SECTION II

FAULT CALCULATIONS

19

Introduction to Fault Calculations

Introduction — Procedure of Fault Calculation — Representation of Power Systems — Per Unit Method — Advantages of Per Unit System — Selection of Bases — Single Phase Circuit — Determination of Per Unit Resistance and Reactance — Summary.

19.1. INTRODUCTION

Section II of this book deals with steady state fault calculations. This section covers symmetrical faults, unsymmetrical faults, method of symmetrical components and use of digital computer and network analyzer in fault calculations. Some simple problems have been solved for understanding of the procedure of fault calculations.

The circuit-breakers should be capable of breaking and making the currents as per their ratings and should also have rated short-time capacity. Hence, for proper selection of circuit-breakers and other switching devices/switchgear components, knowledge of current during normal and abnormal conditions (at various respective locations) is necessary.

The design of machines, bus-bars, isolators, circuit-breakers, etc. is based on considerations of normal and short-circuit currents.

The protective relaying schemes can be selected only after ascertaining the fault levels and normal currents at various locations.

Fault studies are also necessary for system design, stability considerations, selection of layout, etc.

The faults are classified as

1. Three phase faults
2. Single phase to earth fault
3. Phase to phase fault
4. Double phase to earth fault
5. Simultaneous faults.

For steady state fault calculations, the steady state reactances are considered. The current and voltage are in r.m.s. value.

In fault calculations, many assumptions are made for simplifying the calculations *e.g.* resistances are neglected when their value is negligible as compared with the reactance. Capacitance is neglected. Machine reactances are assumed to be constant. Saturation effects are neglected. Generated voltages are assumed to be constant. Contribution of shunt capacitor banks is usually neglected.

Two machine-models are assumed in some problems for understanding the procedure. The fault current and fault levels are calculated for steady state.

Consider a point in the power system. Suppose the normal current flowing through the conductor at the point is I_n amperes and the phase to phase voltage at the system is V_n. The normal MVA supplied through the part is given by :

$$\text{Normal MVA}_n = \sqrt{3}\, V_n\, I_n \qquad \ldots(19.1)$$

where MVA_n = Normal MVA

V_n = normal phase to phase voltage, kV rms.

I_n = normal current, kA rms.

Now, consider a *three phase* fault occurring at the point under considerations, the fault current being I_f. The MVA in case of three phase fault would be equal to

$$\text{Fault} \quad MVA_f = \sqrt{3}\, VI_f \qquad ...(19.2)$$

where MVA_f = Fault MVA

V = Phase to phase voltage, kV, rms

I_f = Fault current, kA. rms, (90° lag)

The fault impedance being low, the power flowing into the fault depends on the system reactance upto the fault point. Fault MVA is generally several times the normal MVA, and with lagging p.f.

Table 19.1
Typical Values of Fault Currents in Distribution and Transmission Systems in India

Nominal Voltage (line to line) kV	*Steady State Fault Levels kA, r.m.s*
11	10 to 40
33	10 to 25
132	10 to 30
220	15 to 40
400	20 to 40

With increase in generation and new interconnection, the fault levels at all points go up.

While determining the rating of circuit-breakers, bus-bars, CT's etc. the fault-level at the point under consideration should be known. Fault MVA is of lagging p.f. with current lagging behind voltage by 90°. Large capacitor banks provide leading MVA and *reduce* the fault level. (Ref. Sec. 20.14)

Effective Fault MVA = [Calculate Fault MVA – MVA rating of capacitor Bank]

The Fault-level at the various points in the power system can be calculated by the well established procedures of Fault-calculations. These are for steady state. (Sec. 3.5)

Faults cause drop in voltage, unbalance and loss of stability. Hence another aim of fault calculations is to provide data required for system studies under various fault conditions.

19.2. PROCEDURE OF FAULT CALCULATIONS

Fault calculations deal with determination of current and voltages for various fault conditions at different locations of the power system. Such calculations provide the necessary data for selections of circuit-breakers and design of protective scheme. Fault calculations normally begin with drawing single line or one line diagram of the given system. Next, suitable kV and kVA bases are chosen for each voltage level. From these, the base quantities for current and impedance are calculated for each voltage level. Thereafter reactance diagram or positive sequence network of the system is drawn. These are the preliminary steps in fault calculations.

The faults are classified as symmetrical faults and unsymmetrical faults. Symmetrical faults include three phase faults. Such faults can be solved on per phase basis. The system is represented by a single phase system considering phase and neutral. The unsymmetrical faults are solved by using the method of symmetrical components.

For simple systems, calculations can be performed directly be means of calculator. But for modern complex systems, a.c. network analyzers or digital computers are used for faults calculations.

Per unit system is adopted for fault calculations as it simplifies the analysis. Steady state rms values are calculated.

19.3. REPRESENTATION OF POWER SYSTEMS

A balanced three phase system can be conveniently solved on single-phase basis. It can be represented by a single-phase system having one phase and a neutral. The first step in fault calculation is normally drawing a *Single Line Diagram*. In this diagram the components of the system are usually drawn in the form of their symbol. The neutral earthing is indicated. Fig. 19.1 shows single line diagram of a simple system.

