Fault Calculations

1- Introduction

Most of the faults on the power system lead to a short-circuit condition. When such a condition occurs, a heavy current (called short circuit current) flows through the equipment, causing considerable damage to the equipment and interruption of service to the consumers. There is probably no other subject of greater importance to an electrical engineer than the question of determination of short circuit currents under fault conditions. The choice of apparatus and the design and arrangement of practically every equipment in the power system depends upon short-circuit current considerations. In this chapter, we shall confine our discussion to fault currents due to symmetrical faults. We will learn how to perform short circuit calculations in an electrical network for symmetrical. The unit will show you the necessary steps to derive the fault current expressions for a symmetrical fault.

2- Objective

On successful completion of this chapter, you should be able to:

- Define fault level.
- Reduce a power circuit with a symmetrical fault to a single impedance and source.
- Derive the fault current and fault level MVA.
- Solve problems with symmetrical fault

3- Fault Analysis

a- Introduction

An essential part of the design of a power supply network is the calculation of the currents which flow in the components when a symmetrical fault occurs. High currents may cause considerable damage to equipment if they are not immediately isolated. It may also result in system instability if they are not cleared fast. When there is a fault the system becomes unbalanced.

Fault calculations provide the values of currents and voltages on a power system during fault conditions. This information is required to design an adequate protection relaying system and to determine interruption capacity for circuit breakers at each switching location.

In an electric power system, a **fault** or **fault current** is any abnormal electric current. For example, a short circuit is a fault in which current bypasses the normal load. An open-circuit fault occurs if a circuit is interrupted by some failure. In three-phase systems, a fault may involve one or more phases and ground, or may occur only between phases. In a "ground fault" or "earth fault", current flows into the earth. The prospective short circuit current of a predictable fault can be calculated for most situations. In power systems, protective devices can detect fault conditions and operate circuit breakers and other devices to limit the loss of service due to a failure.

b- Types of Faults

In a polyphase system, a fault may affect all phases equally which is a "symmetrical fault". If only some phases are affected, the resulting "asymmetrical fault" becomes more complicated to analyse. The analysis of these types of faults is often simplified by using methods such as symmetrical components.

The design of systems to detect and interrupt power system faults is the main objective of power-system protection.

There are generally two types of faults in power systems: see figure below

- **Symmetrical Faults**

A **symmetric** or **balanced fault** affects each of the three phases equally. In transmission line faults, roughly 5% are symmetric. This is in contrast to an asymmetrical fault, where the three phases are not affected equally.

- **Asymmetrical Faults:**

An **asymmetric** or **unbalanced fault** does not affect each of the three phases equally. Common types of asymmetric faults, and their causes:

Line-to-Line

Is a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator.

