Chapter 2

Fault Analysis

LEARNING OBJECTIVES

After reading this chapter, you will be able to understand:

- Transients in transmission line
- Symmetrical components
- Sequence networks of synchronous generator
- Negative sequence impedance network
- Zero sequence impedance network
- Delta connected load
- Sequence diagrams for transformers
- Unbalanced fault analysis
- Single line to ground fault
- Double line to ground fault

Introduction

Faults in power systems occur because of various reasons like equipment failure, lightning strikes, falling of branches or trees on the transmission lines, switching surges, insulations failures and other electrical or mechanical causes. All these disturbances are collectively called 'faults' in power systems.

A fault usually causes high current flowing through the lines and if enough protection is not provided it may result in damages for the power apparatus. The determination of the values of such currents enables us to make proper selection of circuit breakers, protective relays and also helps to ensure that the associated apparatus will with stand the forces which arise due to the fault currents during the occurrence of fault prior to the interrupting device during the fault.

Percentage wise, the various causes of faults are

1. Lightning	→	6%
2. Equipment failure	→	10%
3. Switching to a fault	→	10%
4. Sleet, wind	→	10%
5. Tree falling, sabotage, etc.	→	10%

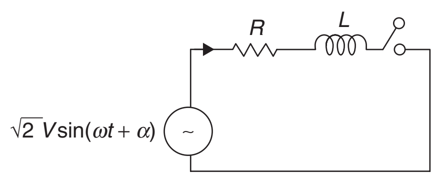
Types of faults and probability of occurrence are given below:

1. Single-phase to ground faults	–	70%
2. Phase-to-phase faults	–	15%
3. Two-phase to ground faults	–	10%
4. Three-phase fault	–	5%

Transients in Transmission Line

Assumptions in the analysis

1. Transmission line is fed from a constant voltage source.
2. Short circuit occurred when the line is unloaded.
3. Line capacitance is neglected and the line is represented by a lumped RL series circuit.



The above figure shows the RL circuit supplied by a voltage source according to given assumptions.

The switch is assumed to be closed at $t = 0$ sec. The parameter 'α' indicates the instant on the voltage source when switch is closed. When the switch is closed, the current flowing through the circuit can be written as

$$i = i_s + i_t.$$

where i_s = Steady-state current
i_t = Transient current

$$i_s = \frac{\sqrt{2}V}{|Z|}\sin(\omega t + \alpha - \theta)$$

$$i_t = \frac{\sqrt{2}V}{|Z|}\sin(\theta-\alpha)e^{-\left(\frac{R}{L}\right)t}$$

where

$$Z = \sqrt{R^2+\omega^2 L^2}\angle\tan^{-1}\frac{\omega L}{R};\theta = \tan^{-1}\frac{\omega L}{R}$$

Total current, $i = \frac{\sqrt{2}V}{|Z|}\sin(\omega t+\alpha-\theta)+\frac{\sqrt{2}V}{|Z|}\sin(\theta-\alpha)$ $e^{-\left(\frac{R}{L}\right)t}$

Steady-state sinusoidal current is called 'symmetrical short-circuit current and the unidirectional transient component is called the 'DC off set current'. First peak in this transient current is known as 'maximum momentary short-circuit current' and it is expressed as

$$i_{mm} = \frac{\sqrt{2}V}{|Z|}\sin(\theta-\alpha)+\frac{\sqrt{2}V}{|Z|}$$

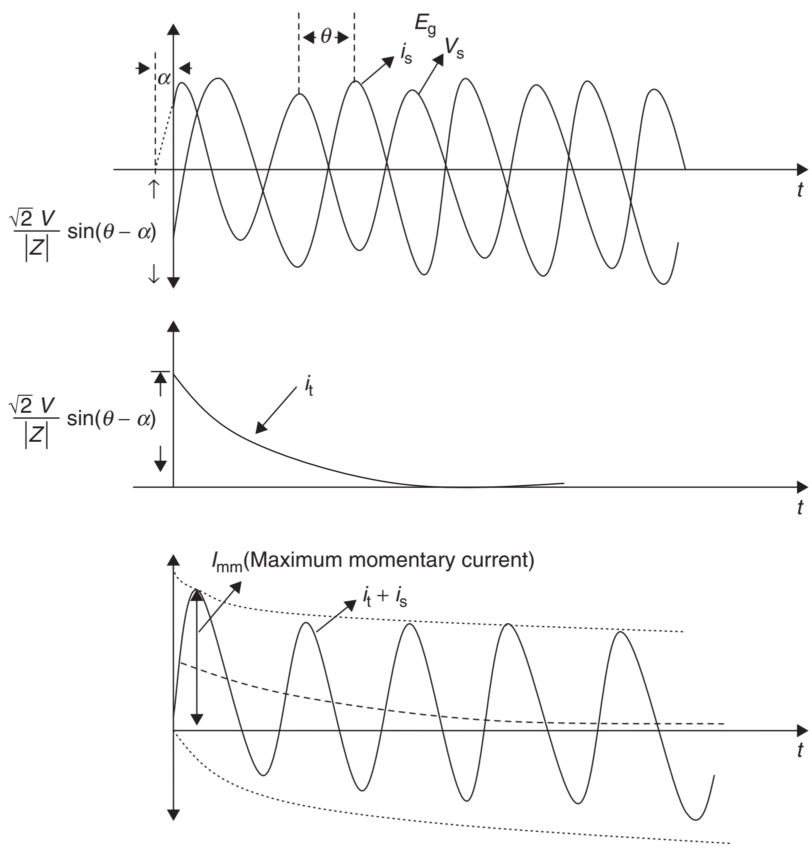
Since the transmission line resistance is small,

$$\theta \cong 90^\circ$$

and i_{mm} has maximum possible value for $\alpha = 0$.

$$i_{mm} = 2\frac{\sqrt{2}V}{|Z|}$$

$= 2 \times$ Maximum symmetrical short-circuit current



Short Circuit of an Unloaded Synchronous Generator

When a three-phase symmetrical short circuit occurs at the terminals of an unloaded synchronous generator, it is assumed that there is no DC off set in the armature current and the magnitude of the current decreases exponentially from a high initial value. The instantaneous expression for the fault current is given by

$$i_f(t) = \sqrt{2}V_t\left[\left(\frac{1}{x''_d}-\frac{1}{x'_d}\right)e^{-t/T''_d}+\left(\frac{1}{x'_d}-\frac{1}{x_d}\right)e^{-t/T'_d}+\frac{1}{x_d}\right]$$
$$\sin\left(\omega t+\alpha-\frac{\pi}{2}\right)$$

where V_t is the magnitude of the terminal voltage.
'α' is the phase angle of the voltage.
X''_d is the direct axis subtransient reactance.
X'_d is the direct axis transient reactance.
X_d is the direct axis synchronous reactance.

With $X''_d < X'_d < X_d$. The time constants are.
T''_d is the direct axis sub transient time constant.
T'_d is the direct axis transient time constant.

If the fault occurs in the system at $t = 0$, the RMS value of the current is given as

$$I_f(0) = I_f'' = \frac{V_t}{X_d''}$$

which is called the 'subtransient fault current'. The duration of the sub transient current is dictated by the time constant T_d''. As the time progresses and $T_d'' < t < T_d'$, the first exponential term of fault current will short decaying and will eventually vanish. However, since 't' is still nearly equal to zero, we have the following RMS value of the current.

$$I_f' = \frac{V_t}{X_d'}$$

This is called the transient fault current. Now as the time progress, further and the second exponential term also decays, we get the following RMS value of the current for the sinusoidal steady state.

$$I_f = \frac{V_t}{X_d}$$

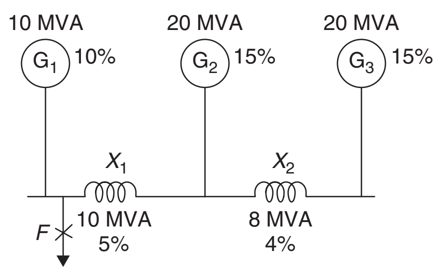
In addition to the AC, the fault currents will also contain the DC offset, the maximum value of the DC off set is given by

$$i_{DC}^{max} = \sqrt{2} I_f'' e^{-t/T_A}$$

where T_A is the armature time constant.

Solved Examples

Example 1: An interconnected generator–reactor system is shown in figure. The base values for a given per cent reactance are the ratings of the individual pieces of equipment. A three-phase short circuit occurs at point 'F'. Determine the fault current and the fault kVA if the busbar line to line voltage is 11 kV and base MVA is 50 MVA.



Solution: Reactance diagram of the system is to be represented on 50 MVA base. New values of reactance on new base are

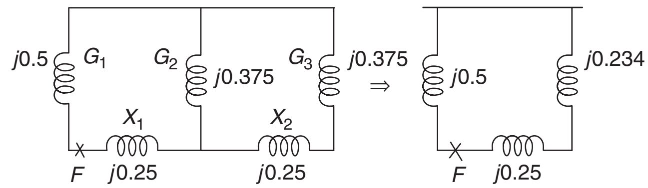
$$X_{G_1} = 0.10 \times \frac{50}{10} = 0.10 \times \frac{\text{New VA}}{\text{Old VA}} = 0.5 \text{ p.u.}$$

$$X_{G_2} = 0.15 \times \frac{50}{20} = 0.375 \text{ p.u.}$$

$$X_{G_3} = 0.15 \times \frac{50}{20} = 0.375 \text{ p.u.}$$

$$X_1 = 0.05 \times \frac{50}{10} = 0.25 \text{ p.u.}$$

$$X_2 = 0.04 \times \frac{50}{8} = 0.25 \text{ p.u.}$$



Total reactance from the fault point to neutral is per unit

$$\text{reactance} = j\frac{0.5(0.2344 + 0.25)}{0.5 + 0.2344 + 0.25}$$

$$= j0.246$$

$$\text{Fault MVA} = \frac{\text{Base MVA}}{Z_{F_{p.u.}}} = \frac{50 \times 10^6}{0.246} = 203.25 \text{ MVA}$$

$$\text{Fault current} = \frac{\text{Fault MVA}}{\sqrt{3}\ \ 11 \text{ kV}} = \frac{203.25 \times 10^6}{\sqrt{3} \times 11 \times 10^3} = 10.66 \text{ kA}$$

Example 2: A 60 Hz alternator is rated 500 MVA, 20 kV, with X_d = 1.0 p.u. and X_d'' = 0.3 p.u. It supplies a purely resistive load of 400 MVA at 20 kV. The load is directly connected across the generator terminals when a symmetrical fault occurs at the load terminals. The initial RMS current in the generator circuit is

(A) 4.811 p.u. (B) 11.54 p.u.
(C) 4.16 p.u. (D) 8.33 p.u.

Solution: (C)

Initial fault current depends on sub-transient reactance $X_d'' = 0.3$ p.u.

$$\text{Initial fault current} = \frac{E}{X_{F_{actual}}}$$

$$X_{F_{actual}} = X_{d\ actual}'' = 0.3 \times \frac{V_{base}^2}{VA_{base}}$$

$$= 0.3 \times \frac{20^2}{500} = 0.24\ \Omega$$

Initial fault current

$$= \frac{E}{X_{F_{actual}}} = \frac{\left(\frac{20}{\sqrt{3}}\right) \times 10^3}{0.24} = 48.11 \text{ kA}$$

Base current in load circuit

$$= \frac{\text{Load MVA}}{\sqrt{3} \times \text{kV}} = \frac{400 \times 10^6}{\sqrt{3} \times 20 \times 10^3} = 11.547 \text{ kA}$$

$$\text{Per-unit value of fault current } I_F = \frac{I_{F\ actual}}{I_{base}}$$

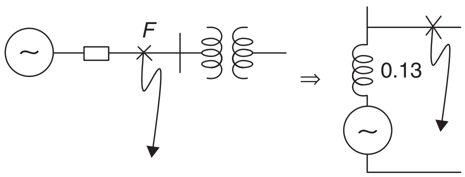
$$= \frac{48.11}{11.547} = 4.16 \text{ p.u.}$$

Example 3: A three-phase generator rated at 110 MVA, 11 kV is connected through circuit breakers to a transformer. The generator is having direct axis sub-transient reactance

$X''_d = 13\%$ and synchronous reactance $X_d = 130\%$. The generator is operating at no-load and rated voltage when a three-phase short-circuit fault occurs between the breaker and the transformer. The magnitude of initial symmetrical RMS current in the breaker will be

(A) 76.9 kA (B) 44.4 kA
(C) 38.45 kA (D) 7.69 kA

Solution: (B)



Fault current $I_f = \dfrac{E}{X''_d} = \dfrac{1}{0.13} = 7.69$ p.u.

$$I_{\text{fault actual}} = I_{\text{base}} \times I_{\text{f p.u.}} = \frac{110\times10^6}{\sqrt{3}\times11\times10^3}\times7.69$$

$$= 44.4 \text{ kA}$$

Example 4: At a 220 kV substation of a power system, it is given that the three-phase fault level is 3500 MVA. Calculate the driving point reactance at the faulted bus

(A) 4.61 Ω (B) 27.65 Ω
(C) 6.91 Ω (D) 13.82 Ω

Solution: (D)

The short-circuit MVA = $3V_{\text{base}}I_{\text{sc}}$

Short-circuit current $(I_{\text{sc}}) = \dfrac{V_{\text{base}}}{X_f}$

$$\therefore \quad 3.V_{\text{base}}\cdot\frac{V_{\text{base}}}{X_{f_{eq}}} = 3500$$

$$X_{f_{eq}} = \frac{3V_{\text{base}}^2}{3500} = \frac{3\times\left(\dfrac{220}{\sqrt{3}}\right)^2}{3500}$$

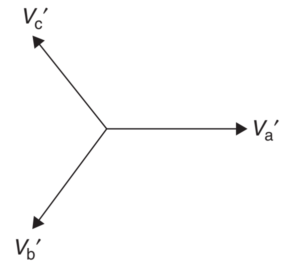
$$X_{f_{eq}} = 13.82\ \Omega$$

Symmetrical Components

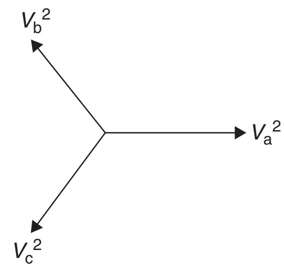
The key idea of symmetrical component analysis is to decompose the unbalanced system into three sequences of balanced networks. The networks are then coupled only at the point of the unbalanced.