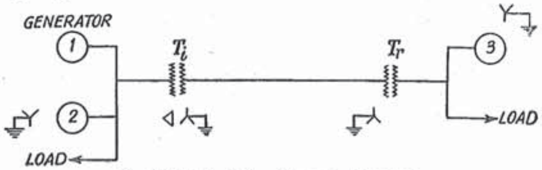


Fig. 19.1. Single line diagram of system.

The next step is to draw :

'Impedance or Reactance Diagram' or 'Positive Sequence Network'.

In impedance diagram each component is represented by its equivalent circuit. Fig. 19.2 represents impedance diagram of systems of Fig. 19.1. In majority of problems of fault calculations, resistance is neglected. Further, some more approximations can be made such as neglecting the capacitance and magnetizing current, etc. the rotating machines are represented by e.m.f. source in series with a reactance. Static loads are omitted. The induction motors are omitted for steady state analysis. Thereby the impedance diagram reduces to simplified reactance diagram. Contribution of large capacitor banks is considered. *Effective Fault MVA* is obtained by subtracting capacitor bank MVA from calculated Fault MVA.

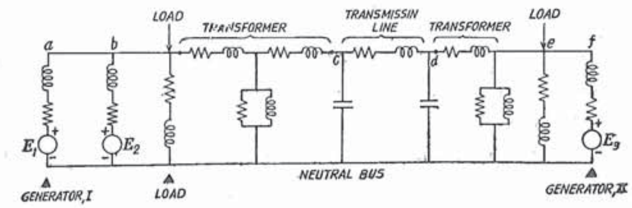


Fig. 19.2. Impedance diagram of Fig. 19.1.

Fig. 19.3 shows the reactance diagram of the system of Fig. 19.1. Reactance diagram is also called 'Positive Sequence Network'.

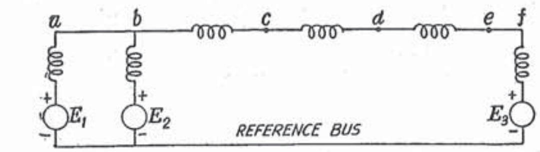


Fig. 19.3. 'Reactance diagram' or 'Positive Sequence Network of the system in Fig. 19.1.

19.4. PER UNIT METHOD

The quantities voltage (V), current (I), kVA, impedance Z are often expressed as percentage or per unit of their selected bases. Such a method simplifies the calculations.

For example let us call, 200 volts equal to 1 per unit or 100 per cent. Then 200 volts is the base voltage. Now, other voltages are expressed as multiple the base voltage as follow :

$$\text{Per unit voltage} = \frac{\text{Actual voltage}}{\text{Base voltage}}$$

e.g.,

$$20\text{ V} = \frac{20}{200} = 0.1\text{ p.u. or 10 per cent}$$

$$100\text{ V} = \frac{100}{200} = 0.5\text{ p.u. or 50 per cent}$$

and likewise.

Similarly, other quantities, I, Z etc. are expressed as per unit of their selected bases, *e.g.*, if base current is 10 amperes, 100 amperes will be 10 p.u., 10 amperes will be 1.p.u. etc.

After completing the calculations, the actual values of I, V, Z etc., are obtained by the reverse method, *i.e.*,

$$\text{Actual value} = \text{p.u. Value} \times \text{Base value.}$$

Example 19.1. Per Unit Method. *For a single phase system, selected bases are as follows :*

Base current 10 amperes.

Base voltage 200 volts.

Calculate base impedance.

Express the following quantities in per unit form

20 A, 0.2 A, 50 V, 1000 V, 2 Ω.

Solution. Base current = 10 A

Base voltage = 200 V

$$\text{Base impedance} = \frac{\text{Base Voltage}}{\text{Base current}} = \frac{200}{10} = 20\text{ ohms.}$$

$$20\text{ A} : \frac{20}{10} = 2\text{ p.u.} \qquad \text{[Current]}$$

$$0.2\,A = 0.02\text{ p.u.}$$

$$50\text{ V} : \frac{50}{200} = 0.25\text{ p.u.} \qquad \text{[Voltage]}$$

$$2\,\Omega : \frac{2}{20} = 0.1\text{ p.u.} \qquad \text{[Resistance]}$$

19.5. ADVANTAGES OF PER UNIT SYSTEM

1. Calculations are simplified.

2. For circuits connected by transformers, per unit system is particularly suitable. By choosing suitable base kV's for the circuits the per unit reactance remains the same, referred to either sides of the transformer. Therefore, the various circuits can be connected in the reactance diagram.

3. Machine reactances given in per unit, give a basis for comparison. The micro-machines are built to represent the actual machines for the purpose of research. They have nearly the same per unit reactance as their parent machine. Thus per unit system gives a method of comparison.

19.6. SELECTION OF BASES

(*I*) As a rule only two bases should be selected first and from these two, the remaining bases should be calculated. This is so, because kV, kVA, I and Z are interrelated. They must obey Ohm's law. If we choose Base kV and kVA, the other bases, *i.e.*, Base I and Base Z are calculated from Base kV and Base kVA. As we will see later, it is convenient to select Base kV and Base kVA.

