Electrical Engineering

Power Systems

Comprehensive Theory

with Solved Examples and Practice Questions

MADE EASY
Publications

MADE EASY Publications

Corporate Office: 44-A/4, Kalu Sarai (Near Hauz Khas Metro Station), New Delhi-110016
E-mail: infomep@madeeasy.in
Contact: 011-45124660, 8860378007
Visit us at: www.madeeasypublications.org

Power Systems

First Edition : 2015
Second Edition : 2016
Third Edition : 2017
Fourth Edition : 2018
Fifth Edition : 2019

Sixth Edition : 2020

Contents

Power Systems

Chapter 1

Chapter 2

Chapter 3

Chapter 4

Chapter 5

Chapter 6

Chapter 7

Chapter 8

Chapter 9

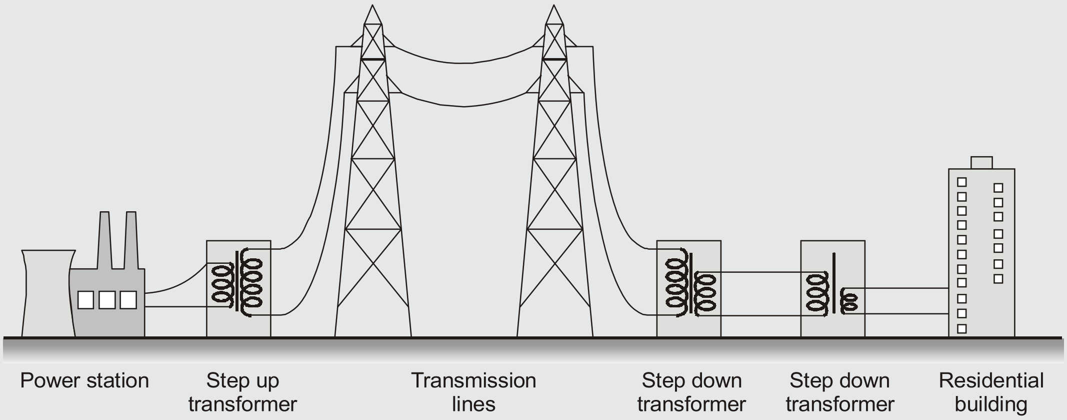
Chapter 10

Power Systems

Introduction to Power Systems

An ***"Electric power system"*** is a network of electrical components used to supply, transmit and use electric power. An example of an electric power system is the network that supplies a region's home and industry with power for sizable regions, this power system is called ***"the grid"*** and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating stations to the load centers and the distribution system that feeds the power to nearby homes and industries. Small power systems are also found in industry, hospitals, homes and commercial buildings. The majority of these systems relay upon ***"three-phase AC power"*** the standard for large scale power transmission and distribution across the modern world. Specialized power systems that do not rely upon the three-phase AC power are found in aircraft, electric rail systems, automobiles etc.

This course material embodies the principles and objectives of elements of power system. The aim of the course material on power system is to instill confidence and understanding of those concepts of power system that are likely to be encountered in the study and practice of electric power engineering. The presentation is tutorial with emphasis on a thorough understanding of fundamentals and underlying principles. This course material has been prepared in such a way to help the engineering students in understanding the basic concept of power system which will help them to excel in the competitive exams like GATE, IES, PSUs and other various competitive examinations. In each chapter, after every topic, wide number of solved examples have been discussed for the better understanding of the topics.



CHAPTER

5

Fault Analysis

5.1 Introduction

Whenever there is insulation failure of equipment in a power system or flashover of the lines initiated by a lightning stroke or accidental faulty operation of the system, a heavy symmetrical short circuit current flows in the system. The system must be protected against flow of that heavy short circuit currents by disconnecting the faulty part of the system by means of circuit breakers operated by protective relays. The main objective of fault analysis is to determine the fault level or the fault MVA at the fault location. This fault MVA is the breaking capacity of the circuit breaker that has to be kept at the point of fault location.