The three sequence networks are known as the

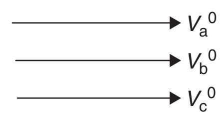
1. Positive-sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase, and having the same phase sequence as the original phasors.



2. Negative-sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase, and having the phase sequence opposite to that of the original phasors.



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



Assume three unbalanced voltage phasors, V_A, V_B and V_C having a positive sequence (*abc*). Using symmetrical components, it is possible to represent each phasor voltage as

$$V_A = V_A^0 + V_A^1 + V_A^2$$

$$V_B = V_B^0 + V_B^1 + V_B^2$$

$$V_C = V_C^0 + V_C^1 + V_C^2$$

Operator '*a*': Function of the operator '*a*' was introduced, when it is operated upon a phasor that is rotated by +120° without changing the magnitude of it.

$$a = 1\angle120° = e^{j120°} = -0.5 + j0.866$$

$$a^2 = 1\angle240° = e^{-j120°} = -0.5 - j0.886$$

$$a^3 = 1\angle360° = 1\angle0° = e^{j360°} = 1$$

$$\therefore \quad 1 + a + a^2 = 0$$

$$a^4 = a;\ a^5 = a^2;\ a^6 = 1$$

$$a - a^2 = j\sqrt{3};\ a^2 - a = -j\sqrt{3}$$

Assuming phase '*a*' as reference, the above relation between the unsymmetrical components of phase '*b*' and '*c*' in terms of symmetrical components of phase '*a*' is given by

$$V_a = V_a^0 + V_a^1 + V_a^2$$

$$V_b = V_a^0 + a^2 V_a^1 + a V_a^2$$

$$V_c = V_a^0 + a V_a^1 + a^2 V_a^2$$

Matrix representation of the above relation is given by

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix} = [T] \begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix}$$

Inverse relation is given

$$\begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix}$$

The complex power flowing into a three-phase circuit through three lines a, b and c is

$$S_3\phi = P + jQ = V_a I_a^* + V_b I_b^* + V_c I_c^*$$

where V_a, V_b and V_c are the voltages and I_a, I_b and I_c are the currents flowing into the circuit in the three lines.

$$S_{3\phi} = \left(T V_a^{012}\right)^T \left(T I_a^{012}\right)^*$$

$$= V_a^{012^T} T^T T^* I_a^{012^*}$$

Since $T^T T^* = 3$,

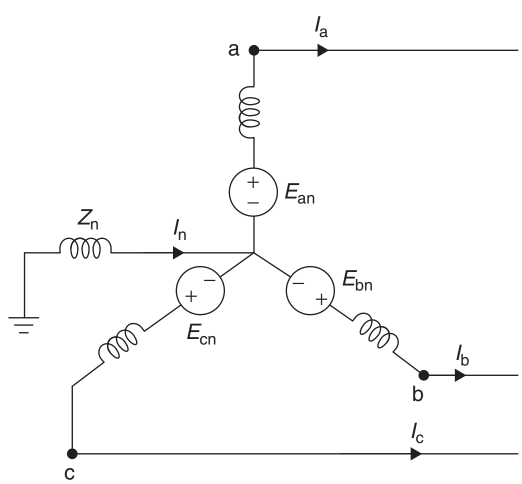
$$\therefore \qquad S_3\phi = 3\left(V^{012^T} I^{012^*}\right)$$

$$S_3 = 3V^0 I^{0*} + 3V' I'^* + 3V^2 I^{2*}$$

The above equation shows that the total unbalanced three-phase power is equal to the sum of the three symmetrical component powers.

Sequence Networks of Synchronous Generator

A Synchronous generator, grounded through a reactor is shown in figure below.



When the fault takes place at the terminals, the current I_a, I_b and I_c flows in the lines. Whenever the fault involves ground, the total current $I_a + I_b + I_c = I_n$ flows into the neutral of the generator and the line currents can be resolved into symmetrical components.

Positive Sequence Impedance and Network

Synchronous generator induces positive sequence emf's only due to its symmetrical winding designs. When the machine carries positive sequence currents only, this mode of operation is the balanced mode. As the short circuit progresses in time, 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 reactance (X_d). If the armature resistance is assumed negligible, the positive sequence impedances of machine is

$$Z_1 = jX_d'' \text{ (sub transient period} \rightarrow 1 \text{ cycle)}$$

$$= jX_d' \text{ (transient period} \rightarrow 3\text{–}4 \text{ cycles)}$$

$$= jX_d \text{ (steady-state value)}$$

Since the neutral current $I_n = 0$, the neutral impedance Z_n does not appear in the model. Since the positive-sequence network is a balanced network, it can be represented by the single-phase network model as shown in figure.

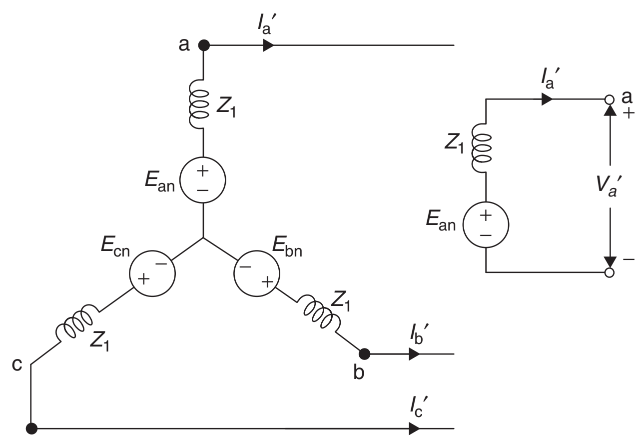


Figure 1 Positive-sequence network and its single-phase equivalent

Negative Sequence Impedance Network

Synchronous machine has no negative sequence induced voltages. With the flow of negative sequence currents in the stator, a rotating field is created which rotates in opposite direction to that of the positive sequence, therefore, at double synchronous speed with respect to rotor. The negative sequence mmf is alternately presented with reluctance of direct and quadrature axes. The negative sequence impedance presented by the machine with consideration given to the damper windings is defined as

$$Z_2 = j\frac{X_q' + X_d''}{2}; |Z_2| < |Z_1|$$

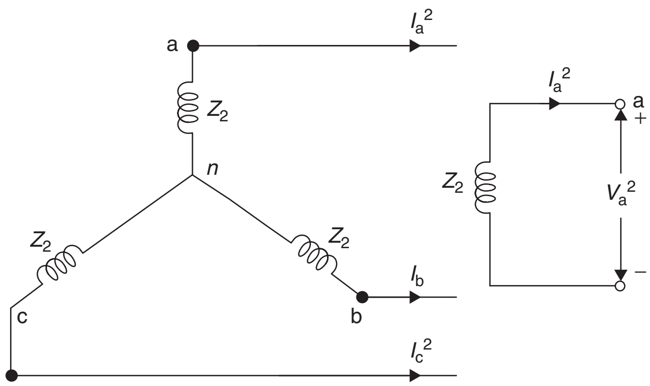


Figure 2 Negative-sequence network and its single-phase equivalent

Zero-sequence Impedance Network

Synchronous machine has no zero-sequence voltages induced, the flow of zero-sequence currents creates three mmf's which are in time phase, but are distributed in space by 120°. The current flowing through the impedance Z_n between neutral to ground is $I_n = 3I_{a0}$. The zero-sequence voltage drop of zero sequence from point 'a' to ground is

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

The zero-sequence circuit, which is a single-phase circuit assumed to carry only the zero-sequence current of one phase, must therefore have an impedance of $3Z_n + Z_{g0}$. The total zero-sequence impedance through which I_a^0 flows is

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

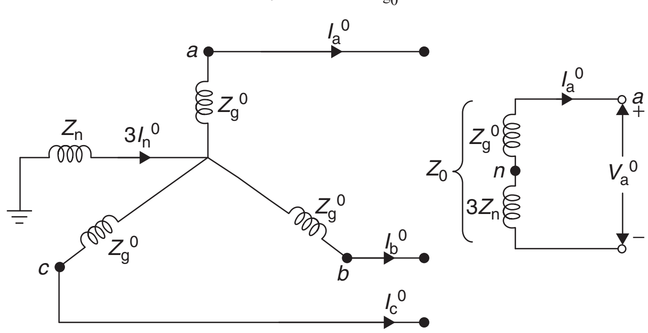
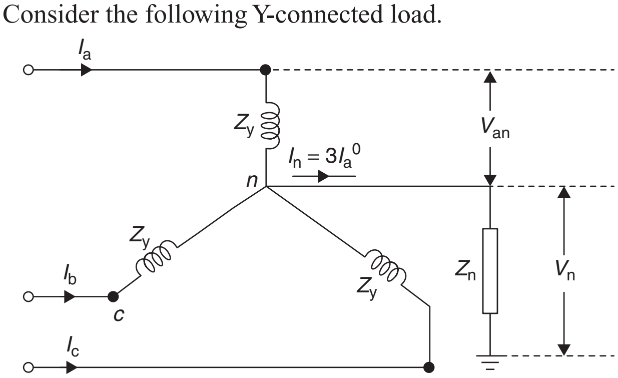


Figure 3 Zero-sequence network and its single-phase equivalent

Sequence Circuit of Y- and Δ-connected Loads

Consider the following Y-connected load.



In the above Y-connected load, sum of the line current is equal to the neutral current I_n and it is given by

$$I_n = I_a + I_b + I_c$$

Voltage of phase 'a' with respect to neutral is given by

$$V_a = V_{an} + V_n,$$

where $V_n = 3I_a^0 Z_n$

We can also write the voltage drops to ground from each of the lines a, b and c as

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} + \begin{bmatrix} V_n \\ V_n \\ V_n \end{bmatrix} = Z_Y \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} + 3I_a^0 Z_n \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

The a–b–c voltages and currents in the above equation can be replaced by their symmetrical components and the symmetrical component relation is given by

$$\begin{bmatrix} V^0 \\ V^1 \\ V^2 \end{bmatrix} = \begin{bmatrix} Z_Y + 3Z_n & 0 & 0 \\ 0 & Z_Y & 0 \\ 0 & 0 & Z_Y \end{bmatrix} \begin{bmatrix} I^0 \\ I^1 \\ I^2 \end{bmatrix}$$

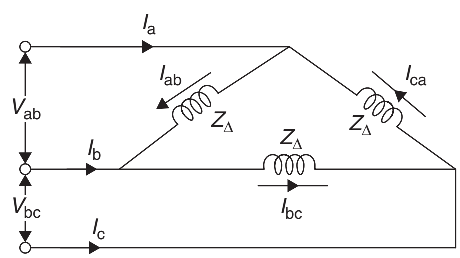
Delta-Connected Load

The delta (Δ) circuit cannot provide a path through neutral. Therefore for a delta-connected load or its equivalent 'Y' connected cannot contain any zero-sequence component.

$$V_{ab} = Z_\Delta \cdot I_{ab}$$

$$V_{bc} = Z_\Delta \cdot I_{bc}$$

$$V_{ca} = Z_\Delta \cdot I_{ca}$$



The sum of line-to-line voltages or phase currents is always zero.

$$\frac{1}{3}(V_{ab} + V_{bc} + V_{ca}) = V_{abc} = 0$$

$$\frac{1}{3}(I_{ab} + I_{bc} + I_{ca}) = I_{abc} = 0$$

Therefore, for a delta-connected load without sources or mutual coupling there will be no zero-sequence currents at the lines (there are some cases where a circulating currents may circulate inside a delta load and not seen at the terminals of the zero sequence circuit).