(*II*) For circuits connected by transformer, choose same kVA base for both the circuits. Choose base kV's such that the ratio of Base kV's is same as the ratio of transformer. Such a selection gives same p.u. reactance of transformer referred to both the circuits [Refer example 19.4]

19.7. SINGLE PHASE CIRCUITS : DETERMINATIONS OF BASE-IMPEDANCE (or Resistance or Reactance)

Select Base kV and Base kVA

Actual kV given in kV

$$\text{P.u. kV} = \frac{\text{Actual kV}}{\text{Base kV}}$$

$$\underset{\text{(Amperes)}}{\text{Base Current } I} = \frac{\text{Base kVA}}{\text{Base kV}} \qquad \text{...(1)}$$

$$\underset{\text{(Ohms)}}{\text{Base Impedance } Z} = \frac{\text{Base kV} \times 1000}{\text{Base Current } I} \qquad \text{...(2)}$$

$$= \text{Base kV} \times \frac{\text{Base kV}}{\text{Base kVA}} \times 1000 \qquad \text{...(3)}$$

$$= \frac{[\text{Base kV}]^2 \times 1000}{\text{Base kVA}} \qquad \text{...(4)}$$

$$\text{Base power kW} = \text{Base kVA}$$

$$\text{P.u. Impedance} \quad Z = \frac{\text{Actual Z}}{\text{Base Z}} \qquad \text{...(5)}$$

$$= \text{Actual } Z \times \frac{\text{Base kVA}}{(\text{Base kV})^2 \times 1000} \qquad \text{...(6)}$$

19.8. CHANGE OF BASE

From Eq. (6) we get important conversion :

P.u. Z referred to new base

$$= \text{P.u. } Z \text{ referred to old base} \times \left(\frac{\text{Base kV old}}{\text{Base kV new}}\right)^2 \times \left(\frac{\text{Base kVA new}}{\text{Base kVA old}}\right) \qquad \text{...(7)}$$

Example 19.2. *Convert 2 ohms into per unit. Base kV 11, Base kVA 1000.*

Solution. $\text{Base } Z = \frac{\text{Base } kV^2 \times 1000}{\text{Base kVA}} = \frac{11^2}{1000} \times 1000 = 121$

Hence $121\,\Omega = 1\text{ p.u.}$

Then $2\,\Omega = \frac{2}{121} = 0.0165\text{ p.u.}$

Example 19.3. *A 11 kV, 15,000 kVA generator has reactance of 0.15 p.u. referred to its ratings as bases. The new bases chosen for calculations are 110 kV and 30,000 kVA.*

Calculate the new p.u. reactance.

Solution. Eq. (6) gives

$$\text{New p.u. } Z = \text{Old p.u. } Z \times \left(\frac{\text{Old kV Base}}{\text{New kV Base}}\right)^2 \times \left(\frac{\text{New kVA Base}}{\text{Old kVA Base}}\right)$$

In this problem,

$$\text{P.u. } X \text{ new} = 0.15 \times \left(\frac{11}{110}\right)^2 \times \left(\frac{30{,}000}{15{,}000}\right)$$

$$= 0.15 \times (0.1)^2\,(2) = 0.0003\text{ p.u.}$$

Three phase Systems

(*i*) Three-phase systems are solved on single phase basis, the base voltage represents phase to neutral voltage, and currents represents the phase currents. On this basis, the equations for base impedance are as follows :

Base kV phase to neutral kV

$$\text{Base kVA} = \frac{\text{3-phase kVA}}{3}$$

$$\text{Base current} = \frac{\text{Base kVA}}{\text{Base kV}}$$

$$\text{Base Impedance (ohms)} \quad = \frac{\text{Base kV}^2}{\text{Base kVA}} \times 1000.$$

(*ii*) Suppose we take a three phase base kVA and base kV as phase to phase kV, we obtain the following expressions :

$$\text{Base Current} \quad = \frac{\text{Base kVA}}{\sqrt{3} \times \text{Base kV}}$$

$$\text{Base impedance} \quad = \frac{\left(\dfrac{\text{Base kV}}{\sqrt{3}}\right)^2 \times 1000}{\text{Base kVA/3}} = \frac{\text{Base kV}^2 \times 1000}{\text{Base kVA}}$$

We note that, the same expression of p.u. impedance is obtained for a single phase and three phase systems. In power system problems the data are given in terms of 3-phase kVA, phase to phase kV. The machine reactances are given in percentage of p.u. quantities based on machine kVA and machine phase to phase kV rating.

Further the direct axis synchronous reactance is also known as positive sequence reactance of the machine.

19.9. CIRCUITS CONNECTED BY TRANSFORMER

Consider two circuits *A* and *B* connected by means of a transformer. While selecting the bases for these two circuits choose same kVA base for both the circuits, but different kV bases. The kV bases for the two circuits should have the same ratio of transformation. With such a selection of bases the p.u. reactance referred to either side with bases of that side remains same (Refer Example 19.4).

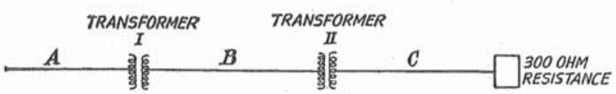


Fig. 22·4. Single line diagram.