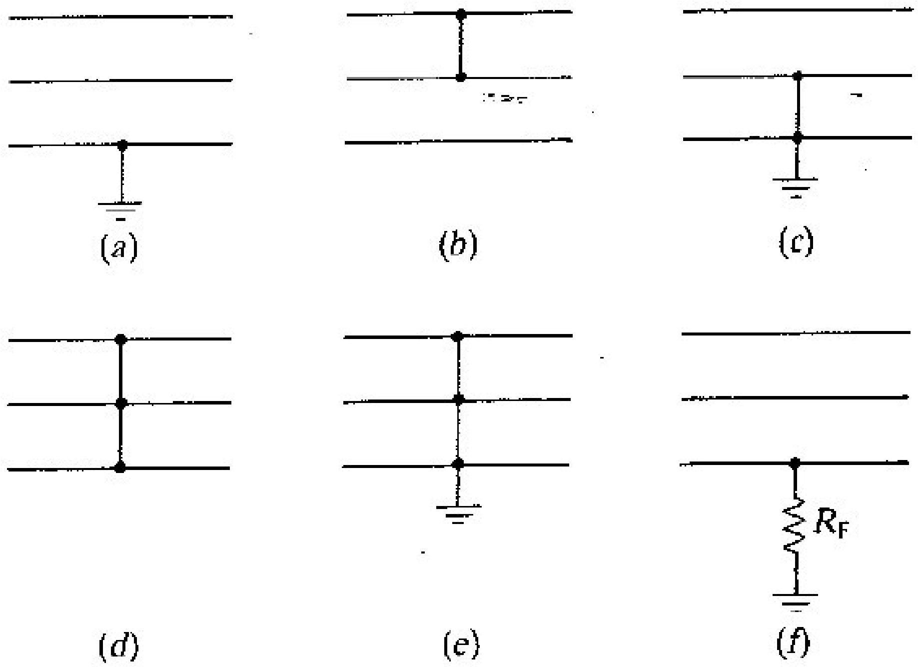
Line-to-Ground

Is a short circuit between one line and ground, very often caused by physical contact, for example due to lightning or other storm damage.

Double Line-to-Ground

Is two lines come into contact with the ground (and each other), also commonly due to storm damage.

While three-phase symmetrical faults are uncommon in practice, it can be analyzed quite easily by using the single phase equivalent circuit.



line-to–ground fault (a) line-to-line fault (b) line-to-line-to-ground fault (c) three-phase-to-ground fault or three-phase-fault) (d) (e)

c- Assumptions made in fault calculations

a) The generator is represented by a voltage source in series with an impedance (or reactance if resistance is neglected).
b) Load is represented by constant impedance.
c) Resistances of the circuit are neglected. In a power system, the reactances of the machines and transformers usually predominant. This gives an error on the safe side.
d) All transformers are assumed to be at nominal taps and magnetizing currents are neglected, i.e. they are represented as series elements.
e) Load current is ignored as it is small compared with the fault current.
f) Internal emf of all generators are equal in magnitude and are in-phase. Hence, all voltage sources can be lumped together into one single equivalent generator.

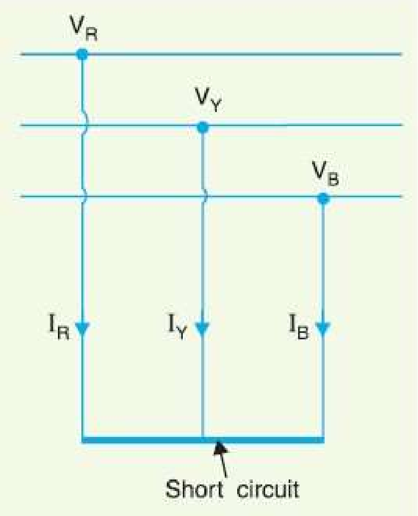
4- Symmetrical Faults calculation

In this type of faults, the three-phase lines are shorted together to the ground. The magnitude of the fault current in each phase will be the same and displaced by 120^0 from each other.

Because of balanced nature of fault, only one phase need be considered in calculations since condition in the other two phases will also be similar. The following points may be particularly noted:

(i) The symmetrical fault rarely occurs in practice as majority of the faults are of unsymmetrical nature. However, symmetrical fault calculations are being discussed in this chapter to enable the reader to understand the problems that short circuit conditions present to the power system.

(ii) The symmetrical fault is the most severe and imposes more heavy duty on the circuit breaker.

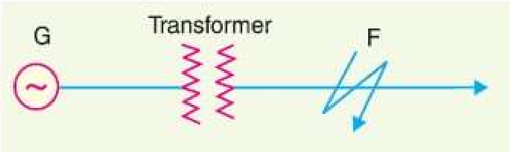


*** Balanced three-phase faults, like balanced 3-φ loads, may be handled on a line-to-neutral basis.**

5- Limitation of Fault Current

When a short circuit occurs at any point in a system, the short-circuit current is limited by the impedance of the system upto the point of fault. Thus referring to Fig. 17.2, if a fault occurs on the feeder at point *F*, then the short circuit current from the generating station will have a value limited by the impedance of generator and transformer and the impedance of the line between the generator and the point of fault. This shows that the knowledge of the impedances of various equipment and circuits in the line of the system is very important for the determination of short-circuit currents.

In many situations, the impedances limiting the fault current are largely reactive, such as transformers, reactors and generators. Cables and lines are mostly resistive, but where the total reactance in calculations exceeds 3 times the resistance, the latter is usually neglected. The error introduced by this assumption will not exceed 5%.