System parameters relations are decoupled and written as

$$V^0 = (Z_Y + 3Z_n)I^0$$

$$V^1 = Z_Y I^1$$

$$V^2 = Z_Y I^2$$

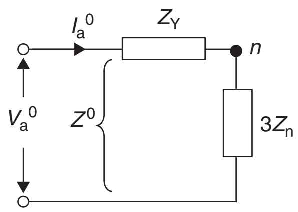


Figure 4 Zero sequence network

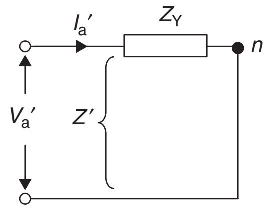


Figure 5 Positive sequence

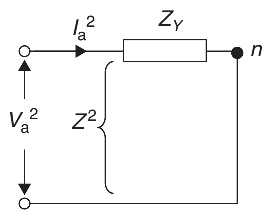
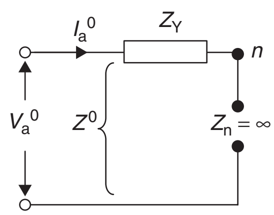


Figure 6 Negative sequence

For ungrounded or Isolated neutral star-connected loads, no zero sequence current can flow and $Z_n = \infty$. Then the positive- and negative-sequence networks remain unchanged but zero-sequence network is as shown in the figure below.



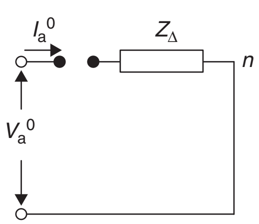


Figure 7 Zero sequence circuit

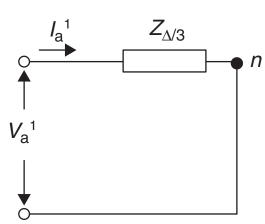


Figure 8 Positive sequence circuit

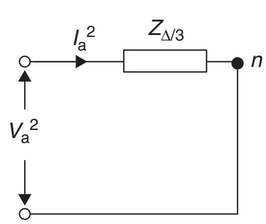
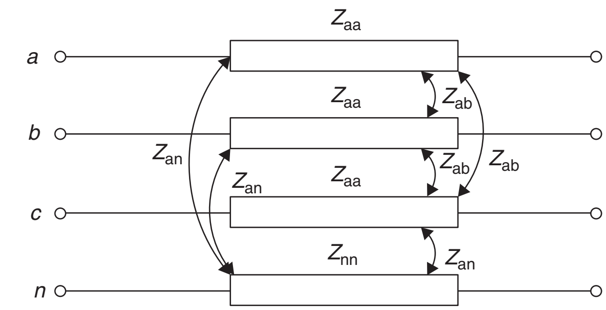


Figure 9 Negative sequence circuit

Sequence Diagrams of Transmission Lines

For transmission lines, assume we have the following, with mutual impedances.



The phase relationships are given by

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

where Z_s = Self-impedance of the phase $= Z_{aa} + Z_{nn} - 2Z_{an}$

Z_m = Mutual impedance between the phases

$= Z_{ab} + Z_{nn} - 2Z_{an}$

$\therefore \quad \Delta V = ZI$

After converting relationships to sequence representation

$$\Delta V_s = A^{-1} Z A I_s$$

ΔV_s and I_s are symmetrical voltages and currents.

$$A^{-1} ZA = \begin{bmatrix} Z_s - Z_m & 0 & 0 \\ 0 & Z_s - Z_m & 0 \\ 0 & 0 & Z_s - Z_m \end{bmatrix}$$

$$\therefore \quad Z^1 = Z_s - Z_m$$

$$Z^2 = Z_s - Z_m$$

$$Z^0 = Z_s + 2Z_m$$

where $\quad Z_s = Z_{aa} + Z_{nn} - 2Z_{an}$

$$Z_m = Z_{ab} + Z_{nn} - 2Z_{an}$$

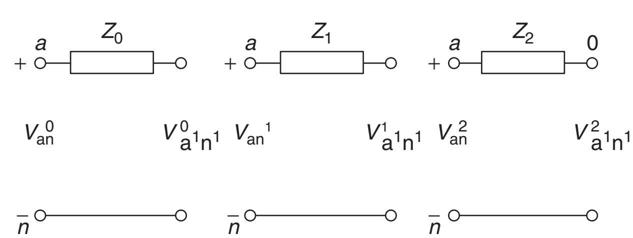


Figure 10 Positive-, negative- and zero-sequence networks of transmission lines

Sequence Diagrams for Transformers

Similar to the transmission lines, the positive and negative sequence diagrams for transformers are same and equal to its leakage impedances.

$$Z^1 = Z^2 = Z_{\text{leakage}}$$

The zero-sequence network of the transformer depends on how the transformer is grounded and its type of connection current flows only through the winding connected in star and the star point in earthed. For delta winding, a star winding or with neutral isolated, the zero-sequence current cannot flow.

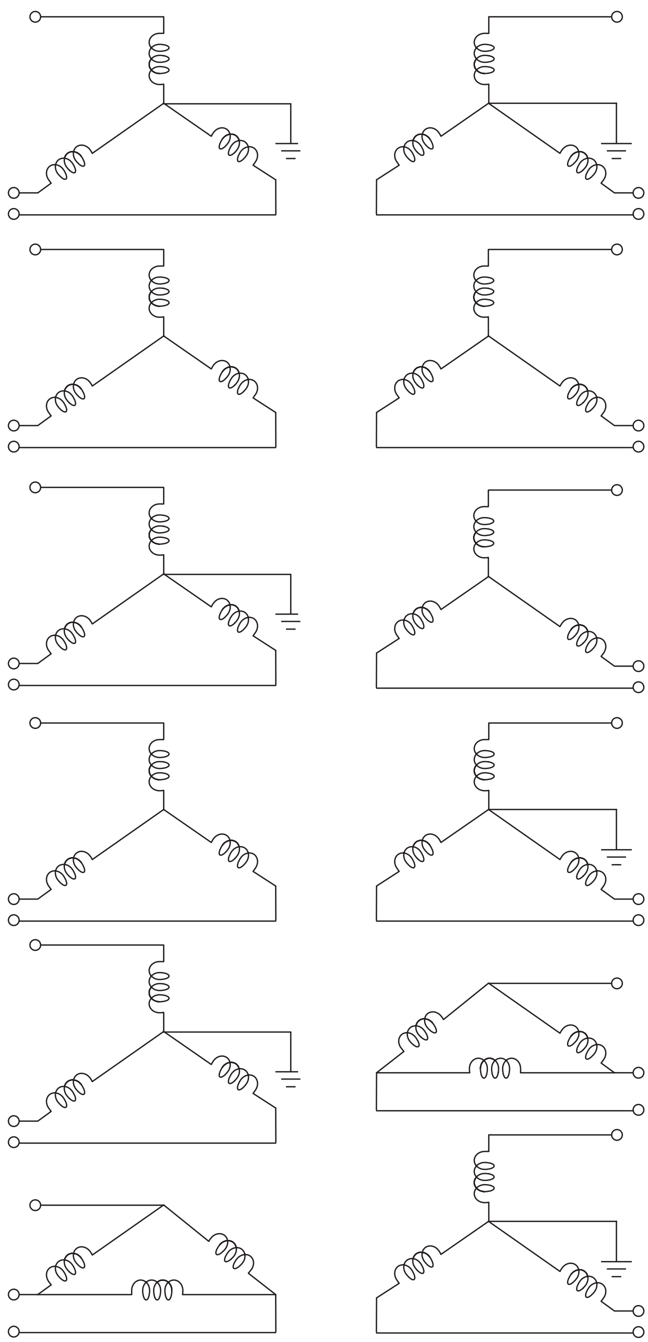


Figure 11 (Continued)

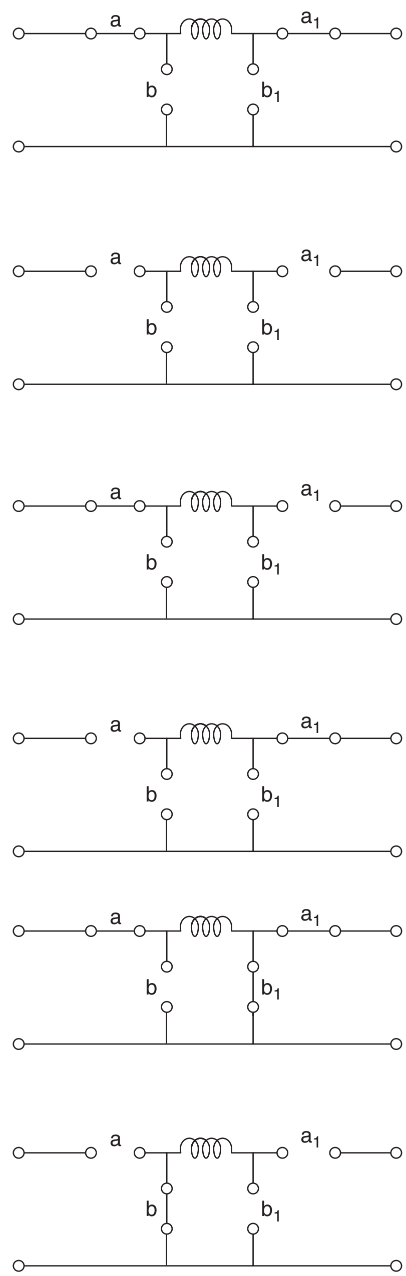


Figure 12 (Continued)

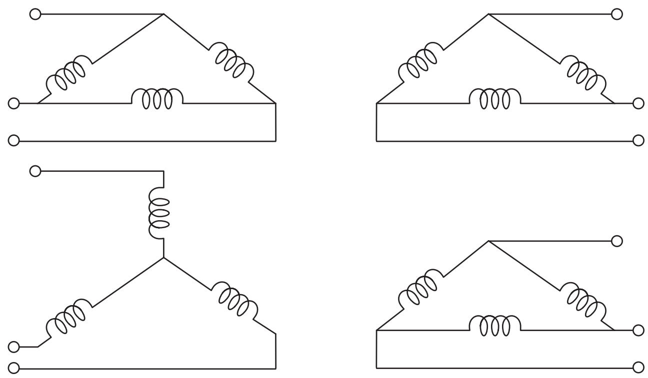


Figure 11 Type of transformer connection

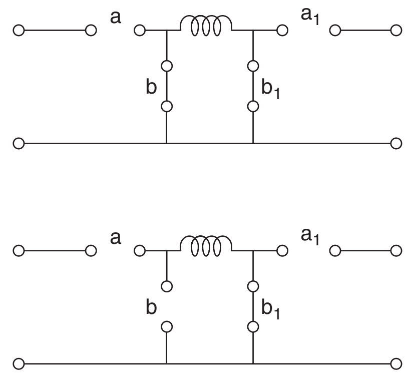


Figure 12 Zero-sequence network

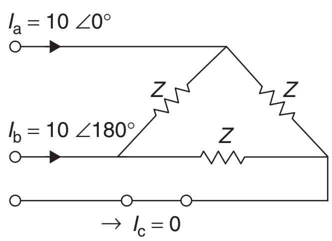
Example 5: One conductor of a 3-ϕ line is open. The current flowing to the Δ-connected load through line '*a*' is 10 A with the current in line '*a*' as reference and assuming that line '*c*' is open, find symmetrical components of line currents.

Solution: Circuit is shown in figure, and the line currents are given by

$$I_a = 10\angle 0° \text{ A}$$

$$I_b = 10\angle 180° \text{ A}$$

$$I_c = 0 \text{ A}$$



$$\begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

$$\begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} 10\angle 0 \\ 10\angle 180° \\ 0 \end{bmatrix}$$

$$I_a^0 = 0 \text{ A}$$

$$I_a^1 = 5.78\angle -30° \text{ A}$$

$$I_a^2 = 5.78\angle 30° \text{ A}$$

$$I_b^0 = a^2\, I_a^0 = 0 \text{ A}$$

$$I_b^1 = a^2\, I_a^1 = 5.78\angle -50° \text{ A}$$

$$I_b^2 = a^2\, I_a^2 = 5.78\angle 150° \text{ A}$$

$$I_c^0 = aI_a^0 = 0 \text{ A}$$

$$I_c^1 = aI_a^1 = 5.78\angle 90° \text{ A}$$

$$I_c^2 = aI_a^2 = 5.78\angle -90° \text{ A}$$

Note: Symmetrical components of phase '*c*' are non-zero even though there is no current in that phase but the sum of the corresponding phase symmetrical components is equal to zero.