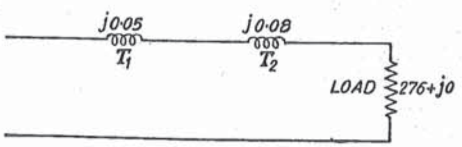


Fig. 19.5. Reactance diagram of the system. (Ans.)

Example 19.4. *Three-single-phase circuit A, B, C are connected as shown in Fig. 19.4. Draw reactance diagram of the system. Transformer I is rated 10,000 kVA and has a ratio 11/22 kV, leakage reactance of 5%. Transformer II has rating of 10,000 kVA, ratio 22/3.3 kV and leakage reactance 8%. Load is 300 ohm resistance. Draw reactance diagram for the system.*

Solution. Select same base kVA for *A*, *B*, *C*. Say 10,000 kVA.

Select base kV's of the same ratio as the transformation ratio. If we take base kV for circuit *A* as 11 kV. Base kV for circuit *B* is 22 kV Base, kV for circuit *C* is 3.3 kV.

$$\text{Base Impedance} \quad = \frac{\text{Base kV}^2 \times 1000}{\text{Base kVA}}$$

$$\text{For circuit } A: \quad \frac{(11)^2 \times 1000}{10,000} = 12.1 \text{ ohm}$$

$$\text{Circuit } B: \quad \frac{(22)^2 \times 1000}{10,000} = 48.4 \text{ ohm}$$

$$\text{Circuit } C: \quad \frac{(3.3)^2 \times 1000}{10,000} = 1.09 \text{ ohm}$$

Load impedance $= 300\ \Omega$ (resistive)

$$\text{In circuit } C: \quad \frac{300}{1.09} = 276 \text{ p.u.} \qquad ...(i)$$

Load impedance referred to circuit *B*

$$= 300 \times \left(\frac{22}{3.3}\right)^2 = 13,350 \text{ ohms}$$

In p.u. this is equal to

$$\frac{13,350}{48.4} = 276 \text{ p.u.} \qquad ...(ii)$$

Load impedance referred to circuit *A*

$$= 133,50 \left(\frac{11}{22}\right)^2 = 3337.5 \text{ ohms.}$$

In p.u. from which is equal to

$$\frac{3337.5}{12.1} = 276 \text{ p.u. (ohms)} \qquad ...(iii)$$

From (*i*), (*ii*), (*iii*), we note that the p.u. Impedance of load has same value in all the three circuits, with the proper selection of bases. The reactance diagram shows the two transformers and load represented as reactances the reactance diagram is given by Fig. 19.5.

The principle of selecting base kV and base kVA, mentioned above can also be applied to 3-phase transformers, irrespective of their connections of various star-delta combinations.

19.10. REACTANCES OF CIRCUIT ELEMENTS

The manufacturer mentions the percentage or per unit reactance of the machine. It is understood that the base quantities are machine ratings. Tables are available giving approximate values of per unit impedances of synchronous machines, transformers, induction motors.

19.11. INDUCTION MOTORS

Induction motors of large size have their own contribution to fault current which cannot be neglected. The kVA rating of the motor is taken from rating plate.

19.12. SYNCHRONOUS MOTOR

kVA rating is taken from rating plate.

19.13. THEVENIN'S THEOREM

The current in a branch of a network having one or more voltage sources can be conveniently determined by Thevenin's theorem. The current in the branch I_b is given by the expression

$$I_b = \frac{V_{oc}}{Z_{th} + Z_b}$$

where V_{oc} is the voltage across the terminal, with the branch disconnected.

Z_{th} = Thevenin's equivalent impedance, *i.e.* The impedance of the network between the terminals of the branch with the branch disconnected and the voltage sources replaced by short circuits.

Z_b = Impedance of the branch whose current is to be determined.

Thevenin's theorem will be used in the fault calculations.

Table 19.1
Reference Values for Reactance of Two Winding Power Transformers

kV of hv, side / *MVA rating*	*3.3 kV*	*11kV*	*33kV*	*66kV*	*132kV*	*275kV*	*400kV*
Less than 1 MVA	4.75	4.75—6	4.75—6	6			
5 MVA		6—7	6—7	7.5			
10 MVA		12—15	12—15	11	10		
15 MVA		12—15	13	11	10		
30 MVA			12.5	11	10		
60 MVA				11	12.5		
120 MVA						15	
210 MVA						5	
600 MVA							15

Note. The percentage reactance depends on kV rating of h.v. side

Table 19.2
Reference Values for Percentage Reactances of Alternators*

Rating and type	X''	X'	X_s	X_2	X_o	*SCR*
11 kV Salient Pole, Without Damper	25	35	112	20	6	
11.6 kV, 600 MW, Turbo	11	17	200	13	6	0.55
11.6 kV, 60 MW, Gas-Turbo	11	14	175	13	5.2	0.7
13.5 kV, 100 MW, Turbo	20	29	205	22	10	0.58
18.5 kV, 300 MW, Turbo	20	26	260	19	11	0.4
22.2 kV, 500 MW, Turbo	20	28	250	20	9	0.4

*Where X'' : Sub transient reactance
X' : Transient reactance
X_s : Steady state reactance
} Positive Sequence Reactance
X_2 : Negative sequence reactance
X_0 : Zero sequence reactance

$$SCR : \text{Short circuit ratio} = \frac{\text{Field current to get rated o.c. voltage}}{\text{Field current to get rated s.c. current}}$$

For steady state calculations, use the steady state reactance value X_s..