6- Percentage Reactance

The reactance of generators, transformers, reactors *etc*. is usually expressed in ***percentage reactance*** to permit rapid short circuit calculations. The percentage reactance of a circuit is defined as under:

It is the percentage of the total phase-voltage dropped in the circuit when full-load current is flowing i.e.,

$$\% X = (I X / V) \times 100$$

Where I = full-load current
V = phase voltage
X = reactance in ohms per phase

It may be worthwhile to mention here the advantage of using percentage reactance instead of ohmic reactance in short-circuit calculations. Percentage reactance values remain unchanged as they are referred through transformers, unlike ohmic reactances which become multiplied or divided by the square of transformation ratio. This makes the procedure simple and permits quick calculations.

7- Percentage Reactance and Base kVA

It is clear from exp. (*ii*) above that percentage reactance of an equipment depends upon its kVA rating. Generally, the various equipments used in the power system have different kVA ratings. Therefore, it is necessary to find the percentage reactances of all the elements on a common kVA rating. This common kVA rating is known as ***base kVA*.** The value of this base kVA is quite unimportant and may be :

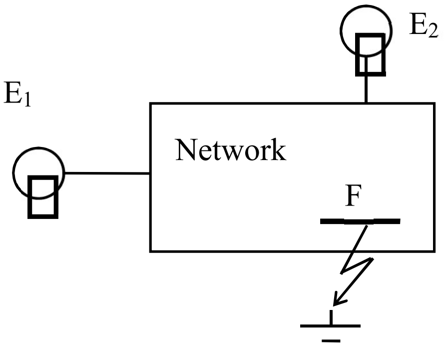
(i) equal to that of the largest plant
(ii) equal to the total plant capacity
(iii) any arbitrary value

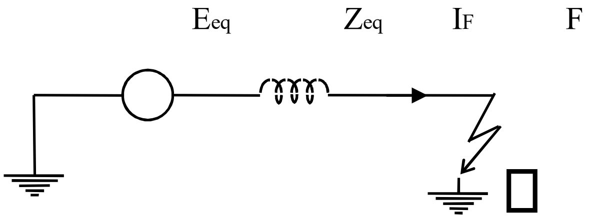
8- Fault Current Calculation

The voltage at the point where fault occurs is considered zero. However, there will be some value for the voltage when fault resistance is taken into account.

The system is considered in a balanced state and per phase analysis is applied. The singleline diagram of a faulty system is shown below.

The idea is to obtain Thevenin's equivalent source and impedance as shown below.





a- Calculation of Fault Current in Amps

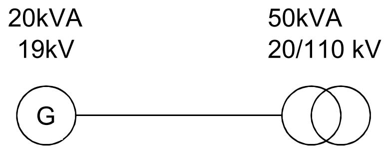
The per unit fault current is calculated using Ohm's Law

$$\mathbf{I_{F\,PU} = E_{PU} / Z_{F\,PU}}$$

The fault per unit impedance $Z_{F\,PU}$ represents the equivalent impedance. The fault current flows through it during the fault. All the resistors and the reactances that Z_F represent must found for the same base apparent power which is the $S_{BASE.}$

Normally, it is assumed that the generators are operated at rated voltages almost equal to the base voltages, i.e. $E_{PU} = V_{PU} \approx 1.0$ pu. Therefore,

Example: $V_{PU} = V_{ACT} / V_{BASE} = 19/20 = 0.95 \approx 1$ pu



$V_{BASE} = 20$kV

Therefore $\mathbf{I_{F\,PU} = 1 / Z_{F\,PU}}$

The base current $I_{BASE} = S_{BASE} / \sqrt{3}\ V_{BASE}$

Therefore the fault current in Amps will be equal to:

$$I_{F\,ACT} = I_{F\,PU} \times I_{BASE} = (1 / Z_{F\,PU}) \times I_{BASE} = I_{BASE} / Z_{F\,PU}$$

$$\mathbf{I_{F\,ACT} = I_{F\,PU} \times I_{BASE} = I_{BASE} / Z_{F\,PU}}$$

b- Fault Level or short circuit Level MVA Calculation

In a power system, the maximum the fault current (or fault MVA) that can flow into a zero impedance fault is necessary to be known for switchgear solution. This can either be the balanced three phase value or the value at an asymmetrical condition. The Fault Level defines the value for the symmetrical condition. The fault level is usually expressed in MVA (or corresponding per-unit value), with the maximum fault current value being converted using the nominal voltage rating.