Example 6: The parameters of transposed overhead transmission line are given as

$$\text{Self-reactance } X_s = 0.45\ \Omega/\text{km}$$

$$\text{Mutual reactance } X_m = 0.12\ \Omega/\text{km}$$

The positive-sequence reactance X_1 and zero-sequence reactance X_0, respectively, in Ω/km are

(A) 0.69, 0.33 (B) 0.33, 0.69
(C) 0.33, 0.66 (D) 0.66, 0.33

Solution: (B)

Positive-sequence reactance $= X_s - X_m$

$$= 0.45 - 0.12 = 0.33\ \Omega/\text{km}$$

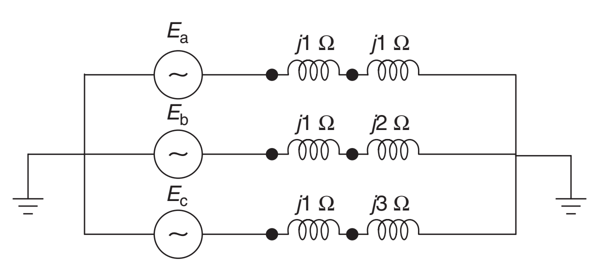
Zero-sequence reactance $= X_s + 2X_m$

$$= 0.45 + 0.24 = 0.69\ \Omega/\text{km}$$

Example 7: A three-phase alternator generating unbalanced voltages is connected to an unbalanced load through a three-phase transmission line as shown in figure. The neutral of the alternator and the star point of the load are solidly grounded. The phase voltages of the alternator are

$$E_a = 10\angle 0° \text{ V},\quad E_b = 10\angle -90° \text{ V},\quad E_c = 10\angle 120° \text{ V}$$

The negative sequence component of the load current is



(A) 0.33 A (B) 5 A (C) 3.33 A (D) 2.5 A

Solution: (A)
Since the circuit is grounded on both the sides, each phase can be treated as a single-phase circuit and the phase currents can be written as

$$I_a = \frac{E_a}{X_a} = \frac{10\angle 0°}{j2} = 5\angle -90°$$

$$I_b = \frac{E_b}{X_b} = \frac{10\angle -90°}{j3} = 3.33\angle -180°$$

$$I_c = \frac{E_c}{X_c} = \frac{10\angle 120°}{j4} = 2.5\angle 30°$$

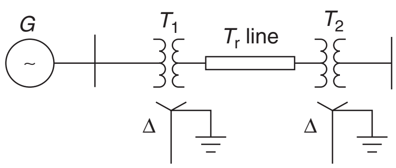
$$\text{Negative-sequence currents} = I_a^2 = \frac{1}{3}\left(I_a + a^2 I_b + aI_c\right)$$

$$= \frac{1}{3}\left(5\angle -90° + 3.33\angle -300 + 2.5\angle 150°\right)$$

$$= 0.33\angle -120$$

Example 8: A three-phase, 30 MVA, 6.6 kV alternator having 15% reactance is connected through a 30 MVA, 6.6/33 kV delta–star-connected transformer of 5% reactance to a 33 kV transmission line having a negligible resistance and a reactance of 4 Ω. At the receiving end of the transmission line there is a 30 MVA, 33/6.6 kV delta–star-connected transformer of 5% reactance stepping down the voltage at 6.6 kV, both the transformers have their neutral solidly grounded. Draw the one-line diagram and the positive-, negative- and zero-sequence networks of this system.

Solution: One-line diagram of the system is shown in the figure below



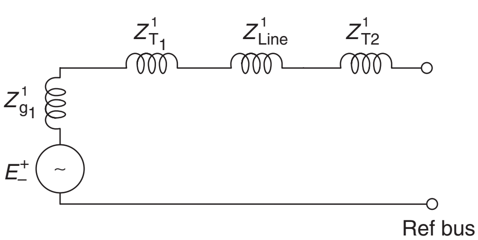


Figure 13 Positive-sequence equivalent network

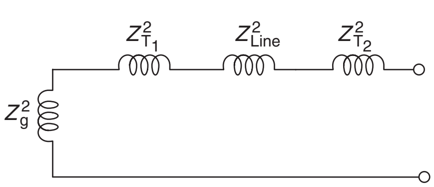


Figure 14 Negative-sequence equivalent network

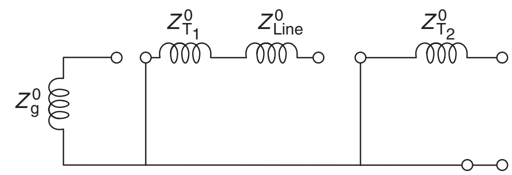
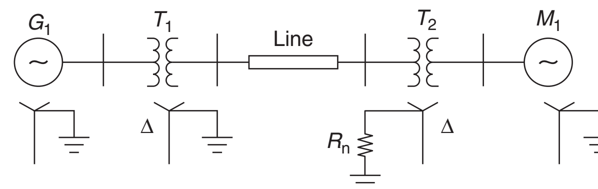
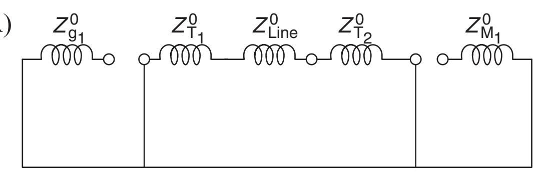


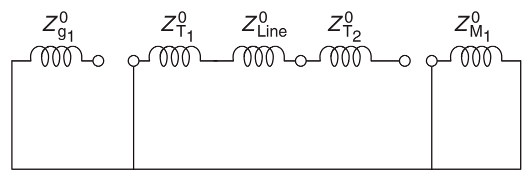
Figure 15 Zero-sequence equivalent network

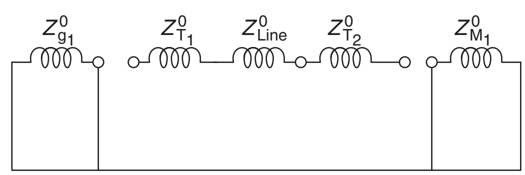
Example 9: Single-line diagram of a power system is given by

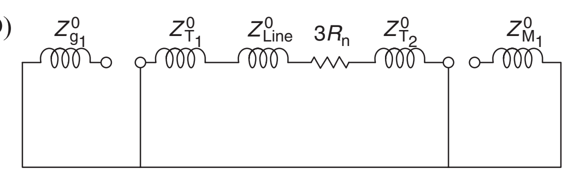


Which one of the following is the zero-sequence equivalent of the above system?

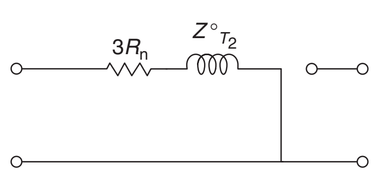
(A)


(B)


(C)


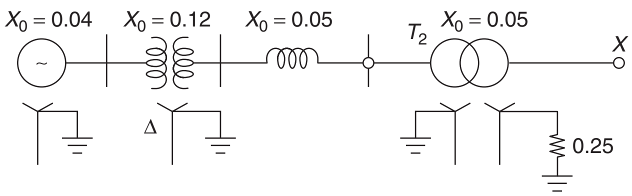
(D)


Solution: (D)
For 3-ϕ transformer 2, equivalent circuit is given by



Example 10: A generator is connected to a transformer which feeds another transformer through a short transmission line. The zero-sequence impedances values are expressed in p.u. on a common base and are indicated in

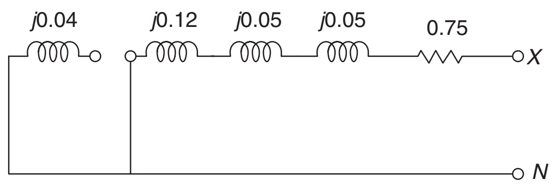
figure. The Thevenin's equivalent zero-sequence impedance at point 'X' is



(A) $0.75 + j0.22$ (B) $0.75 + j0.26$
(C) $0.25 + j0.26$ (D) $0.25 + j0.22$

Solution: (A)

Zero-sequence equivalent network is given by



Equivalent impedance at point 'X' is, $Z_{X_n} = j\,0.22 + 0.75$

Unbalanced Fault Analysis

Various types of unsymmetrical faults that occurs in power systems are

Shunt type faults

1. Single line to ground (LG) fault
2. Line to line (LL) fault
3. Double line to ground (LLG) fault

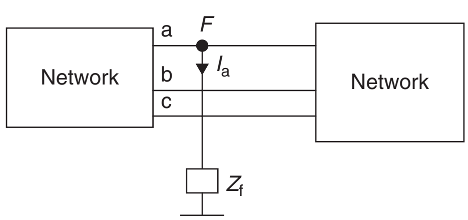
Series type of faults

1. One conductor open fault
2. Two conductor open fault

Symmetrical components are very commonly used in calculating currents arising from unbalanced short circuits.

Single Line to Ground Fault

A single line to ground fault at a point in power system is through a fault impedance as shown in the figure.



At the point of fault occurrence, the currents come out of the network and line to ground voltages are given by

$$I_b = 0$$

$$I_c = 0$$

$$V_a = I_a Z_f$$

Symmetrical components of the fault currents are,

$$\begin{bmatrix} I_a^0 \\ I_a^1 \\ I_a^2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix}$$

$$\therefore \qquad \Rightarrow I_a^1 = I_a^2 = I_a^0 = \frac{1}{3} I_a \qquad (1)$$

Similarly symmetrical components of the fault voltages are

$$V_a^1 + V_a^2 + V_a^1 = Z_f\, I_a = 3Z_f\, I_a^1 \qquad (2)$$

Expression (1) and (2) together describes the sequence networks connection shown in the figure.

Note: Positive-, negative- and zero-sequence components currents of a phase are equal if there is a LG fault in that particular phase.

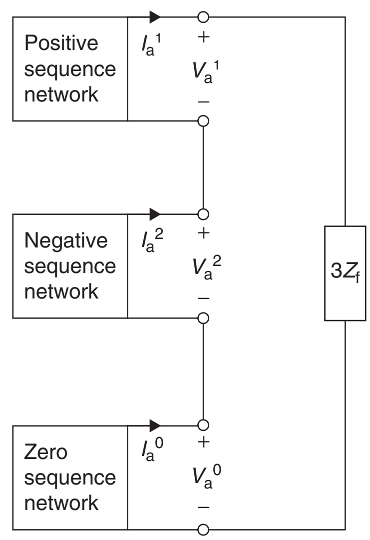
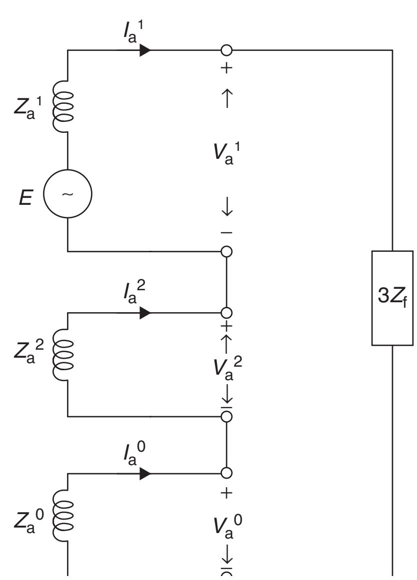


Figure 16 Sequence connection for LG Fault

The Thevenin's equivalent of sequence networks is given by



From the above equivalent reactance diagram,

$$I_a^1 = \frac{E_a}{(Z_1 + Z_2 + Z_0) + 3Z_f}$$

Fault current in phase 'a'

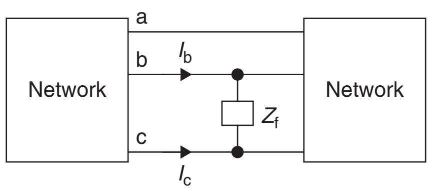
$$I_a = 3I_{a_1} = \frac{3E_a}{(Z_1 + Z_2 + Z_0) + 3Z_f}$$

Phase voltage in faulted phase

$$V_a = I_a Z_f = \frac{3E_a}{(Z_1 + Z_2 + Z_0) + 3Z_f} . Z_f$$

Line-to-Line Fault

A line-to-line fault in a power system on phases 'b' and 'c' through a fault impedance Z_f is shown in the following figure.