Example 19.5. *Thevenin's Theorem. Determine the fault current in the circuit [Fig. 19.6 (a)]. Impedance of fault is negligible.*

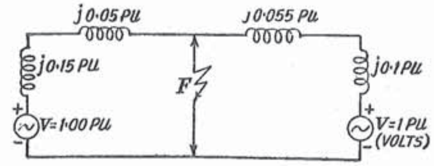


Fig. 19.6 (*a*). Ex. 19.5.

Solution. Since load current is zero the o.c. voltage across F is 1 p.u. Hence $V_{oc} = 1$. The Thevenin's impedance is obtained between terminals of F by shunting the voltage sources.

$$Z_{th} = \frac{j0.2 \times j0.155}{j0.2 + j0.155}$$

$$= j\frac{0.0310}{0.355} = j\,0.087 \text{ p.u.}$$

$$I_f = \frac{V_{oc}}{Z_{th} + Z_f}$$

$$Z_f = 0$$

$$I_f = \frac{1 + j0}{j0.087} = -j\,11.5 \text{ p.u.}$$

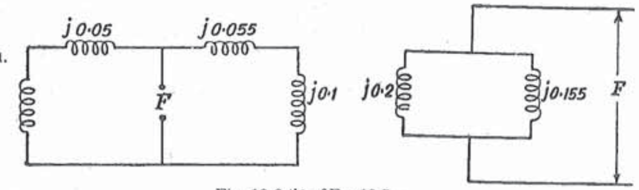


Fig. 19.6 (*b*) of Ex. 19.5.

Example 19.6. *Draw reactance diagram of the system shown in Fig. 19.7. The generator is 11 kV, 30,000 kVA with sub-transient reactances of 15%. The generator supplies power to two motors through a transmission line having transformers at both the ends. Motors have rated input 10,000 kVA, at 11 kV, 11/110 kV with leakage reactance of 10 per cent. Series reactance of transmission line 80 ohms.*

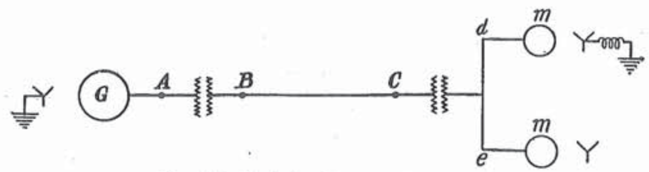


Fig. 19.7. Single line diagram of Ex. 19.6.

Solution.

Base kVA for the complete system	30,000 kVA
Base kV's generator circuit	11 kV
Transmission line circuit	110 kV
Motor circuit	11 kV

Base impedance $= \dfrac{\text{Base kV}^2}{\text{Base kVA}} \times 1000$

Base impedance of transmission line circuit

$$= \frac{(110)^2}{30{,}000} \times 1000 = 403.3 \text{ ohms.}$$

P.u. reactance of transmission line

$$\frac{80}{403.3} = 0.198 \text{ p.u.}$$

P.u. reactance of transformer to new base kVA

$$= j0.1 \times \frac{30{,}000}{35{,}000} = j\,0.0857 \text{ p.u.}$$

P.u. reactance of motor to new base kVA

$$= j0.2 \times \frac{30{,}000}{10{,}000} = j\,0.6 \text{ p.u.}$$

The reactance diagram or positive sequence network is drawn from these p.u. values (Refer Fig. 19.8) **(Ans.)**

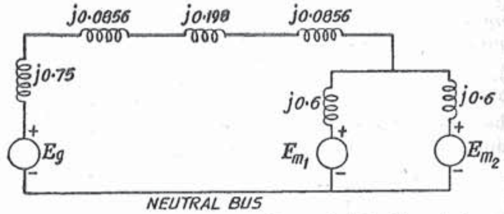


Fig. 19.8. Reactance diagram of Example 19.6. Also called positive sequence network. (Ans.)

Per Unit Impedance of Three Winding Transformers. The three windings of a three winding transformer may have different kVA ratings. Impedance of each winding may be given in per unit based on the rating of that winding. However, the per unit impedances in impedance diagram must be expressed on the same base kVA. The impedance measured from short circuit test may be denoted as follows :

Z_{ps} = leakage impedance measured in primary with secondary short circuited and tertiary open.

Z_{pt} = leakage impedance in primary with tertiary short-circuited and secondary open.

Z_{st} = leakage impedance measured in secondary with tertiary short-circuited and primary open.