Fault Level (or Fault level MVA) is defined as

$$\text{Fault Level } MVA_F = \sqrt{3} \times \text{Rated Line Voltage} \times \text{Fault Current}$$

$$\textbf{Fault Level MVA} = \sqrt{3} \times V_{BASE} \times I_F$$

Rated line voltage = base voltage line

- Fault level is the value of the apparent power during the fault. We don't represent it by S_F but we call it fault level or short-circuit level MVA_F
- Since the fault current is high. The fault level takes high value in MVA. That is why it is called also fault level MVA or short-circuit MVA

Another formula is used to find the MVA

We know that the fault current is equal to $I_F = I_{F\,PU} \times I_{BASE} = I_{BASE} / Z_{F\,PU}$

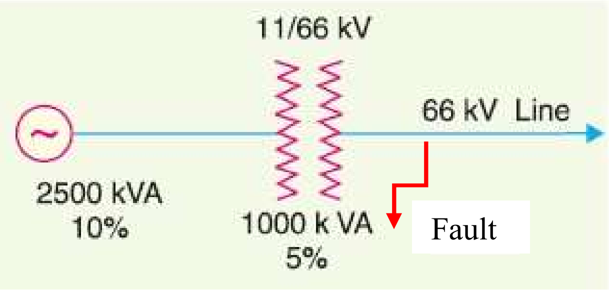
$$\text{Fault Level MVA} = \sqrt{3}\ V_{BASE}\, I_F = \sqrt{3}\ V_{BASE} \times I_{BASE} / Z_{F\,PU} = S_{BASE} / Z_{F\,PU}$$

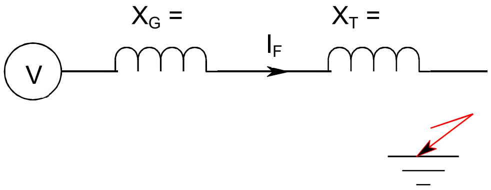
$$\textbf{Fault Level MVA} = S_{BASE} / Z_{F\,PU}$$

In both cases, if you want to find the fault current or fault level in MVA, you need to find first the per unit impedance during the fault $Z_{F\ PU}$ where the fault current flows through from the source to fault point to ground

Example # 1:

Consider a 3-phase transmission line operating at 66 kV and connected through a 1000kVA transformer with 5% reactance to a generating station bus-bar. The generator is of 2500 kVA with 10% reactance. The single line diagram of the system is shown in Figure below. Suppose a short-circuit fault between three phases occurs at the high voltage terminals of transformer. It will be shown that whatever value of base kVA we may choose, the value of short-circuit current will be the same.





(i) Suppose we choose 2500 kVA as the common base kVA.

On this base value, the reactances of the various elements in the system will be:

Reactance of generator at 2500 kVA base

$$\mathbf{X_{NEW} = X_{OLD} \times (S_{NEW} / S_{OLD}) \qquad V_{OLD} = V_{NEW}}$$

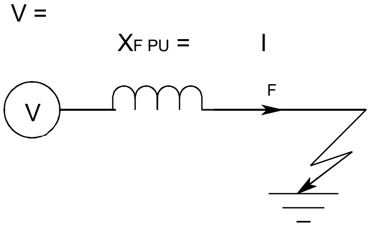
$$X_G = 0.1 \times 2500/2500 = 0.1 \text{ pu}$$

Reactance of transformer at 2500 kVA base:

$$X_T = 0.05 \times 2500 /1000 = 0.125 \text{ pu}$$

Total percentage reactance X_F on the common base kVA

$$X_F = 0.125 + 0.1 = 0.225 \text{ pu}$$



The base current corresponding to 2500 kVA base at 66 kV is given by;

$$I_{BASE} = S_{BASE} / \sqrt{3} \text{ x } V_{BASE} = 2500/ \sqrt{3} \text{ x } 66 = 21{\cdot}87 \text{ A}$$

