***) Positive sequence impedance (Z_1).
(***ii***) Negative sequence impedance (Z_2).
(***iii***) Zero sequence impedance (Z_0).

The impedance offered by an equipment or circuit to positive sequence current is called positive sequence impedance and is represented by Z_1. Similarly, impedances offered by any circuit or equipment to negative and zero sequence currents are respectively called negative sequence impedance
(Z_2) and zero sequence impedance (Z_0).

The Following Points May Be Noted:

(***a***) In a 3-phase balanced system, each piece of equipment or circuit offers only one impedance– the one offered to positive or normal sequence current. This is expected because of the absence of negative and zero sequence currents in the 3-phase balanced system.

(***b***) In a 3-phase unbalanced system, each piece of equipment or circuit will have three values of impedance *viz.* positive sequence impedance, negative sequence impedance and zero sequence impedance.

(***c***) The positive and negative sequence impedances of linear, symmetrical and static circuits (*e.g.* transmission lines, cables, transformers and static loads) are equal and are the same as those used in the analysis of balanced conditions. This is due to the fact that impedance of such circuits is independent of the phase order, provided the applied voltages are balanced.

It may be noted that positive and negative sequence impedances of rotating machines (*e.g.* synchronous and induction motors) are normally different.

(***d***) The zero sequence impedance depends upon the path taken by the zero sequence current. As this path is generally different from the path taken by the positive and negative sequence currents, therefore, zero sequence impedance is usually different from positive or negative sequence impedance.

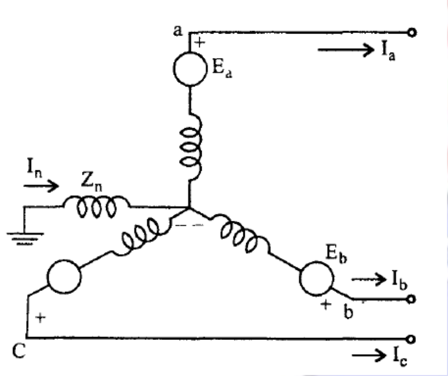
6-1 Sequence Impedances of Power System Elements

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:

(*i*) Synchronous generators
(*ii*) Transformers
(*iii*) Transmission lines

6- 1-1 Sequence Impedances of Synchronous Generator

Figure below depicts an unloaded synchronous machine (generator or motor) grounded through a reactor (impedance Zn). E_a, E_b and E_c are the induced EMFs of the three phases when a fault (not shown in the figure) takes place at machine terminals currents I_a, I_b and I_c flow to neutral from ground via $Z_{n.}$ unbalance line current can be resolved into three symmetrical components, I_{a1}, I_{a2}, and I_{a0}
before we can prosses with fault analyses we must know the equivalent circuits presented by the machine to the flow of positive negative and zero sequence currents, respectively. Because of winding symmetry currents of a particular sequence produce voltage drops of that sequence only. Therefore, there is a no coupling between the equivalent circuits of various sequences.



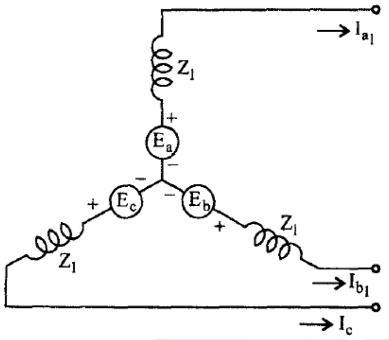
1. Positive Sequence Impedance and Network

Since asynchronous machine is Designed with symmetrical windings, it induces emfs of positive sequence only, i.e. no negative or zero sequence voltages are induced in it ' When the machine carries positive sequence current. only, this mode of operation is the balanced mode. The armature reaction field caused 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 reduces from sub transient reactance (X''_d) to transient reactance (X'_d) and finally to steady state (synchronous) reactance

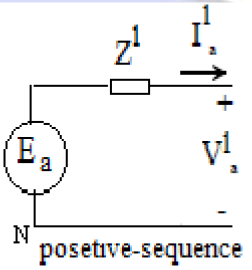
(X_d), as the short circuit transient progresses in time. If armature resistance is assumed negligible, the positive sequence impedance of the machine is

$Z_1 = jX''_d$ (if I cycle transient is of interest)
$= jX'_d$ (if 3-4 cycle transient is of interest)
$= jX_d$ (if steady state value is of interest

If the machine short circuit takes place from unloaded conditions, the
Terminal voltages constitutes the positive sequence voltage; on the other hand. If the short circuit occurs from loaded condition the voltage behind an appropriate reactance (sub transient, transient or synchronous) constitutes the positive sequence voltage.