The current and voltages at the fault can be expressed as

$$I_a = 0$$

$$I_b = -I_c \text{ and } V_b - V_c = I_b Z_f$$

Symmetrical components of fault currents and voltages are given by

$$I_a^0 = 0 \text{ and } I_a^1 = -I_a^2$$

$$V_a^1 = V_a^2 \text{ and } V_a^1 - V_a^2 = Z_f I_a^1$$

The above relations describe the sequence network connections as shown in the figure.

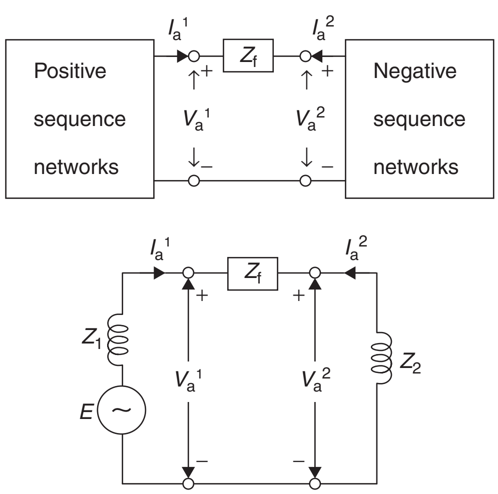


Figure 17 Sequence networks connection and their Thevenin's equivalent network

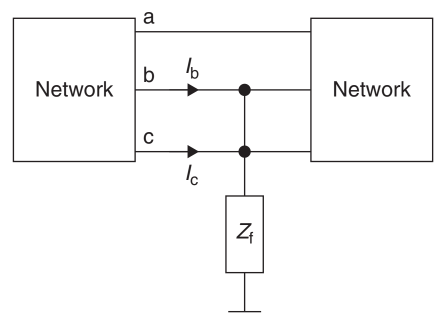
From the equivalent reactance diagram,

$$I_a^1 = \frac{E_a}{Z_1 + Z_2 + Z_f}$$

$$I_f = I_b = -I_c = \frac{-j\sqrt{3}\, E_a}{Z_1 + Z_2 + Z_f}$$

Double Line to Ground Fault

A double line to ground fault in power system is shown in the figure below.



The voltage and current conditions at the fault are expressed as

$$I_a = 0 \text{ or } I_a^1 + I_a^2 + I_a^0 = 0$$

$$V_b = V_c = Z_f(I_b + I_c) = 3Z_f I_a$$

Symmetrical voltages and currents relations are given by

$$V_a^1 = V_a^2 = \frac{1}{3}\left[V_a + \left(a + a^2\right)V_b\right]$$

$$V_a^0 = \frac{1}{3}\left(V_a + 2V_b\right)$$

$$V_a^1 - V_a^0 = \frac{1}{3}\left(2 - a - a^2\right) = V_b = 3Z_f\, I_{a_0}$$

The above relations describe the sequential network connections as shown in the following figure.

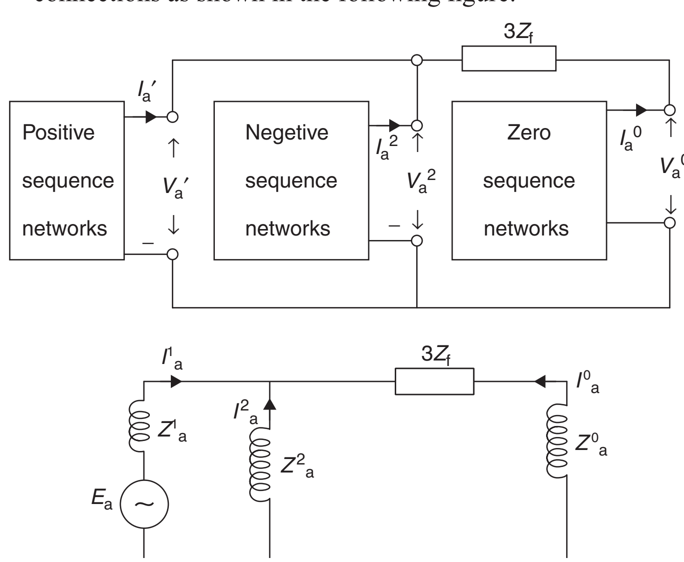


Figure 18 Sequence-network connections and their Thevenin's equivalent network

From the above sequential networks,

$$\Rightarrow \quad I_a^1 = \frac{E_a}{Z_a^1 + \dfrac{Z_a^2\left(Z_a^0 + 3Z_f\right)}{Z_a^0 + Z_a^2 + 3Z_f}}$$

$$I_f = 3I_{a_0} = 3\left[\frac{E_a}{Z_a^2} - \left(\frac{Z_a^1 + Z_a^2}{Z_a^2}\right) I_a^1\right]$$

Example 11: The severity of the line to ground and three-phase fault at the terminals of an unloaded synchronous generator is to be same. If the terminal voltage is 'E' and the positive, negative and zero-sequence impedances are Z_1, Z_2 and Z_0, respectively, then the required inductive reactance for neutral grounding is

(A) $2Z_1 - Z_2 - Z_0$ (B) $\frac{1}{3}[2Z_1 - Z_2 - Z_0]$
(C) $Z_1 + Z_2 + Z_0$ (D) $\frac{1}{3}[Z_1 + Z_2 + Z_3]$

Solution: (B)
For 3-ϕ fault, fault current $I_f = \dfrac{E}{Z_1}$ p.u.

For fault of line to ground

$$I_{f_{Lg}} = \frac{3E}{Z_1 + Z_2 + Z_0 + 3Z_n} \text{ p.u.}$$

If severity of line to ground and 3-ø faults are same

$$\frac{E}{Z_1} = \frac{3E}{Z_1 + Z_2 + Z_0 + 3Z_n}$$

$$Z_1 + Z_2 + Z_0 + 3Z_n = 3Z_1$$

$$Z_n = \frac{2Z_1 - Z_2 - Z_0}{3}$$

$$\Rightarrow \quad Z_n = \frac{1}{3}\left[2Z_1 - Z_2 - Z_0\right]$$

Example 12: The per-unit values of positive-, negative- and zero-sequence reactance of a network at fault are 0.2, 0.17 and 0.12 p.u., respectively. The fault current for double line to ground fault is

(A) 4.718 p.u. (B) 2.04 p.u.
(C) 1.57 p.u. (D) 16.26 p.u.

Solution: (A)
For LLG fault

$$I_f = \frac{3\left(Z_2 + Z_0\right)}{Z_1 Z_2 + Z_1 Z_0 + Z_2 Z_0}$$

$$= \frac{3\left(0.17 + 0.12\right)}{0.2 \times 0.7 + 0.2 \times 0.12 + 0.17 \times 0.12}$$

$$I_f = 4.718 \text{ p.u.}$$

Example 13: Zero-sequence current of fault current is 100 A, then the SLG fault current is

(A) 100 A (B) 33.33 A
(C) 300 A (D) 200 A

Solution: (C)
Single-line to ground fault current $= 3I_{a_0}$

$$= 3 \times 100 \text{ A}$$

$$= 300 \text{ A}$$

Example 14: A 500 MVA, 22 kV generator has $X_d'' = X_1 = X_2 = 15\%$ and $X_0 = 5\%$. Its neutral is grounded through a reactor of 0.3 Ω. The generator is operating at rated voltage, and no load. If it is disconnected from the system when a SLG fault occurs at its terminals, the sub-transient current in the fault phase is

(A) 13.12 kA (B) 31.5 kA
(C) 2.4 kA (D) 10.5 kA

Solution: (B)
Fault current for SLG fault $I_f = 3I_{a1}$

$$I_f = 3I_{a_1} = \frac{3E_a}{Z_1 + Z_2 + Z_0 + 3Z_n}$$

$$= \frac{3}{0.15 + 0.15 + 0.05 + 0.9} = 2.4 \text{ p.u.}$$

$$I_{base} = \frac{S_{base}}{\sqrt{3}V_{base}} = \frac{500}{\sqrt{3} \times 22} = 13.12 \text{ kA}$$

Fault current $= I_{f\,p.u.} \times I_{base}$

$$= 2.4 \times 13.12 \text{ kA}$$

$$= 31.49 \text{ kA}$$

Example 15: A 25 MVA, 11 kV alternator has positive, negative and zero sequence reactance of 0.3 p.u., 0.35 p.u. and 0.05 p.u., respectively. What value of resistance must be put in the generator neutral so that the fault current for a line to ground fault of zero fault impedance will not exceed the rated line current?

(A) 4.84 Ω (B) 4.7 Ω (C) 0.972 Ω (D) 2.35 Ω

Solution: (B)
Rated current in per unit $I_{rated} = 1$ p.u.

Fault current for SLG fault

$$I_f = \frac{3E_a}{Z_1 + Z_2 + Z_0 + 3Z_n} = 1$$

$$\frac{3 \times 1}{j\left(0.3 + 0.35 + 0.05\right) + 3R_n} = 1$$

$$R_n = \frac{1}{3}\sqrt{3^2 - \left(0.3 + 0.35 + 0.05\right)^2}$$

$$= \frac{1}{3}\sqrt{9 - 0.49} = 0.972 \text{ p.u.}$$

$$Z_{base} = \frac{(KV)_{base}^2}{MVA_{base}} = \frac{11^2}{25} = 4.84\ \Omega$$

Actual $R_n = R_{n\,p.u.} \times Z_{base}$

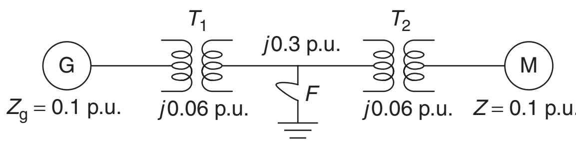
$$= 0.972 \times 4.84 = 4.7\ \Omega$$

Exercises

Practice Problems I

Directions for questions 1 to 20: Select the correct alternative from the given choices.

1. A power system is represented by a single line diagram with all the reactance marked in per unit (p.u) on the same base



The system is on no load when three-phase fault occurs at F on the high voltage side of the transformer T_2. The fault current will be

(A) $-j0.726$ p.u. (B) $-j0.84$ p.u.
(C) $-j7.42$ p.u. (D) $-j8.4$ p.u.

2. The 3-ϕ power system operating at 122 kV with 0.6 p.f. Recovery voltage = 0.8 times full line value, Breaking current is symmetrical, frequency of oscillation of restriking voltage is 20 kHz. Assuming the neutral is grounded and the fault does not involve with the ground, the average rate of rise of restriking voltage is

(A) 20.82 kV/ms (B) 30.76 kV/ms
(C) 56.5 V/ms (D) 30.76 V/s

3. Two 11 kV, 30 MVA, 3 f star-connected generators operate in parallel. The positive-, negative- and zero-sequence reactances of each are $j0.2$ p.u., $j0.35$ p.u., $j0.15$ p.u., respectively. Assume that the generator is grounded solidly. Voltage of the healthy phase for a double line to ground fault at the terminals is

(for solid fault, $z_f = 0$)

(A) 0.625 V (B) 0.766 V
(C) 0.52 V (D) 0.25 V

4. A 15 MVA, 13.2 kV alternator has $X_1 = X_2 = 30\%$ and $X_0 = 8\%$ Reactance that must be put in the generator neutral so that the fault current for a line to ground fault of zero fault impedance will not exceed the rated current is

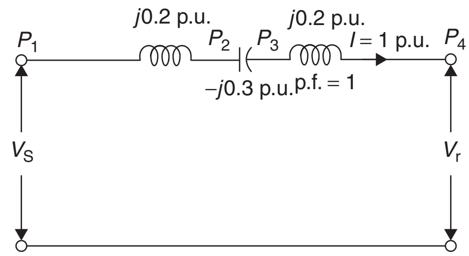
(A) 2.6 W (B) 6.8 W
(C) 9 W (D) 4.8 W

5. In a three-phase, 4-wire system, the line currents under abnormal conditions are given by

$(10 + j6)$, $(12 - j8)$ and $(-14 + j12)$. The positive sequence currents in lines will be

(A) $-2 + 4j$ (B) $-1.26 + 2.7j$
(C) $3.4 - 2.4j$ (D) $1.26 - 2.7j$

6. For the transmission line model with a series capacitor at its midpoint, the maximum voltage on the line is at location



(A) P_1 (B) P_2 (C) P_3 (D) P_4

7. A power system network with the capacity of 150 MVA has a source impedance of 15% at a point. The fault at the point is