Short-circuit current I_F,

$$I_{F\ PU} = 1 / X_{F\ PU} = 1 / 0.225 = 4.44 \text{ pu}$$
$$I_F = I_{PU} \times I_{BASE} = 4.44 \text{ x } 21.87 = 97.1\text{A}$$

Or we can directly find I_F (there is no need to calculate I_F in pu)

$$\mathbf{I_F = I_{BASE} / X_{F\ PU}} = 21.87 / 0.225 = 97.01\text{A}$$

(*ii*) **Now, suppose we choose 5000 kVA as the common base value.**

Reactance of generator at 5000 kVA base

$$X_{NEW} = X_{OLD} \text{ x } (S_{NEW} / S_{OLD})$$

$$X_G = 0.1 \times 5000/2500 = 0.20 \text{ pu}$$

Reactance of transformer at 2500 kVA base:

$$X_T = 0.05 \times 5000 /1000 = 0.25 \text{ pu}$$

Total percentage reactance X_F on the common base kVA

$$X_F = 0.2 + 0.25 = 0.45 \text{ pu}$$

The base current corresponding to 2500 kVA base at 66 kV is given by;

$$I_{BASE} = S_{BASE} / \sqrt{3} \text{ x } V_{BASE}$$

$$= 5000/ \sqrt{3} \text{ x } 66 = 43.74 \text{ A}$$

Short-circuit current,

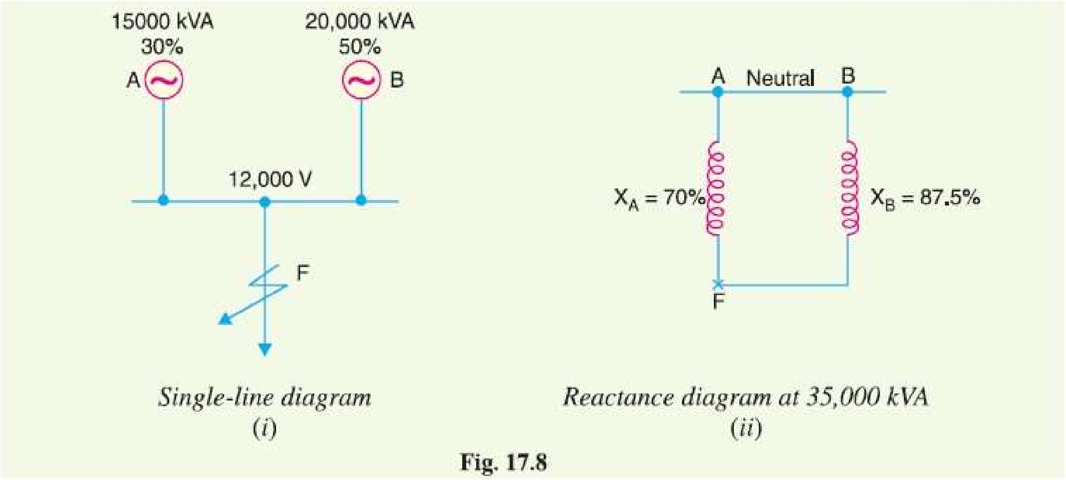
$$I_{F\ PU} = 1 / X_F = 1 / 0.45 = 2.22 \text{ pu}$$
$$I_F = I_{PU} \times I_{BASE} = 2.22 \text{ x } 43.74 = 97.1\text{A}$$

This is the same as in the previous case.

From the above illustration, it is clear that whatever may be the value of base kVA, shortcircuit current is the same. However, in the interest of simplicity, numerically convenient value for the base kVA should be chosen.

Example 17.1. *Fig. 17.8 (i) shows the single line diagram of a 3-phase system. The percentage reactance of each alternator is based on its own capacity. Find the short-circuit current that will flow into a complete 3-phase short-circuit at F.*

Fig. 17.8 (*ii*) shows the reactance* diagram of the network at the selected base kVA.