If the three impedances measured in ohms are referred to voltage of one of the windings, the impedances of each separate winding referred to that winding are as follows :

$$Z_{ps} = Z_p + Z_s$$
$$Z_{pt} = Z_p + Z_t$$
$$Z_{st} = Z_s + Z_t$$

Where Z_p, Z_s and Z_t are the impedances of primary, secondary and tertiary winding referred to primary circuits, solving the equations simultaneously, we get

$$Z_p = \tfrac{1}{2}\,[Z_{ps} + Z_{pt} - Z_{st}]$$
$$Z_s = \tfrac{1}{2}\,[Z_{ps} + Z_{st} - Z_{pt}]$$
$$Z_t = \tfrac{1}{2}\,[Z_{pt} + Z_{st} - Z_{ps}]$$

The three impedances are star connected to represent single-phase equivalent circuit. The three outer points of star connection are connected to the parts of the impedance diagram which represent in connections of primary, secondary and tertiary.

Example 19.7. *A three phase rating of a three winding transformers are :*

Primary — Star connected 66 kV, 10 MVA.
Secondary — Star connected 11 kV, 7.5 MVA.
Tertiary — Delta connected 3.3 kV, 5 MVA.

The leakage impedances defined as mentioned earlier are :

$$Z_{ps} = 7\% \text{ based on 10 MVA, 66 kV base}$$
$$Z_{pt} = 9\% \text{ based on 10 MVA, 66 kV base}$$
$$Z_{st} = 6\% \text{ based on 7.5 MVA, 11 kV base.}$$

Find p.u. impedances of equivalent circuit for 10 MVA, 66kV base on primary circuit.

Solution. Bases primary 10 MVA, 66 kV.

Secondary 10 MVA, 11 kV.

Tertiary 10 MVA, 3.3 kV.

$$Z_{st} = 0.06 \times \frac{10}{7.5} = 0.08 \text{ p.u.}$$

$$Z_p\ \tfrac{1}{2}\,[Z_{ps} + Z_{pt} - Z_{st}]$$
$$Z_p = \tfrac{1}{2}\,[j\,0.07 + j\,0.09 - j\,0.08] = j\,0.04 \text{ p.u.}$$
$$Z_s = \tfrac{1}{2}\,[Z_{ps} + Z_{st} - Z_{pt}]$$
$$= [j\,0.07 + j\,0.08 - j\,0.09] = j\,0.03 \text{ p.u.}$$
$$Z_t = \tfrac{1}{2}\,[Z_{pt} + Z_{st} - Z_{ps}]$$
$$= \tfrac{1}{2}\,[j\,0.09 + j\,0.08 - j\,0.07] = j\,0.05 \text{ p.u.}$$

Equivalent Circuit

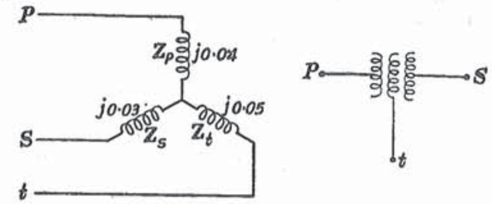


Fig. 19.8 (a). Solution of Ex. 19.7.

Example 19.8. *Define percentage reactance of an electrical machine and show that the short-circuit current is inversely proportional to percentage reactance.*

Solution. Let E be the rated voltage and I be the rated current. If the electrical machine is the only impedance in the circuit the short-circuit current is given by E/X which is

$$I_{sh} = \frac{E}{X}$$

The percentage reactance of the machine is defined as

$$\%X\ \frac{IX}{E} \times 100$$

Therefore, $$I_{sh} = \frac{I \times 100}{\%X} \quad \textbf{Ans.}$$

Example 19.9. *Fault level at a 110 kV bus in a receiving substation neglecting new capacitor bank was 5000 MVA. A new 200 MVA, 110 kV capacitor bank was commissioned. Calculate new fault level.*

Solution. New fault level = Effective fault level
= Fault MVA – Capacitor Bank MVA
= 5000 – 200 = 4800 MVA.

19.14. SOME TERMS

1. **Fault Power.** Also called Fault level or Short-circuit level-(Symbol : *Sa*). It is the product :

$\sqrt{3}$ × Fault current × System voltage.

Fault power in MVA = $\sqrt{3}$ kV × kA

where kV = line to line voltage
kA = fault current

3-phase fault is assumed. Contribution of Capacitor Banks is neglected.

2. **Initial Symmetrical Fault Power**

(Symbol *Sa″*)

$\sqrt{2}$ × initial symmetrical fault current × Service voltage.

3. **Peak Short Circuit Current,** I_S. The highest instantaneous value of current after appearance of short-circuit.

With full asymmetry.

Peak value $= 1.8 \sqrt{2} \times$ a.c. component.

4. **Initial Symmetrical Short Circuit Current,** I_k''. The r.m.s. value of symmetrical short circuit current at the instant of short circuit, determined from sub-transient reactances X_d''.

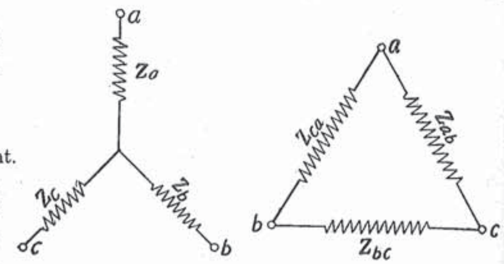


Fig. 19.9. Star-delta transformation.