(A) 10 MA (B) 150 MVA
(C) 3500 MVA (D) 1000 MVA

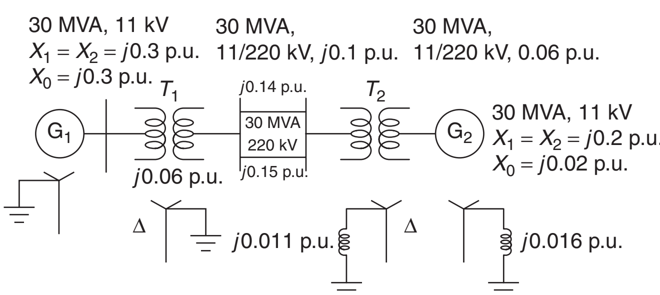
8. The positive-, negative- and zero-sequence impedances of a solidly grounded system under steady-state condition follow the relations

(A) $Z_1 > Z_2 > Z_0$
(B) $Z_1 < Z_2 < Z_0$
(C) $Z_0 < Z_1 < Z_2$
(D) None of these

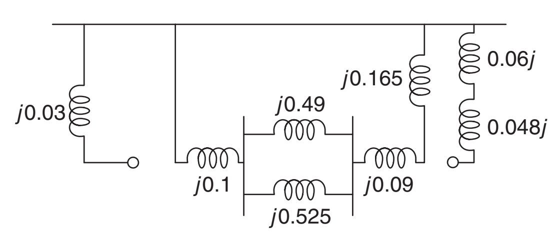
9. A 3-ϕ. 10 MVA, 2.8 kV alternator with a reactance of 6% is connected to a feeder of series impedance of $0.2 + j0.6$ ohm/phase per km. The transformer rated at 5 MVA, 1.8/22 kV has a reactance of 5%. The fault current supplied by the generator operating under no load with a voltage of 3.8 kV, when a 3-ϕ symmetrical fault occurs at a point 10 km along the feeder is

(A) $(1406 \angle 76.288)$ A
(B) $(436 \angle 76.288)$ A
(C) $(15 + j80)$ A
(D) $(400 - j83.4)$ A

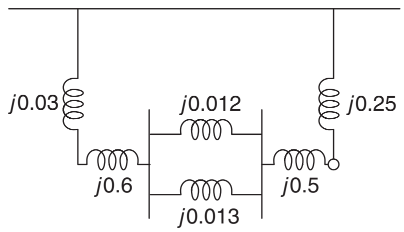
10. The zero-sequence network of the single-line diagram is shown below.



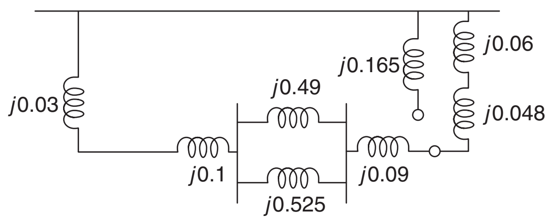
(A)



(B)



(C)



(D) None of these

11. An earth fault occurs on a busbar to which 3, 20 MVA, 3.3 kV, 3-ϕ alternators are connected in parallel. When only one alternator is solidly grounded and others are isolated, the fault current is [Given $X_d'' = 12\%$, $X_2 = 10\%$ and $X_0 = 13.5\%$]

(A) 8.895×10^4 A (B) 6.85×10^4 A
(C) 0.00789 A (D) 5.65 mA

12. A single-phase load of 100 kVA is connected across line bc of a three-phase supply of 3.3 kV. The symmetrical components of line currents are

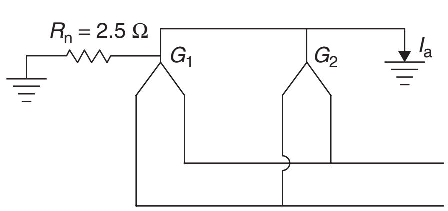
(A) 17.5, –17.5 and 0 (B) –17.5, 17.5 and 0
(C) 12.5, –12.5 and 0 (D) –12.5, 12.5 and 0

13. A generator is unloaded and operated at rated voltage when a fault occurs. Neglecting resistance identify the fault. The values of currents and voltages are given as follows

$I_{a0} = j2.37$ p.u.
$I_{a1} = -j8.45$ p.u.
$I_{a2} = j6.08$ p.u.
$V_{a0} = V_{a1} = V_{a2} = j0.237$ p.u.

(A) L–G fault (B) L–L fault
(C) L–L–G fault (D) Open conductor fault

Common data for Questions 14–16:
Two 12.8 kV, 25 MVA, three-phase, star-connected generators operate in parallel as shown in the following figure.



The positive, negative and zero sequence reactances are, respectively, $j0.20$, $j0.16$, $j0.12$ p.u. The star point of one of the generator is isolated and that of the other is earthed through a 2.5 Ω resistor. A single line to ground fault occurs at the terminals of one of the generators

14. The fault current will be

(A) 2.55 ∠–15° p.u. (B) 1.0675 ∠–15° p.u.
(C) 2.93 ∠–30° p.u. (D) 3.0675 ∠–30° p.u.

15. The current in the grounding resistor is

(A) 3.0675 ∠–30° p.u (B) 2.55 ∠–15° p.u
(C) 1.0675 ∠–15° p.u (D) 2.93 ∠–30° p.u

16. The voltage across the grounding resistor is

(A) 3067.5 ∠– 15° p.u. (B) 2.9223 ∠– 15° p.u.
(C) 3.0675 ∠– 15° p.u. (D) 0.9551 ∠– 15° p.u.

17. A three-phase, 20 MVA, 13.2 kV 50 Hz generator with solidly earthed neutral has sub transient reactance X_d'' of 25%; direct-axis reactance X_d' of 20% and synchronous reactance X_d of 50%. Negative – sequence reactance $X_2 = 10\%$ and zero-sequence reactance $X_0 = 6\%$. The generator is operated on open circuit when fault occurs. Take $E_a = 1.0$. If the fault is a three-phase short without an impedance, the value of initial symmetrical sub transient, transient and sustained RMS values of the line current under faulty condition will be

(A) $-j4.0, -j5.0, -j2$ p.u.
(B) $-j1.667, -j4.0, -j5.0$ p.u.
(C) $-j15, -j14, -j11.667$ p.u.
(D) $-j11.667, -j14, -j15$ p.u.

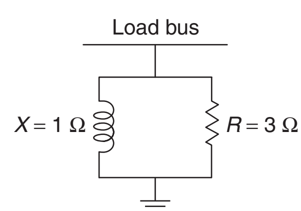
18. Three 10 MVA, 13.8 kV, three-phase star-connected alternators are operating in parallel. Each has $X_d'' = 10\%$, $X_2 = 8\%$ and $X_0 = 3\%$. If an earth fault occurs on one bus bar, the value of fault current when all the three alternators are solidly grounded is

(A) $j25{,}000$ A (B) $-j\,4062.27$ A
(C) $j5{,}000$ A (D) $j15{,}000$ A

19. A 20 MVA, 6.6 kV alternator with solidly grounded neutral has a sub transient reactance of 0.25 p.u. The negative and zero sequence reactances are 0.30 p.u. and 0.15 p.u., respectively. A single phase to ground fault occurs at the terminals of this unloaded generator. The fault impedance is 0.01 p.u. Then the value of three sequent components of voltages as percentage of rated values will be

(A) 65.75%, –41.1% and –20.55%
(B) –65.75%, 41.1% and 20.55%
(C) 41.75%, –36.2% and –15.4%
(D) –41.75%, 36.2% and 15.4%

20. A load of 25 kVA rating is connected to the bus as shown. If the bus voltage is 400 V, the p.u. value of resistance is



(A) 0.469 (B) 0.0469
(C) 0.187 (D) 0.0187

Practice Problems 2

Directions for questions 1 to 17: Select the correct alternative from the given choices.

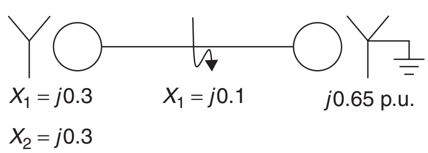
1. Which of the following statements are true?
1. A balanced three-phase system consists of positive sequence components only.
2. The magnitude of zero-sequence component is one third of current in neutral wire.
3. In a delta-connected load, zero-sequence component is equal to neutral current.
4. The current of a single-phase load drawn from a three-phase system comprises equal positive-, negative- and zero-sequence components.

(A) 1, 2 only (B) 2, 3 only
(C) 2, 3, 4 (D) 1, 2, 3, and 4

2. A generator of negligible resistance having 1.0 per unit voltage behind transient reactance is subjected to a line to line fault resulting in a fault current of 2.68 p.u. The per unit value of zero-sequence reactance when it is subjected to a line to ground fault resulting in 2.68 p.u. fault current is

(A) 0.473 p.u. (B) 0.265 p.u.
(C) 0.98 p.u. (D) 1 p.u.

3. A single line to ground fault occurs in a star-connected three-phase generator. It supplies power to a star-connected inductive load through a transmission line. The star point of the load is grounded and the generator neutral is ungrounded. The single-line diagram is shown below. Fault takes place half way down the line.



Prior to fault, the network is balanced and voltage at fault location is $1\angle 0°$ p.u. The current through the fault path is

(A) $-j2.36$ p.u. (B) $j1.45$ p.u.
(C) $j3.26$ p.u. (D) $j3.4$ p.u.

4. A 100 kVA, 400 V synchronous generator (0.2 p.u. sub-transient reactance) is supplying a 80 kW load at 0.8 lagging power factor. The initial symmetrical RMS current for a three-phase fault at generator terminals is

(A) 0.08 p.u. (B) 0.06 p.u.
(C) 0.04 p.u. (D) 0.02 p.u.

5. Ratio of L-G fault current to three-phase fault

(A) $\dfrac{3X_1}{X_1 + X_2 + X_0}$ (B) $\dfrac{1.732X_1}{X_1 + X_2}$

(C) $\dfrac{X_1}{3\left(X_1 + X_2 + \dfrac{X_0}{3}\right)}$ (D) Both (A) and (C)

6. The generator emf is 0.5 p.u. and the transient reactance is 0.15. The value of transient current is

(A) $2.5\angle -90°$ (B) $5\angle 30°$
(C) $3.33\angle -90°$ (D) $2.5\angle 30°$

7. $E_g = 0.5$ p.u. and $X_d = 0.2$. The value of short-circuit current is

(A) $2.5\angle -90°$ (B) $5\angle -90°$
(C) $2.5\angle 90°$ (D) $5\angle 90°$

8. Which is true for steady state, transient and sub-transient reactances for a synchronous machine?

(A) $X_d > X'_d > X''_d$ (B) $X''_d > X'_d > X_d$
(C) $X'_d > X''_d > X_d$ (D) $X_d > X''_d > X'_d$

9. X_1, X_2 and X_0 values of two generators operated parallely are given as 0.08, 0.24 and 0.10 per unit, respectively. If the generator is solidly grounded, the voltage of healthy phase for a double line to ground fault at terminals of generator is

(A) 0.603 p.u. (B) 0.969 p.u.
(C) 0.152 p.u. (D) 0.846 p.u.

10. The fault which causes a greater electro-magnetic interference between the power line and a nearby communication line

(A) Three-phase fault (B) L–L–G fault
(C) L–L fault (D) L–G fault

11. The zero-sequence impedances of an ideal star–delta-connected transformer (star-grounded)

(A) Looking from star side is zero and looking from delta side is infinite
(B) Looking from star side as well as delta side is infinite
(C) Looking from star side as well as delta side is zero
(D) Looking from star side is infinite and looking from delta side is zero.