Single-line diagram
(*i*)

Reactance diagram at 35,000 kVA
(*ii*)

Fig. 17.8

Solution.

Let the base kVA be 35,000 kVA.

Per unit impedance calculation

$$\mathbf{X_{NEW} = X_{OLD} \times (S_{NEW} / S_{OLD})(V_{OLD} / V_{NEW})^2}$$

% Reactance of alternator *A* at the base kVA is $X_A = 0.3 \times (35\,000 / 15000) = 0.7$ pu

% Reactance of alternator B at the base kVA is $X_B = 0.5 \times (35000 / 20\,000) = 0.875$ pu

Total % reactance from generator neutral up to fault point is

$$X_F = X_A \parallel X_B = (X_A \times X_B) / (X_A + X_B) = 0.7 \times 0.875 / (0.7 + 0.875) = 0.388\%$$

Short-circuit current calculation

Base current corresponding to 35000 kVA at 12 kV is

$$I_{BASE} = S_{BASE} / \sqrt{3} \times V_{BASE} = 35\,000 / (\sqrt{3} \times 12) = 1684\text{A}$$

$I_{F\ PU} = (1 / X_{F\ PU}) = 1/0.388 = 2.57$ pu

$$I_F = I_{F\ PU} \times I_{BASE} = 2.577 \times 1684 \approx \mathbf{4340A = 4.34\ kA}$$

Or $I_F = I_{BASE} / X_{PU} = 1684 / 0.388 =$ **4330A**

9- Steps for Symmetrical Fault Calculations

It has already been discussed that 3-phase short-circuit faults result in symmetrical fault currents *i.e.* fault currents in the three phases are equal in magnitude but displaced 120o electrical from one another.

Therefore, problems involving such faults can be solved by considering one phase only as the same conditions prevail in the other two phases. The procedure for the solution of such faults involves the following steps:

1- Draw a single line diagram of the complete network indicating the rating, voltage and percentage reactance of each element of the network.

2- Choose a numerically convenient value of base kVA and convert all percentage reactances to this base value.

3- Find out the voltage base for each part of the system.

Note that the primary and the secondary voltages of the transformer impose the base voltage.

4- Corresponding to the single line diagram of the network, draw the reactance diagram showing one phase of the system and the neutral. Indicate the per unit reactances on the base kVA in the reactance diagram. The transformer in the system should be represented by a reactance in series.

Note that the calculation of the reactance in MVA or kVA base for the line is different than for other elements (X or R line = Actual value / Z base value). Do not use the formula of "change of base).

5- Find the total per unit reactance of the network up to the point of fault. Let it be $X_{F\ PU}$.

Note that if the resistance of the line is not neglected then the we use the equivalent per unit impedance Z = R + jX. Calculate the module of Z to use it to find the fault current.

6- Find the full-load current corresponding to the selected base kVA or MVA and the normal system voltage at the fault point. Let it be *I* base = S base / √3 x V base (*3ϕ)*

7- Fault current calculation:

$$\mathbf{I_F = I_{F\ PU} \times I_{BASE} = I_{BASE} / Z_{F\ PU}}$$

8- Fault Level calculation:

$$\textbf{Fault Level MVA} = \sqrt{3}\, V_{BASE}\, I_F = S_{BASE} / Z_{F\ PU}$$

10- Reactor Control of Short-Circuit Currents

With the fast expanding power system, the fault level (*i.e.* the power available to flow into a fault) is also rising. The circuit breakers connected in the power system must be capable of dealing with maximum possible short-circuit currents that can occur at their points of connection. Generally, the reactance of the system under fault conditions is low and fault currents may rise to a dangerously high value. If no steps are taken to limit the value of these short-circuit currents, not only will the duty required of circuit breakers be excessively heavy, but also damage to lines and other equipment will almost certainly occur. In order to limit the short-circuit currents to a value which the circuit breakers can handle, additional reactances known as *reactors* are connected in series with the system at suitable points. A reactor is a coil of number of turns designed to have a large inductance as compared to its ohmic resistance. The forces on the turns of these reactors under short-circuit conditions are considerable and, therefore, the windings must be solidly braced. It may be added that due to very small resistance of reactors, there is very little change in the efficiency of the system.

a- Advantages

(i) Reactors limit the flow of short-circuit current and thus protect the equipment from overheating as well as from failure due to destructive mechanical forces.