There are two types of fault occurring in the power system, namely ***"symmetrical fault"*** and ***"unsymmetrical fault"***. The majority of fault occurring in power system are faults involving one line to ground occasionally two lines to ground which are termed as ***"unsymmetrical faults"***. The faults involving all the three phase to ground or all the three phase short-circuited belongs to ***"symmetrical fault".*** The symmetrical faults generally leads to most severe fault current which need to be interrupted. Though the operating conditions at the time of fault are important, the loads can be neglected during fault, as voltage dip very low so that currents drawn by loads can be neglected in comparison to fault current. The most common and dangerous fault, that occur in a power system, is the ***short-circuit*** or ***shunt faults*** which involves power conductor or conductors-to-ground or short-circuit between conductors and causes a heavy current, called the ***"short-circuit current"***. Short circuit calculation are very important since they provide data, which is necessarily required for designing the protective scheme for the power system."

Type of Faults in a Power System

There are basically two types of faults occurring in a power system namely:

1. **Symmetrical faults:**
   These constitutes the fault involving:
   (*i*) All the three phase to earth (3-phase fault, **3% chances of occurrence**).
   (*ii*) All the three short-circuited.
2. **Unsymmetrical faults:**
   This types of fault constitutes the fault involving:
   (*i*) Single phase to ground **(85% chances)** – SLG (Single Line to Ground fault)
   (*ii*) Phase to phase **(5% chances)** – LL (Line to Line fault)
   (*iii*) Two phases to ground **(7% chances)** – LLG (Line-Line to Ground fault)

NOTE

- Although the unsymmetrical faults are more prevalent, the symmetrical fault usually give the more severe duty on the circuit breaker.
- The calculation of symmetrical short-circuit current or symmetrical short-circuit KVA at a certain point in power system is, therefore, very important for the purpose of determination of circuit breaker ratings.
- The different kinds of faults in order of decreasing severity are:

  Three phase fault **(3-ϕ fault)** > Double line to ground **(LLG)** fault > Line to line **(LL)** fault > Single line to ground **(LG)** fault.

5.2 Per Unit System

- In power system, it is usual to express voltage, current, volt-amperes and impedance of an any electrical circuit in per unit or percentage.
- The per unit (pu) value of any quantity is defined as ***"the ratio of the quantity (in some unit) to it's base value (in same unit)".***

i.e. $$\text{pu value of a quantity} = \left[\frac{\text{the actual value in any unit}}{\text{the base or reference value in the same unit}}\right]$$

Selection of Base Values for pu System

1. Single-Phase System:

Let,

Base Mega volt-amperes = $(MVA)_b$

or, Base kilovolt-ampere = $(kVA)_b$

Base kilovolts = $(kV)_b$

Now, Base current, $$I_b = \frac{(MVA)_b}{(kV)_b}\times 1000 = \frac{(KVA)_b}{(kV)_b}\text{ Amperes}$$

∴ Base impedance, $$Z_b = \frac{(kV)_b^2}{(MVA)_b} = \frac{(kV)_b^2}{(KVA)_b}\times 1000\text{ ohms}$$

Hence, per unit impedance;

$$Z(\text{pu}) = \frac{(MVA)_b}{(kV)_b^2}\times Z\text{ (ohms)} \quad \text{or} \quad Z_{1-\phi}(\text{pu}) = \frac{(kVA)_b\times Z(\text{ohms})}{(kV)_b^2\times 1000} \qquad \dots(1)$$

2. Three-Phase System:

Let, the base Mega volt-amperes = $(MVA)_b$

and line-to-line base kilovolts = $(kV)_b$

For star connected circuit, we have,

Base current, $$I_b = \frac{(MVA)_b\times 1000}{\sqrt{3}\times (kV)_b} A$$

Base impedance, $$Z_b = \frac{(kV)_b\times 100}{\sqrt{3}\times I_b}\text{ ohms} = \frac{(kV)_b^2}{(MVA)_b} = \frac{(KV)_b^2\times 1000}{(kVA)_b}\text{ ohms}$$

∴ pu impedance is, $$Z_{3-\phi}(\text{pu}) = \frac{(MVA)_b\times 1000}{(kV)_b^2} = \frac{(kVA)_b\times Z(\text{ohms})}{(kV)_b^2\times 1000} \qquad \dots(2)$$