12. For a line-to-line fault analysis using symmetrical components

(A) The positive-, negative- and zero-sequence networks at the fault point are connected in series
(B) The positive-, negative- and zero- sequence networks at the fault point are connected in parallel
(C) The positive- and negative-sequence networks at the fault point are connected in series
(D) The positive- and negative-sequence networks at the fault point are connected in parallel

13. The line currents in ampere in phases a, b and c, respectively, are $(300 + j200)$, $(50 - j300)$ and $(-200 + j500)$ referred to the same reference vector. The negative sequence components of currents will be

(A) $138.56\angle 200.14$ (B) $11.82\angle 100.02$
(C) $112.82\angle 200.14$ (D) $98.41\angle 100.02$

14. If a positive sequence current passes through a transformer and its phase shift is 60 degrees, the negative sequence current flowing through the transformer will have a phase shift of

(A) 60 deg (B) –60 deg
(C) 120 deg (D) –120 deg

15. The reason for not considering the load currents in short-circuit calculations are

(i) Short-circuit currents are much larger than load currents

(ii) Short-circuit currents are greatly out of phase with load currents

The correct alternative is

(A) Both (i) and (ii) are correct
(C) Both (i) and (ii) are wrong
(D) (i) is correct and (ii) is wrong
(E) (i) is wrong and (ii) is correct

16. For a single line to ground fault, the rise in potential on a healthy phase, if we are considering the voltage as V will be

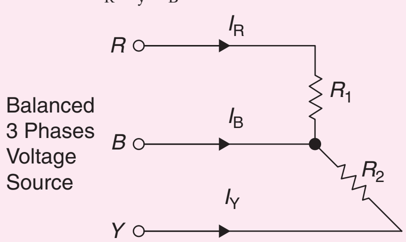
(A) $\frac{1}{\sqrt{2}}$ V kV
(B) $\sqrt{2}$ V kV
(C) $\sqrt{3}$ V kV
(D) $\frac{1}{\sqrt{3}}$ V kV

17. When a line to ground fault occurs, the current in the phase is 120 A. The zero-sequence current is

(A) 0 A (B) 40 A
(C) 20 A (D) 120 A

Previous Years' Questions

1. For the three-phase circuit shown in Figure, the ratio of the current $I_R : I_y : I_B$ is given by **[2005]**



(A) 1:1: $\sqrt{3}$ (B) 1:1:2
(C) 1:1:0 (D) 1:1: $\sqrt{\frac{3}{2}}$

2. The parameters of a transposed overhead transmission line are given as:
Self-reactance x_s = 0.4 Ω/km and mutual reactance x_m = 0.1 Ω/km
The positive sequence reactance x_1 and zero sequence reactance x_0, respectively, in Ω/km are **[2005]**

(A) 0.3, 0.2 (B) 0.5, 0.2
(C) 0.5, 0.6 (D) 0.3, 0.6

Common Data for Questions 3 and 4:
At a 220 kV substation of a power system, it is given that the three-phase fault level is 4000 MVA and single-line to ground fault level is 5000 MVA. Neglecting the resistance and the shunt susceptances of the system,

3. The positive-sequence driving point reactance at the bus is: **[2005]**

(A) 2.5 Ω (B) 4.033 Ω
(C) 5.5 Ω (D) 12.1 Ω

4. And the zero-sequence driving point reactance at the bus is: **[2005]**

(A) 2.2 Ω (B) 4.84 Ω
(C) 18.18 Ω (D) 22.72 Ω

5. Three identical star-connected resistors of 1.0 p.u. are connected to an unbalanced three-phase supply. The load neutral is isolated. The symmetrical components of the line voltages in p.u. are:
$V_{ab1} = X\angle\theta_1$, $V_{ab2} = Y\angle\theta_2$. If all the p.u. calculations are with the respective base values, the phase-to-neutral sequence voltages are **[2006]**

(A) $V_{an_1} = X\angle(\theta_1 + 30°)$, $V_{an_2} = Y\angle(\theta_2 - 30°)$
(B) $V_{an_1} = X\angle(\theta_1 - 30°)$, $V_{an_2} = Y\angle(\theta_2 + 30°)$
(C) $V_{an_1} = \frac{1}{\sqrt{3}} X\angle(\theta_1 - 30°)$,
$V_{an_2} = \frac{1}{\sqrt{3}} Y\angle(\theta_2 + 30°)$
(D) $V_{an_1} = \frac{1}{\sqrt{3}} X\angle(\theta_1 - 60°)$,
$V_{an_2} = \frac{1}{\sqrt{3}} Y\angle(\theta_2 - 60°)$

Common Data for Questions 6 and 7:
For a power system the admittance and impedance matrices for the fault studies are as follows.

$$Y_{bus} = \begin{bmatrix} -j8.75 & j1.25 & j2.50 \\ j1.25 & -j6.25 & j2.50 \\ j2.50 & j2.50 & -j5.00 \end{bmatrix}$$

$$Z_{bus} = \begin{bmatrix} j0.16 & j0.08 & j0.12 \\ j0.08 & j0.24 & j0.16 \\ j0.12 & j0.16 & j0.34 \end{bmatrix}$$

The pre-fault voltages are 1.0 p.u. at all the buses. The system was unloaded prior to the fault. A solid three-phase fault takes place at bus 2.

6. The post fault voltages at buses 1 and 3 in per unit, respectively, are **[2006]**

(A) 0.24, 0.63 (B) 0.31, 0.76
(C) 0.33, 0.67 (D) 0.67, 0.33

7. The per unit fault feeds from generators connected to buses 1 and 2, respectively, are **[2006]**
(A) 1.20, 2.51 (B) 1.55, 2.61
(C) 1.66, 2.50 (D) 5.00, 2.50

8. A three-phase balanced star-connected voltage source with frequency ω rad/s is connected to a star-connected balanced load which is purely inductive. The instantaneous line currents and phase to neutral voltages are denoted by (i_a, i_b, i_c) and $(\upsilon_{an}, \upsilon_{bn}, \upsilon_{cn})$, respectively, and their RMS values are denoted by V and I.

$$\text{If } R = [\upsilon_{an}, \upsilon_{bn}, \upsilon_{cn}] \begin{bmatrix} 0 & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\ -\frac{1}{\sqrt{3}} & 0 & \frac{1}{\sqrt{3}} \\ \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} & 0 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix},$$

then the magnitude of R is **[2007]**
(A) 3VI (B) VI (C) 0.7 VI (D) 0

9. Suppose we define a sequence transformation between '*a-b-c*' and '*p-n-o*' variables as follows:

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = k \begin{bmatrix} 1 & 1 & 1 \\ \alpha^2 & \alpha & 1 \\ \alpha & \alpha^2 & 1 \end{bmatrix} \begin{bmatrix} f_p \\ f_n \\ f_o \end{bmatrix}, \text{ where } \alpha = e^{j\frac{2x}{3}} \text{ and } k \text{ is}$$

a constant.

$$\text{Now, if it is given that: } \begin{bmatrix} V_P \\ V_n \\ V_0 \end{bmatrix} = \begin{bmatrix} 0.5 & 0 & 0 \\ 0 & 0.5 & 0 \\ 0 & 0 & 2.0 \end{bmatrix} \begin{bmatrix} i_p \\ i_n \\ i_0 \end{bmatrix}$$

$$\text{and } \begin{bmatrix} V_a \\ V_b \\ -V_c \end{bmatrix} = Z \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \text{ then,}$$ **[2007]**

(A) $Z = \begin{bmatrix} 1.0 & 0.5 & 0.75 \\ 0.75 & 1.0 & 0.5 \\ 0.5 & 0.75 & 1.0 \end{bmatrix}$

(B) $Z = \begin{bmatrix} 1.0 & 0.5 & 0.5 \\ 0.5 & 1.0 & 0.5 \\ 0.5 & 0.5 & 1.0 \end{bmatrix}$

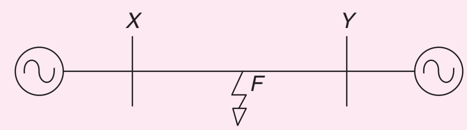
(C) $Z = 3k^2 \begin{bmatrix} 1.0 & 0.75 & 0.5 \\ 0.5 & 1.0 & 0.75 \\ 0.75 & 0.5 & 1.0 \end{bmatrix}$

(D) $Z = \frac{k^2}{3} \begin{bmatrix} 1.0 & -0.5 & -0.5 \\ -0.5 & 1.0 & -0.5 \\ -0.5 & -0.5 & 1.0 \end{bmatrix}$

10. A 230 V (phase), 50 Hz, three-phase, 4-wire system has a phase sequence ABC. A unity power-factor load of 4 kW is connected between phase A and neutral N. It is desired to achieve zero neutral current through the use of a pure inductor and a pure capacitor in the other two phases. The value of inductor and capacitor is **[2007]**
(A) 73.95 mH in phase C and 139.02 mF in phase B
(B) 72.95 mH in phase B and 139.02 mF in phase C
(C) 42.12 mH in phase C and 240.79 mF in phase B
(D) 42.12 mH in phase B and 240.79 mF in phase C

11. A two-machine power system is shown below. Transmission line XY has positive-sequence impedance of Z_1 Ω and zero-sequence impedance of Z_0 Ω.

An '*a*' phase to ground fault with zero fault impedance occurs at the centre of the transmission line. Bus voltage at X and line current from X to F for the phase '*a*' are given by V_a V and I_a A, respectively. Then, the impedance measured by the ground distance relay located at the terminal X of line XY will be given by **[2008]**



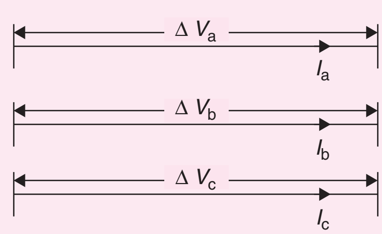
(A) $\frac{Z_1}{2}$ Ω (B) $\frac{Z_0}{2}$ Ω

(C) $\frac{(Z_0 + Z_1)}{2}$ Ω (D) $\frac{V_a}{1_a}$ Ω

12. A three-phase transmission line is shown in the figure voltage drop across the transmission line is given by the following equation

$$\begin{bmatrix} \Delta V_a \\ \Delta V_b \\ \Delta V_c \end{bmatrix} = \begin{bmatrix} Z_s & Z_m & Z_m \\ Z_m & Z_s & Z_m \\ Z_m & Z_m & Z_s \end{bmatrix} \begin{bmatrix} I_s \\ I_b \\ I_c \end{bmatrix}$$

Shunt capacitance of the line can be neglected. If the line has positive-sequence impedance of 15 Ω and zero-sequence impedance of 48 Ω, then the values of Z_s and Z_m will be **[2008]**



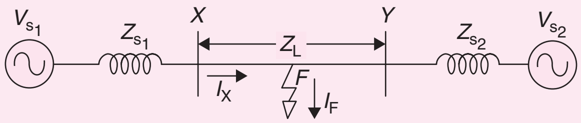
(A) $Z_s = 31.5$ Ω; $Z_m = 16.5$ Ω
(B) $Z_s = 26$ Ω; $Z_m = 11$ Ω
(C) $Z_s = 16.5$ Ω; $Z_m = 31.5$ Ω
(D) $Z_s = 11$ Ω; $Z_m = 26$ Ω

13. A lossless transmission line having surge impedance loading (SIL) of 2280 MW is provided with a uniformly distributed series capacitive compensation of 30%. Then, SIL of the compensated transmission line will be **[2008]**

(A) 1835 MW (B) 2280 MW
(C) 2725 MW (D) 3257 MW

Common Data for Questions 14 to 16:

Consider a power system shown below:



Given that:

$$V_{s1} = V_{s2} = 1.0 + j0.0 \text{ p.u.};$$

The positive-sequence impedances are $Z_{s1} = Z_{s2} = 0.001 + j0.01$ p.u. and $Z_L = 0.006 + j0.06$ p.u.

Three-phase base MVA = 100

Voltage base = 400 kV (Line to line)

Nominal system frequency = 50 Hz

The reference voltage for phase 'a' is defined as $v(t) = V_m \cos(\omega t)$.

A symmetrical three-phase fault occurs at centre of the line, i.e. point 'F' at time t_0. The positive sequence impedance from source S_1 to point 'F' equals $0.004 + j0.04$ p.u. The waveform corresponding to phase 'a' fault current from bus X reveals that decaying DC offset current is negative and in magnitude at its maximum initial value. Assume that the negative-sequence impedances are equal to positive-sequence impedances, and the zero-sequence impedances are three times positive-sequence impedances.

14. The instant (t_0) of the fault will be **[2008]**

(A) 4.682 ms (B) 9.667 ms
(C) 14.667 ms (D) 19.667 ms

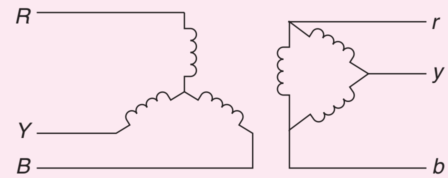
15. The RMS value of the AC component of fault current (I_x) will be **[2008]**

(A) 3.59 KA
(B) 5.07 KA
(C) 7.18 KA
(D) 10.15 KA

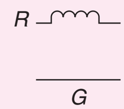
16. Instead of the three-phase fault, if a single line to ground fault occurs on phase 'a' at point 'F' with zero fault impedance, then the RMS value of the AC component of fault current (I_x) for phase 'a' will be **[2008]**

(A) 4.97 p.u.
(B) 7.0 p.u.
(C) 14.93 p.u.
(D) 29.85 p.u.