a- 3-phase model



b- single phase model

With reference to Fig, the positive sequence voltage of terminal a
with respect to the reference bus is given by

$V_{al} = E_a - Z_{al}\ I_{al}$

2. Negative Sequence Impedance and Network

It has already been said that a synchronous machine has zero, negative sequence induced voltages. With the flow of negative sequence currents in the stator a rotating field is created which rotates in the opposite direction to that of the positive sequence field and, therefore, at double 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. The negative sequence impedance presented by the machine with consideration given to the damper windings, is often defined as

$$Z_2 = \frac{X''_q + X''_d}{2} \qquad |Z_2| < |Z_1|$$

Negative sequence network models of a synchronous machine, on a three phase and single-phase basis are shown in Figs. a and b, respectively The
reference bus is of course at neutral potential which is the same as ground

potential. From Fig b the negative sequence voltage of terminal a with respect to reference bus is

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

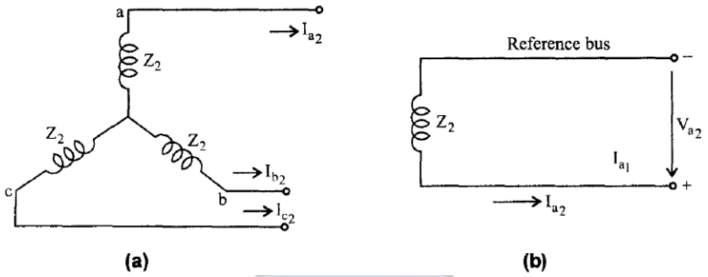
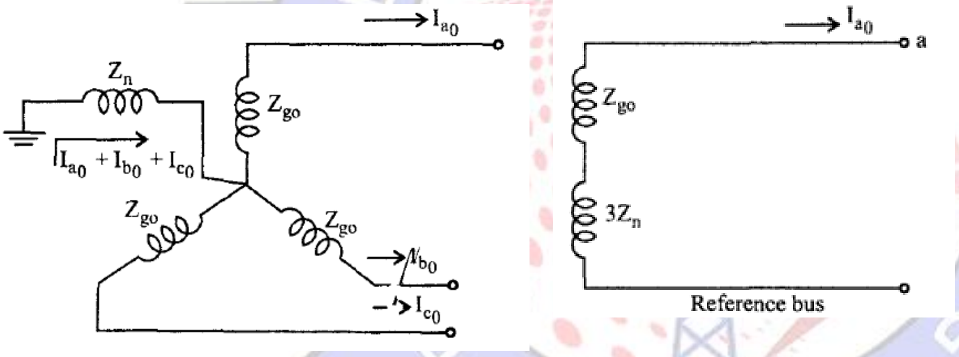


FIG. Negative sequence network of a synchronous machine

3. Zero Sequence Impedance and Network

We state once again that no zero sequence voltages are induced in a synchronous machine. The flow of zero sequence currents creates three mmfs which are in time phase but are distributed in space phase by 120". The resultant air gap field caused by zero sequence currents is therefore zero. Hence, the rotor windings present leakage reactance only to the flow of zero sequence currents ($Z_{og} < Z_2 < Z_1$).



(a)Three-phase model (b)Single-phase model

Fig. Zero sequence network of a synchronous machine

Zero sequence network models on a three- and single-phase basis are shown in Figs. A and b. In Fig. a, the current flowing in the impedance Zn between neutral and ground is $I_n = 3I_{ao}$. The zero-sequence voltage of terminal a with respect to ground, the reference bus. is therefore

$V_{ao}= - 3Zn\ I_{ao} – Z_{og}\ I_{ao} = - (3Z_n + Z_{og})I_{ao}$

Where Zo, is the zero-sequence impedance per phase of the machine.

Since the single-phase zero sequence network of Fig. b carries only per Phase zero sequence current, its total zero sequence impedance must be

Zo=3Zn+Zog

in order for it to have the same voltage from ***a*** to reference bus. The reference bus here is, of course at ground potential. From Fig. b zero sequence voltage of point ***a*** with respect to the reference bus is

$V_{ao} = -Zo\ I_{ao}$

Order of Values of Sequence Impedances of a Synchronous Generator: Typical values of sequence impedances of a turbo-generator rated 5 MVA, 6.6 kV, 3;000 rpm are:

$Z_1 = 12\%$ (sub transient)
$Z_1 = 20\%$ (transient)
$Z_1 = 110\%$ (synchronous)
$Z_2 = 12\%$
$Z_o = 5\%$

thus, it is possible to represent the sequence networks for a power system differently as different sequence currents flow as summarized in Fig