(ii) Troubles are localised or isolated at the point where they originate without communicating their disturbing effects to other parts of the power system. This increases the chances of continuity of supply.

(iii) They permit the installation of circuit breakers of lower rating.

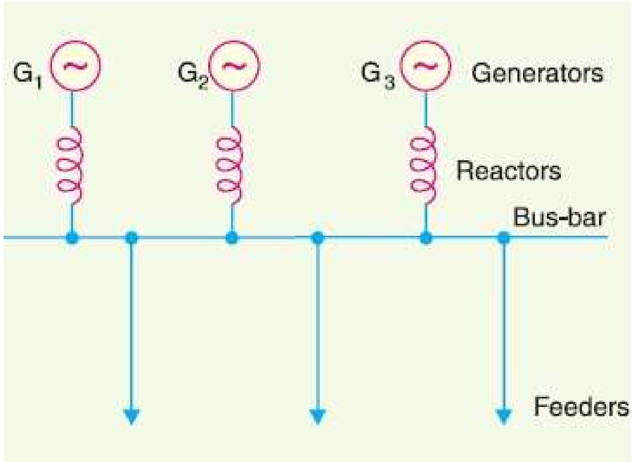
b- Location of Reactors

Short circuit current limiting reactors may be connected

(i) in series with each generator
(ii) in series with each feeder and
(iii) in bus-bars. No definite statement can be given as to which one of the above locations is preferable; each installation has its own particular demands which must be carefully considered before a choice of reactor location can be made.

(1) Generator reactors.

When the reactors are connected in series with each generator, they are known as *generator reactors* (see Fig:) In this case, the reactor may be considered as a part of leakage reactance of the generator ; hence its effect is to protect the generator in the case of any shortcircuit beyond the reactors.



Disadvantages

(i) There is a constant voltage drop and power loss in the reactors even during normal operation.

(ii) If a bus-bar or feeder fault occurs close to the bus-bar, the voltage at the bus-bar will be reduced to a low value, thereby causing the generators to fall out of step.

(iii) If a fault occurs on any feeder, the continuity of supply to other is likely to be affected. Due to these disadvantages and also since modern power station generators have sufficiently large leakage reactance to protect them against short-circuit, it is not a common practice to use separate reactors for the generators.

(2) Feeder reactors.

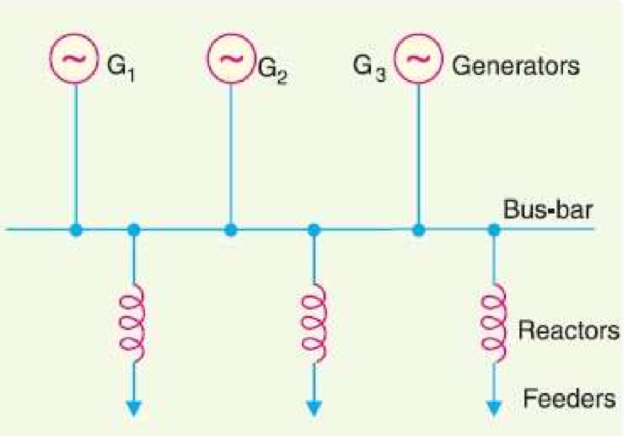
When the reactors are connected in series with each feeder, they are known as *feeder reactors* (see Fig. 17.5). Since most of the short-circuits occur on feeders, a large number of reactors are used for such circuits. Two principal advantages are claimed for feeder reactors. Firstly, if a fault occurs on any feeder, the voltage drop in its reactor will not affect the bus-bars voltage so that there is a little tendency for the generator to lose synchronism. secondly, the fault on a feeder will not affect other feeders and consequently the effects of fault are localised.

Disadvantages

(i) There is a constant power loss and voltage drop in the reactors even during normal operation.