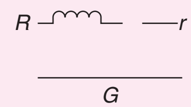
17. The zero-sequence circuit of the three-phase transformer shown in the figure is **[2010]**



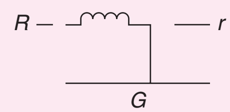
(A)



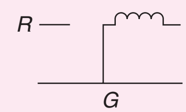
(B)



(C)

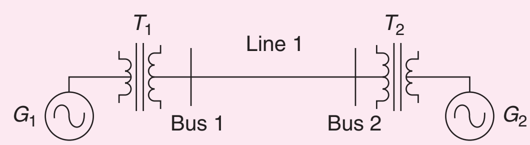


(D)



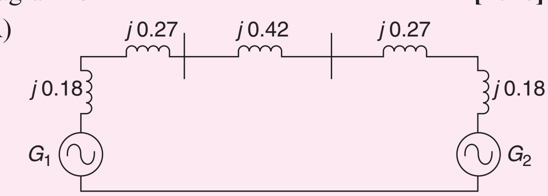
18. For the power system shown in the figure below, the specifications of the components are the following:

G_1: 25 kV, 100 MVA, $X = 9\%$
G_2: 25 kV, 100 MVA, $X = 9\%$
T_1: 25 kV/220 kV, 90 MVA, $X = 12\%$
T_2: 220 kV/ 25 kV, 90 MVA, $X = 12\%$
Line1: 220 kV, $X = 150\ \Omega$

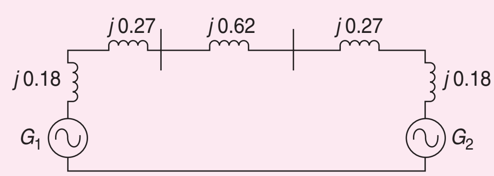


Choose 25 kV as the base voltage at the generator G_1, and 200 MVA as the MVA base. The impedance diagram is **[2010]**

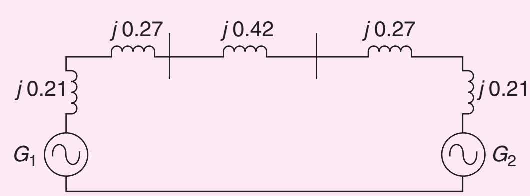
(A)



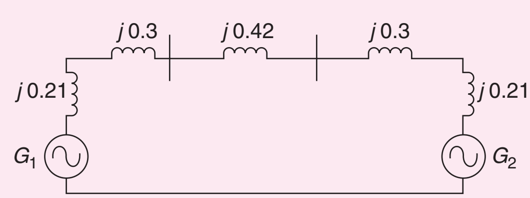
(B)



(C)

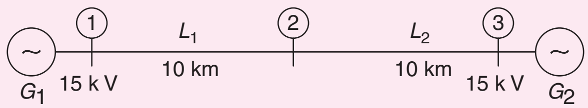


(D)



Common Data for Questions 19 and 20:

Two generator units G_1 and G_2 are connected by 15 kV line with a bus at the mid-point as shown below



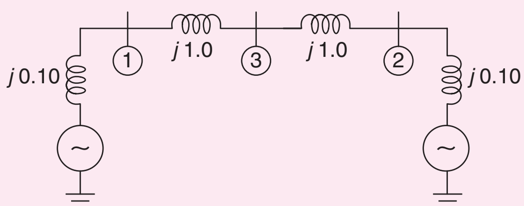
G_1 = 250 MVA, 15 kV, positive-sequence reactance $X = 25\%$ on its own base

G_2 = 100 MVA, 15 kV, positive-sequence reactance $X = 10\%$ on its own base

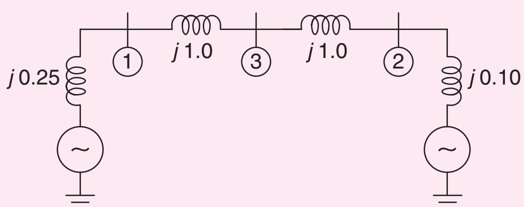
L_1 and L_2 = 10 km, positive-sequence reactance $X = 0.225\ \Omega$/km

19. For the above system the positive sequence diagram with the p.u. values on the 100 MVA, common base is **[2011]**

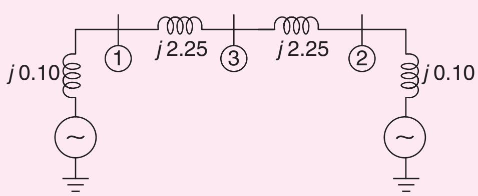
(A)



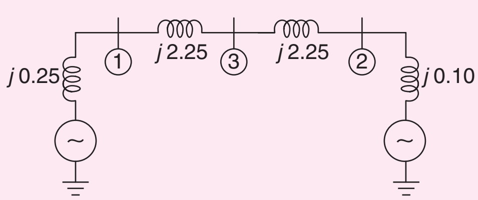
(B)



(C)



(D)



20. In the above system, the three-phase fault MVA at the bus 3 is **[2011]**

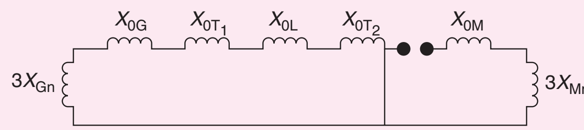
(A) 82.55 MVA
(B) 85.11 MVA
(C) 170.91 MVA
(D) 181.82 MVA

21. The sequence components of the fault current are as follows: $I_{\text{positive}} = j1.5$ p.u., $I_{\text{negative}} = -j0.5$ p.u., $I_{\text{zero}} = -j1$ p.u. The type of fault in the system is **[2012]**

(A) LG (B) LL
(C) LLG (D) LLLG

22. A 2-bus system corresponding zero-sequence network is shown in the figure.

(a)

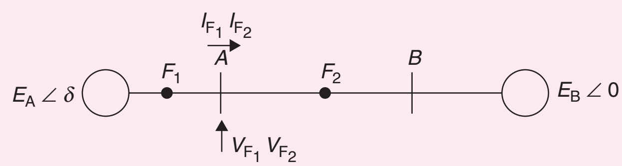


(b)

The transformers T_1 and T_2 are connected as **[2014]**

(A) ⅄ ⅄ and ⅄ Δ
(B) ⅄ ⅄ and ⅄ Δ
(C) ⅄ Δ and Δ ⅄
(D) Δ ⅄ and ⅄ ⅄

23. Three-phase to ground fault takes place at locations F_1 and F_2 in the system shown in the following figure.



If the fault takes place at location F_1, then the voltage and the current at bus A are V_{F_1} and I_{F_1}, respectively. If the fault takes place at location F_2, then the voltage and the current at bus A are V_{F_2} and I_{F_2}, respectively. The correct statement about voltages and currents during faults at F_1 and F_2 is **[2014]**

(A) V_{F_1} leads I_{F_1} and V_{F_2} leads I_{F_2}
(B) V_{F_1} leads I_{F_1} and V_{F_2} lags I_{F_2}
(C) V_{F_1} lags I_{F_1} and V_{F_2} leads I_{F_2}
(D) V_{F_1} lags I_{F_1} and V_{F_2} lags I_{F_2}

24. In an unbalanced three-phase system, phase current $I_a = 1\angle(-90°)$ p.u., negative sequence current $I_{b2} = 4\angle(-150°)$ p.u., zero sequence current $I_{c0} = 3\angle 90°$ p.u. The magnitude of phase current I_b in p.u. is **[2014]**

(A) 1.00
(B) 7.81
(C) 11.53
(D) 13.00

25. A three-phase star-connected load is drawing power at a voltage of 0.9 p.u. and 0.8 power factor lagging. The three-phase base power and base current are

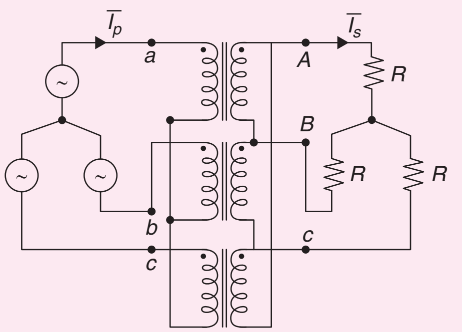
100 MVA and 437.38 A, respectively. The line-to-line load voltage in kV is ______.

[2014]

26. At three-phase, 100 MVA, 25 kV generator has solidly grounded neutral. The positive, negative, and the zero sequence reactances of the generator are 0.2 p.u., 0.2 p.u., and 0.05 p.u., respectively, at the machine base quantities. If a bolted single phase to ground fault occurs at the terminal of the unloaded generator, the fault current in amperes immediately after the fault is ____________.

[2014]

27. A balanced (positive sequence) three-phase AC voltage source is connected to a balanced, star connected load through a star-delta transformer as shown in the figure. The line-to-



line voltage rating is 230 V on the star side, and 115 V on the delta side. If the magnetizing current is neglected and $\overline{I_s} = 100\angle 0°$ A, then what is the value of $\overline{I_p}$ in Ampere? **[2015]**

(A) $50\angle 30°$ (B) $50\angle -30°$
(C) $50\sqrt{3}\angle 30°$ (D) $200\angle 30°$

28. The magnitude of three-phase fault currents at buses A and B of a power system are 10 pu and 8 pu, respectively. Neglect all resistances in the system and consider the pre-fault system to be unloaded. The pre-fault voltage at all buses in the system is 1.0 pu. The voltage magnitude at bus B during a three-phase fault at bus A is 0.8 pu. The voltage magnitude at bus A during a three-phase fault at bus B, in pu, is ____.

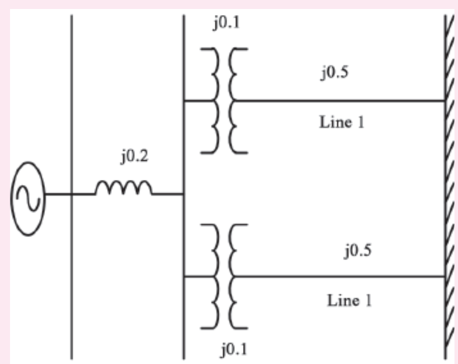
[2016]

29. A 30 MVA, 3-phase, 50 Hz, 13.8 kV, star-connected synchronous generator has positive, negative and zero sequence reactances, 15%, 15% and 5% respectively. A reactance (X_n) is connected between the neutral of the generator and ground. A double line to ground fault takes place involving phases 'b' and 'c', with a fault impedance of j0.1 p.u. The value of X_n (in p.u.) that will limit the positive sequence generator current to 4270 A is **[2016]**

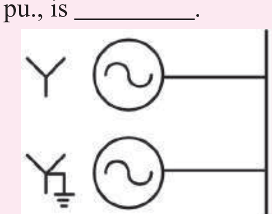
30. A 50MVA, 10KV, 50HZ, star-connected, unloaded three- phase alternator has a synchronous reactance of 1p.u and a sub-transient reactance of 0.2p.u. If a 3-phase short circuit occurs close to the generator terminals, the ratio of initial and final values of the sinusoidal component of the short circuit current is ________. **[2016]**

31. The single line diagram of a balanced power system is shown in the figure. The voltage magnitude at the generator internal bus is constant and 1.0p.u. the p.u reactances of different components in the system are also shown in the figure. The infinite bus voltage magnitude is 1.0p.u. A three phase fault occurs at the middle of line 2.

The ratio of the maximum real power that can be transferred during the pre - fault condition to the maximum real power that can be transferred under the faulted condition is ______



32. Two identical unloaded generators are connected in parallel as shown in the figure. Both the generators are having positive, negative and zero sequence impedances of *j*0.4pu., *j*0.3pu., and *j*0.15pu., respectively. If the pre- fault voltage is 1pu, for a line - to - ground (L – G) fault at the terminals of the generators, the fault current, in pu., is _________. **[2016]**



Answer Keys

Exercises

Practice Problems 1

1. D	**2.** B	**3.** B	**4.** C	**5.** B	**6.** C	**7.** D	**8.** A	**9.** A	**10.** A
11. A	**12.** A	**13.** C	**14.** A	**15.** B	**16.** D	**17.** A	**18.** B	**19.** A	**20.** A

Practice Problems 2

1. D	**2.** A	**3.** A	**4.** C	**5.** A	**6.** C	**7.** A	**8.** A	**9.** A	**10.** D
11. A	**12.** D	**13.** C	**14.** B	**15.** A	**16.** C	**17.** B			

Previous Years' Questions

1. A	**2.** D	**3.** D	**4.** B	**5.** C	**6.** D	**7.** C	**8.** A	**9.** B	**10.** B
11. D	**12.** B	**13.** C	**14.** A	**15.** A	**16.** C	**17.** C	**18.** B	**19.** A	**20.** D
21. C	**22.** B	**23.** C	**24.** C	**25.** 118.8	**26.** 15396	**27.** A	**28.** 0.832	**29.** 1.08	**30.** 5
31. 2.3	**32.** 6								