5. **Transient Short Circuit Current,** I_k'. RMS value of short-circuit current determined from transient reactance X_d'.

6. **Sustained Short Circuit Current,** I_k. Short-circuit current determined from steady-state reactance.

[Refer Sec. 3.5]

19.15. STAR-DELTA TRANSFORMATION

Case I. *Star to Delta*

$$Z_{ab} = \frac{Z_a Z_b + Z_b Z_c + Z_c Z_a}{Z_c}$$

$$Z_{bc} = \frac{Z_a Z_b + Z_b Z_c + Z_c Z_a}{Z_a}$$

$$Z_{ca} = \frac{Z_a Z_b + Z_b Z_c + Z_c Z_a}{Z_b}$$

Case II. *Delta to Star*

$$Z_a = \frac{Z_{ab} Z_{ca}}{Z_{ab} + Z_{bc} + Z_{ca}}$$

$$Z_b = \frac{Z_{bc} Z_{ab}}{Z_{ab} + Z_{bc} + Z_{ca}}$$

$$Z_c = \frac{Z_{ca} Z_{bc}}{Z_{ab} + Z_{bc} + Z_{ca}}$$

19.16. NOTATION j

A vector Z can be written as

$$\overline{Z} = x + jy$$

where x = component of $\overline{Z}$ along real axis

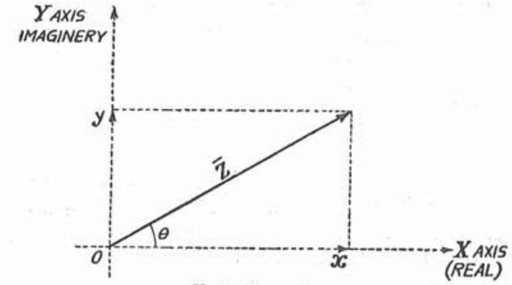
y = component of $\overline{Z}$ along imaginary axis

j = vector operator $= \sqrt{-1}$

$|Z|$ = magnitude of $\overline{Z}$

$= \sqrt{x^2 + y^2}$

$\theta = \tan^{-1} \dfrac{y}{x}$



Vector $Z = x + iy$

Fig. 19.10.

Addition of vectors : $\overline{Z}_1 + \overline{Z}_2 = \overline{Z}$

$$= (x_1 + jy_1) + (x_2 + jy_2)$$

$$= (x_1 + x_2) + j(y_1 + y_2)$$

$$|Z| = \sqrt{(x_1 + x_2)^2 + (y_1 + y_2)^2}$$

Subtraction of $\overline{Z}_1$ and $\overline{Z}_2$

$$\overline{Z} = \overline{Z}_1 - \overline{Z}_2 = (x_1 - x_2) + (y_1 - y_2)$$

Multiplication of $\overline{Z}_1$ and $\overline{Z}_2$

$$\overline{Z}_1 \overline{Z}_2 = (x_1 + jy_1)(x_2 + jy_2)$$

$$= x_1 x_2 + jx_1 y_2 + jx_2 y_1 - y_1 y_2$$

$$= (x_1 x_2 - y_1 y_2) + j(x_1 y_2 + x_2 y_1)$$

$$\overline{Z}_1 \overline{Z}_2 = |Z_1| \, |Z_2| \, \underline{/\theta_1 + \theta_2}$$

Division of $\overline{Z}_2$ and $\overline{Z}_1$

$$\frac{Z_1}{Z_2} = \left|\frac{Z_1}{Z_2}\right| \, \underline{/\theta_1 - \theta_2}$$

19.17. SUMMARY

(*a*) Procedure of fault calculation is as follows :

1. Draw single line diagram of the system in which the machines are represented by their symbols.

2. Draw reactance diagram or positive sequence network.

3. For symmetrical faults, only positive sequence network is enough.

4. For unsymmetrical faults, method of symmetrical components is applied in which three sequence networks are drawn.

(*b*) The per unit system is used for fault calculations. The per unit reactances of machines are given referred to their ratings as the bases.

The kV, *I*, *Z*, kVA are expressed as per unit or per cent of their selected bases ; only two bases, (usually kV and kVA) are selected first then the remaining two bases are calculated.

(c) The p.u. Impedance is given by following expressions.

$$\text{Base} \quad Z = \frac{\text{Base kV}^2}{\text{Base kVA}} \times 1000$$

$$\text{p.u. } Z = \frac{\text{Ohmic Z}}{\text{Base Z}} = \frac{Z \times \text{Base kVA}}{\text{Base kV}^2 \times 1000}$$

Change of Base

$$\text{p.u. } Z_{new} = \text{p.u. } Z_{old} \times \left(\frac{\text{kVA Base New}}{\text{kVA Base Old}}\right) \times \left(\frac{\text{kV base Old}}{\text{kV base New}}\right)^2$$

(d) For circuits connected by transformer choose same kVA base on both sides and different kV bases on either sides. kV bases should have the ratio same as transformation ratio. The p.u. reactance remains same on either sides.