NOTE

When $(MVA)_b$ is changed to $(MVA)_{b,\text{ new}}$ from $(MVA)_{b,\text{ old}}$ and $(kVA)_b$ is changed to $(kV)_{b,\text{ new}}$ from $(kV)_{b,\text{ old}}$ then,

$$Z(\text{pu})_{\text{new}} = Z(pu)_{\text{old}} \times \frac{(MVA)_{b,\text{new}}}{(MVA)_{b,\text{old}}} \times \frac{(kV)^2_{b,\text{old}}}{(kV)^2_{b,\text{new}}} \quad ...(3)$$

Per Unit Representation of Transformer in a Power System Network

Figure 5.1 represents a single-phase transformer in terms of primary and secondary leakage impedances Z_p and Z_s having a transformation ratio of 1 : a. Let the magnetizing reactance be negligible and hence neglected.

Let, $$\frac{(V_1)_b}{(V_2)_b} = 1 : a$$

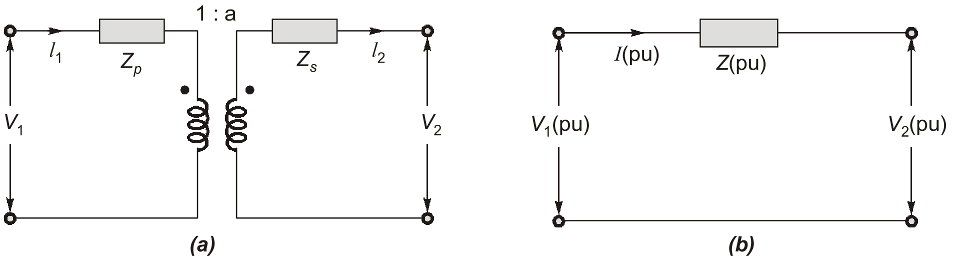


Figure-5.1 : *(a) Representation of single-phase transformer (magnetizing impedance neglected*

(b) Per unit equivalent circuit of single-phase transformer

Let $(V_1)_b$ and $(V_2)_b$ be the base voltage on the two sides of the transformer and a common $(VA)_b$ then,

$$\frac{(V_1)_b}{(V_2)_b} = a \qquad [\text{Since } (VA)_b \text{ is common}]$$

$$\therefore \quad (Z_1)_b = \frac{(V_1)_b}{(I_1)_b} \quad \text{and} \quad (Z_2)_b = \frac{(V_2)_b}{(I_2)_b}$$

From Figure 5.1 (a), we have

$$V_2 = (V_1 - I_1 Z_p)a - I_2 Z_s$$

In pu form, the above equation can be written as:

$$V_2(pu)(V_2)_b = [V_1(pu)(V_1)_b - I_1(pu)(I_1)_b Z_p(pu)(Z_1)_b]\, a - I_2(pu)(I_2)_b Z_s(pu)(Z_2)_b$$

Dividing above equation by $(V_2)_b$ on both sides and using the base relations, we have

$$V_2(pu) = V_1(pu) - I_1(pu)\, Z_p(pu) - I_2(pu)\, Z_s(pu)$$

Now, $$\frac{I_1}{I_2} = \frac{(I_1)_b}{(I_2)_b} = a \quad \text{or} \quad \frac{I_1}{(I_1)_b} = \frac{I_2}{(I_2)_b}$$

or, $$I_1(pu) = I_2(pu) = I(pu)$$

Now, on primary side of the transformer,

$$Z_1 = Z_p + \frac{Z_s}{a^2}$$

$$\therefore \quad Z_1(pu) = \frac{Z_1}{(Z_1)_b} = \frac{Z_p}{(Z_1)_b} + \frac{Z_s}{(Z_1)_b} \times \frac{1}{a^2}$$