(e) Thevenin's theorem and network reduction methods are useful in fault calculations.

QUESTIONS

1. Explain the Per Unit System. What are its advantages ?
   Derive expression for p.u. reactance from the chosen base kVA and base kV.
2. The p.u. reactance of a 11 kV, 20,000 kVA, 3 ph. 50 Hz alternator is 0.20 p.u. What will be its p.u. reactance referred to the base kV 110 and base kVA 10,000?
3. A generator is connected to a transmission line through a transformer. The ratings are as follows :
   Generator : 20,000 kVA, 11 kV, positive sequence reactance 15 p.u.
   Transformer 10,000 kVA, 11/110 kV, leakage reactance 6 per cent. Transmission line total reactance 10 ohms. A fault occurs at the other end of the line. Draw reactance diagram taking suitable base kV and 200,000 base kVA.
   Transmission line total reactance 10 ohms. A fault occurs at the other end of the line. Draw reactance diagram taking suitable base kV and 200,000 base kVA.
4. A 20,000 kVA, 11 kA generator 3 ph. has a direct axis synchronous reactance of 20 per cent. A 3-phase short circuit near the terminals. Calculate the steady short circuit current. Generator is at rated voltage and on load. **[Ans.** 5250 A]
5. Two generators are operating in parallel and have sub-transient reactance $X'' = 10\%$. Generator I is rated 2500 kVA, 3.3 kV, generator 2 is rated 500 kVA, 32 kV. Find p.u. reactances of each generator on 15,000 kVA, 3 kV base. What is equivalent p.u. reactance of the two generators on 1500 kVA, 3 kV base ?
6. Three reactance 0.5, 0.2 and 0.3 are connected in delta. Find the equivalent star reactances.
7. Three motors are connected to a common bus. The motors are rated 5000 h.p., 3.3 kV, 0.8 p.f., $X'' = 17\%$. They are supplied by a generator 20,000 kVA, 11 kV and of $X'' = 10\%$ through a transformer 11/3.3 kV, 18,000 kVA and having 5% leakage reactance. Draw the reactance diagram of the system. Take kVA = 1.10 × H.P. Take 20,000 kVA base.
8. Distinguish clearly between per unit method and percentage reactance method. Show that the per unit reactance referred to the circuits connected by transformer is same if same base kVA is taken for both circuits and the base kVs have ratio equal to transformation ratio.
9. State whether correct or wrong. Write corrected statements if necessary.
   (i) Circuit-breakers open during steady state fault condition.
   (ii) The positive sequence reactance of generators is less than their negative sequence reactance.
   (iii) During short-circuits, the current increases with time during first 10 cycles.
   (iv) Percentage reactance of power transformers is always less than one per cent.
   (v) Short-circuit ratio of generators is less than 1.
   (vi) Power system stability depends upon fault clearing time.

20

Symmetrical Faults and Current Limiting Reactors

Fault MVA and Fault Current – Summary. **Solved Examples 20.1 to 20.22** of various types by different methods — Current Limiting Reactors.

In this chapter some examples on symmetrical faults have been solved. Per unit system and procedure mentioned in chapter 19 has been followed.

Significance of Fault MVA.

High fault MVA at a point signifies high strength of power system at that point, low equivalent reactance upto that point. Therefore, large loads can be connected at that point. Low fault level signifies weak system. Fault level indicates the strength of the power system.

20.1. FAULT MVA AND FAULT CURRENT (STEADY STATE)

Calculate total p.u. reactance upto fault point, by network reduction of positive sequence network or reactance diagram. If same kVA base is taken for complete system

$$\text{P.u. fault current} = \frac{\text{P.u. voltage at fault point}}{\text{P.u. } X_{equivalent}}$$

P.u. fault level = √3 p.u. fault current × p.u. service voltage. Or in other way

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\text{P.u. } X_{equivalent}} \text{ (MVA)} \qquad \text{... reactive, lagging.}$$

$$\text{Fault current} = \frac{\text{Fault MVA} \times 10^3}{\sqrt{3} \times \text{Base kV}} \text{ (Amp.) } \angle -90°$$

Hence for three phase (symmetrical) fault, we get the expressions, neglecting load current

$$\text{Fault MVA} = \frac{\text{Base MVA}}{X_{\text{p.u. the venine's equivalent}}} \qquad \text{... reactive, lagging.}$$

$$\text{Fault current} = \frac{\text{Fault MVA} \times 1000}{\sqrt{3} \times \text{Base kA}} \text{ (Amp.) } \angle -90°$$

(Base kV at the fault point, assuming the fault occurs at normal voltage. Fault current is of lagging power factor).

20.2. SOLVED EXAMPLES 20.1 TO 20.21

Note. In this chapter some problems on symmetrical faults have been solved. Further, the term sub-transient, transient and steady state are described in Ch. 3 (Notation j is omitted).

Example 20.1. *A 3-phase, 5000 kVA, 6.6 kV generator having 12% sub-transient reactance. A 3-phase short circuit occurs at its terminals, calculate fault MVA and current.*

Solution. (Method I)

$$\text{Fault MVA} = \frac{\text{Base MVA}}{\%\text{Reactance}} \times 100$$