But, $$a^2(Z_1)_b = (Z_2)_b$$

$$\therefore \quad Z_1(pu) = Z_p(pu) + Z_s(pu) = Z(pu) \quad ...(1)$$

On secondary side of the transformer,

$$Z_2 = Z_s + a^2 Z_p$$

$$\therefore \quad Z_2(pu) = \frac{Z_2}{(Z_2)_b} = \frac{Z_s}{(Z_2)_b} + a^2 \frac{Z_p}{(Z_2)_b}$$

$$\text{or,} \quad Z_2(pu) = Z_s(pu) + Z_p(pu) = Z(pu) \qquad \text{...(2)}$$

Conclusion

From equation (1) and (2), we conclude that the per unit impedance of the transformer is the same whether computed from primary or secondary side so long as the voltage bases on the two sides have a ratio equal to the transformation ratio.

NOTE

- In a circuit consisting of a transformer, two sets of base voltages are selected, one for LV and the other for HV side having ratio equal to transformation ratio.
- A common base power is selected for both HV and LV sides and also for the entire network.

Advantages of Per Unit Method in Power System

Following are the various advantages of per unit method in power system:

- It makes the power system calculations simpler and more convenient.
- The *pu* impedance of the transformer are equal whether referred to primary or secondary which is not so if the absolute values of these impedance are considered.
- In *pu* system, there is less chance of committing mistake in line and phase voltages, single phase or three phase quantities.
- There is correctness of analysis more in a *pu* system by expressing the parameters of transformers as well as rotating machines in per unit since their numerical values lies in almost same range when *pu* system is adopted.

5.3 Single Line Diagram of a Power System Network

A 3-phase network consisting of transmission lines, generators, transformers can be solved as a single phase circuit, composed of one of the three lines and a neutral return. In a single line diagram the neutral is omitted (as the system works under balance condition) and the components are represented by standard symbols. Figure 5.2 show a simple power system by a single line diagram.

In a single line diagram the neutral becomes a ***"zero-power bus"*** if the 3-ϕ system is balanced.

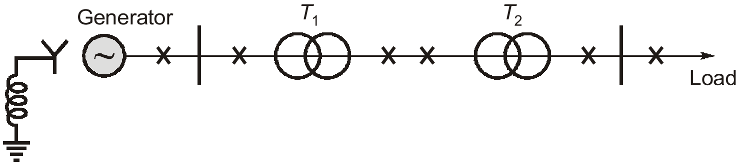


Figure-5.2 : *A single diagram representation of a power system*

5.4 Method of Short-circuit Calculations for Symmetrical Faults

The various steps involved in symmetrical fault analysis are as follows:

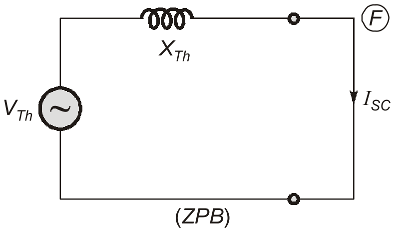
Step-I: Draw a single line diagram of the complete network indicating on each component, its voltage, rating and reactances.

Step-II: Choose appropriate base value and convert the given single line diagram into *pu* reactance diagram.

Step-III: Obtain Thevenin's equivalent circuit across the faulted bus and zero power bus (reference bus) as shown in figure.

Step-IV: Calculate the short circuit current,

$$I_{SC} = \frac{V_{Th}}{X_{Th}}$$



Calculation of Short-circuit KVA

Short circuit current,

$$I_{SC} = \frac{V}{X}$$

Now, percentage reactance,

$$\% X = \frac{IX}{V} \times 100 \quad \text{or} \quad X = \frac{(\%X)V}{100I}$$

Putting the value of X in the equation of I_{SC}, we get:

$$I_{SC} = \frac{V}{X} = \frac{V}{\left[(\%x)\frac{V}{100I}\right]} = \frac{100I}{\%X}$$

or, short circuit KVA $= \dfrac{VI_{SC}}{1000} = \dfrac{V \times 100I}{1000 \times (\%X)}$

or, short circuit KVA $= VI \times \dfrac{100}{\%X}$

i.e. short circuit KVA $= (\text{Rated KVA}) \times \left(\dfrac{100}{\%X}\right)$

(where, X = Thevenin equivalent reactance/impedance (Z_{Th}) across the fault and the ground terminal.)

We know that, $I_{SC} = \dfrac{V}{X}$ and $X_{\text{base}} = \dfrac{V}{I}$

$$\therefore \quad X(pu) = \frac{X}{X_{\text{base}}} = \frac{X}{\left(V/I\right)} = \frac{I}{\left(V/X\right)} = \frac{I}{I_{SC}}$$

So, $X(pu) = \dfrac{I\,(\text{in Ampere})}{I_{SC}\,(\text{in Ampere})} = \dfrac{I\,(\text{in pu})}{I_{SC}\,(\text{in pu})}$

Hence, $X(pu) = \dfrac{1}{I_{SC}\,(\text{in pu})}$ ....**(Important result)** [Since I (in pu) = 1 = rated value]

and $I_{SC} = \dfrac{1}{X(pu)}$ ....**(Important result)**

Similarly, $Z(pu) = \dfrac{1}{I_{SC}(pu)}$ and $I_{SC} = \dfrac{1}{Z(pu)}$ ....**(Important relations)**

Example - 5.1 The per unit impedance of a circuit element is 0.15. If the base kV and base MVA are halved, then the new value of the per unit impedance of the circuit element will be:

(a) 0.30
(b) 0.075
(c) 0.600
(d) 0.15

Solution: (a)

We know that,

$$Z_{pu,\,new} = Z_{pu,old} \times \left(\frac{MVA_{b,new}}{MVA_{b,old}}\right) \times \left(\frac{KV_{b,old}}{KV_{b,new}}\right)^2$$

Given,

$$Z_{pu,old} = 0.15\ pu,$$

$$KV_{b,new} = \frac{1}{2} KV_{b,old}$$

and

$$\text{MVA}_{b,new} = \frac{1}{2}(MVA_{b,old})$$

So,

$$Z_{pu,new} = 0.15 \times \left(\frac{1}{2}\right) \times (2)^2 = 0.30\ pu$$

Example - 5.2 A power system network with a capacity of 100 MVA has a source impedance of 20% at a point. The fault level at that point is

(a) 1000 MVA
(b) 15 MVA
(c) 500 MVA
(d) 1500 MVA

Solution: (c)

$$\text{Fault level or fault MVA at the point of fault} = \text{Rated MVA} \times \frac{100}{\%X} = 100 \times \frac{100}{20} = 500\text{ MVA}$$

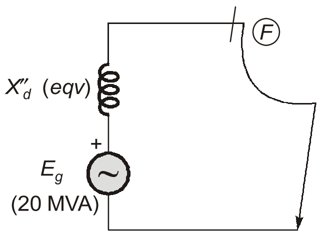
Example - 5.3 Five identical alternators each rated for 20 MVA, 11 KV having a subtransient reactance of 25% are working in parallel. The short circuit level at the bus-bars is

(a) 250 MVA
(b) 80 MVA
(c) 350 MVA
(d) 400 MVA

Solution: (d)

Since five alternative are connected in parallel therefore, the equivalent thevenin reactance (subtransient) will be

$$X_d''(\text{eqv}) = \frac{X_d''}{5} = \frac{25\%}{5} = 5\%$$



Hence, the short circuit MVA at the faulted bus is given by

$$\text{S.S. MVA} = \text{RatedMVA} \times \frac{100}{\% X_d''(eqv)}$$

$$= 20 \times \frac{100}{5} = 400\text{ MVA}$$

5. $$[I]_{abc} = [A]\,[I]_{120}$$

Also, $$[V]_{abc} = [A]\,[V]_{120}$$

where, $$[A] = \begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha^2 & \alpha \\ 1 & \alpha & \alpha^2 \end{bmatrix} = \text{symmetrical component transformation matrix}$$

Also, $$[I]_{012} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

Here, $$[A]^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & \alpha & \alpha^2 \\ 1 & \alpha^2 & \alpha \end{bmatrix}$$

6. For a fully transposed line:

$$Z_1 = Z_2 = j(X_s - X_m) \text{ and } Z_0 = j(X_s + 2X_m)$$

(Here, X_s = self reactance and X_m = mutual reactance of any line (pair)

7. For a solidly grounded alternator, $I_{f,\,LG} = 1.5\, I_{f,\,3\phi}$

For an alternator having neutral tgrounded with impedance Z_n,

if $Z_n < \frac{1}{3}(Z_1 - Z_0)$ then, $I_{f,\,LG} > I_{f,\,3\phi}$

if $Z_n = \frac{1}{3}(Z_1 - Z_0)$ then, $I_{f,\,LG} = I_{f,\,3\phi}$

Student's Assignments 1

Q.1 A two generator station supplies a feeder through a bus as shown in figure below. Additional power is fed to the bus through a transformer from a large system which may be regarded as infinite. A reactor *X* is included between the transformer and the bus to limit the *SC* rupturing capacity of the feeder circuit breaker *B* to 333 MVA (fault close to breaker). Find the inductive reactance of the reactor required. System data area:

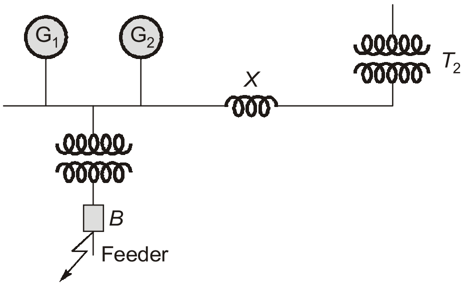
Generator G_1 : 25 MVA, 15% reactance

Generator G_2 : 50 MVA, 20% reactance

Transformer T_1 : 100 MVA, 8% reactance

Transformer T_2 : 40 MVA, 10% reactance

Assume that all reactances are given an appropriate voltage bases choose a base of 100 MVA.



Q.2 A generator transformer unit is connected to a line through a circuit breaker. The unit ratings are:

Generator: 10 MVA, 6.6 kV; $X_d'' = 0.1$ pu, and $X_d' = 0.2$ pu and $X_d = 0.80$ pu

Transformer : 10 MVA, 6.9/33 kV, reactances 0.08 pu

The system is operating on no load at a line voltage of 30 kV, when a three-phase fault occurs on the line just beyond the circuit breaker. Find:

(*i*) the initial symmetrical rms current in the breaker.

(*ii*) the maximum possible DC off-set current in the breaker.

(*iii*) the momentary current rating of the breaker.

(*iv*) the current to be interrupted by the breaker and the interrupting kVA, and

(*v*) the sustained short-circuit current in the breaker.

Q.3 A three-phase synchronous generator has positive, negative and zero-sequence reactances per phase respectively, of 1.0, 0.8 and 0.4 Ω. The winding resistances are negligible. The phase sequence of the generator is *RYB* which a no load voltage of 11 kV between lines. A short-circuit occurs between lines *Y* and *B* and earth at the generator terminals. Calculate sequence currents in phase R and current in the earth return circuit, (*i*) if the generator neutral is solidly earthed; and (*ii*) if the generator neutral is isolated.

Q.4 Three identical resistors are star connected and rated 2500 V, 750 kVA. This three-phase unit of resistors is connected to the *Y* side of a Δ-Y transformer. The following are the voltages at the resistor load:

$$|V_{ab}| = 2000; |V_{bc}| = 2900; |V_{ca}| = 2500 \text{ V}$$

Choose base as 2500 V, 750 kVA and determine the line voltages and currents in per unit on the delta side of the transformer. It may be assumed that the load neutral is not connected to the neutral of the transformer secondary.

Student's Assignments 1 Explanations

1. 2.39 pu

2. (*i*) 0.9277 kA (*ii*) 1.312 kA (*iii*) 1.4843 kA
(*iv*) 1.0205 kA, 53.03 MVA (*v*) 0.1959 kA

3. (*i*) $I_Y = (-5.79 + j5.01)$ kA, $I_B = (5.79 + j5.01)$ kA, $I_G = j10.02$ kA
(*ii*) $I_B = -I_Y = -6.111$ kA, $I_G = 0$

4. $I_A = j1.16$ pu; $V_{AB} = 1.17\angle 109.5°$ pu;
$V_{AB} = 0.953\angle -65.4°$ pu; $V_{CA} = 0.955\angle -113.1°$ pu

Student's Assignments 2

Q.1 The pu impedance of a line to 50 MVA, 132 kV base is 0.4, the pu impedance to a 100 MVA, 132 kV base will be

(a) 0.2
(b) 0.4
(c) 0.8
(d) 1.6

Q.2 Series reactors are used to

(a) improve the transmission efficiency
(b) improve the power factor of the power system
(c) improve the voltage regulation
(d) bring down the fault level within the capacity of the switchgear.

Q.3 In case of power transformer

(a) positive, negative and zero-sequence impedances are all equal
(b) positive and negative sequence impedances are equal but less than zero sequence impedance.
(c) positive sequence impedance is greater than both negative and zero sequence impedances.
(d) positive sequence impedance is less than negative sequence impedance but equal to zero sequence impedance.

Q.4 In an isolated neutral system, when a single line to ground fault occurs

(a) persistent grounds will be developed
(b) voltage in the healthy phase rise to full line value causing insulation breakdown
(c) the capacitive current in the faulty phase rises to 3 times its normal value
(d) all of the above

Q.19 Which of the following network gets affected by the method of neutral grounding
(a) zero sequence network
(b) positive sequence network
(c) negative sequence network
(d) all of these

Q.20 In a transmission line there is a flow of zero sequence current when
(a) there is an occurence of over voltage on line due to a charged
(b) a line to line fault occurs
(c) a 3-phase fault occurs
(d) double line to ground fault occurs

Answer Key:

1. (c)	**2.** (d)	**3.** (b)	**4.** (d)	**5.** (b)
6. (b)	**7.** (a)	**8.** (a)	**9.** (c)	**10.** (a)
11. (a)	**12.** (b)	**13.** (b)	**14.** (a)	**15.** (c)
16. (b)	**17.** (a)	**18.** (c)	**19.** (a)	**20.** (d)

Student's Assignments 2 Explanations

1. (c)
We know that,

$$Z_{\text{pu, new}} = Z_{\text{pu,old}} \times \left(\frac{\text{MVA}_{b,new}}{\text{MVA}_{b,\text{old}}}\right) \times \left(\frac{\text{kV}_{b,\text{old}}}{\text{kV}_{b,\text{new}}}\right)^2$$

$$\therefore \quad Z_{\text{pu, new}} = 0.4 \times \left(\frac{100}{50}\right) \times \left(\frac{132}{132}\right) = 0.8 \text{ pu}$$

2. (d)
A series reactor or a current limiting reactor is an inductive coil having a large inductive reactance in comparison to its resistance and is used for limiting short-circuit currents during fault conditions.

3. (b)
Transformer is a static device having,

$$Z_1 = Z_2 \text{ and } Z_0 >> Z_1$$

5. (b)
For a transmission line,

$$Z_1 = Z_2 \text{ but } Z_0 >> Z_1$$

7. (a)
A three-phase fault is most severse as the fault current is highest.

10. (a)
Single line to ground fault has maximum changes of occurance (around 85% of the all type of faults). Hence, most common

11. (a)
For the zero sequence current to flow, the neutral of the star-connected system must be grounded.

13. (b)

X''_d = Sub-transient reactance (≈ 0.1 to 0.25 pu)

X'_d = Transient reactance (≈ 0.12 to 0.35 pu)

X_d = Steady-state reactance (≈ 1 to 2 pu)

16. (b)
For a transmission line having mutual coupling,

$$X_1 = X_2 = (X_s - X_m)$$

and $$X_0 = (X_s + 2X_m)$$

17. (a)
For a single line-to-ground fault, we have

$$I_{a0} = I_{a1} = I_{a2} = \frac{I_{f,LG}}{3}$$

18. (c)

$$I_{f,\,LG} = 3 \times I_{a0} = 3 \times j3 = j9 \text{ pu}$$

20. (d)
For the flow of zero sequence current, the fault must involve ground (i.e. single line-to-ground fault or double line-to-ground fault).