(ii) If a short-circuit occurs at the bus-bars, no protection is provided to the generators. however, this is of little importance because such faults are rare and modern generators have considerable leakage reactance to enable them to withstand short-circuit across their terminals. 2/8/2016

(iii) If the number of generators is increased, the size of feeder reactors will have to be increased to keep the short-circuit currents within the ratings of the feeder circuit breakers.



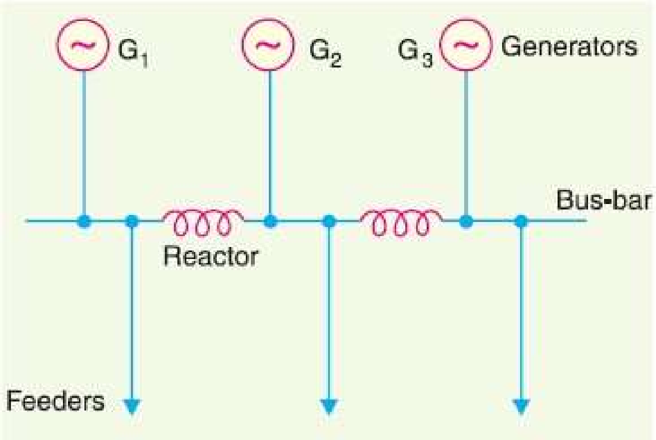
(3) Bus-bar reactors.

The above two methods of locating reactors suffer from the disadvantage that there is considerable voltage drop and power loss in the reactors even during normal operation. This disadvantage can be overcome by locating the reactors in the bus-bars. There are two methods for this purpose, namely ; Ring system and Tie-Bar system.

(i) Ring system.

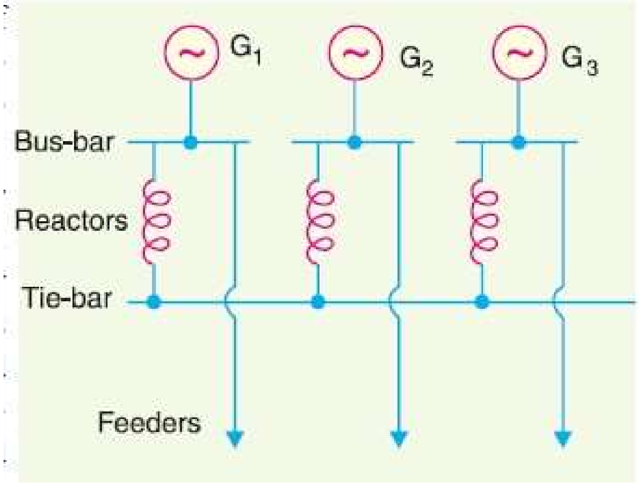
In this system, bus-bar is divided into sections and these sections are connected through reactors as shown in Fig. 17.6. Generally, one feeder is fed from one generator only. Under normal operating conditions, each generator will supply its own section of the load and very little power will be fed by other generators. This results in low power loss and voltage drop in the reactors. However, the principal advantage of the system is that if a fault occurs on any feeder, only one generator (to which the particular feeder is connected) mainly feeds the fault current while the current fed from other generators is small due to the presence of reactors.

Therefore, only that section of bus-bar is affected to which the feeder is connected, the other sections being able to continue in normal operation.



(ii) Tie-Bar system.

Fig. 17.7 shows the tie-bar system. Comparing the ring system with tie-bar system, it is clear that in the tie-bar system, there are effectively two reactors in series between sections so that reactors must have approximately half the reactance of those used in a comparable ring system. Another advantage of tiebar system is that additional generators may be connected to the system without requiring changes in the existing reactors. However, this system has the disadvantage that it requires an additional bus-bar *i.e.* the tie-bar.



Example 17.5. *The section bus-bars A and B are linked by a bus-bar reactor rated at 5000 kVA with 10% reactance. On bus-bar A, there are two generators each of 10,000 kVA with 10% reactance and on B two generators each of 8000 kVA with 12% reactance. Find the steady MVA fed into a dead short circuit between all phases on B with bus-bar reactor in the circuit.*

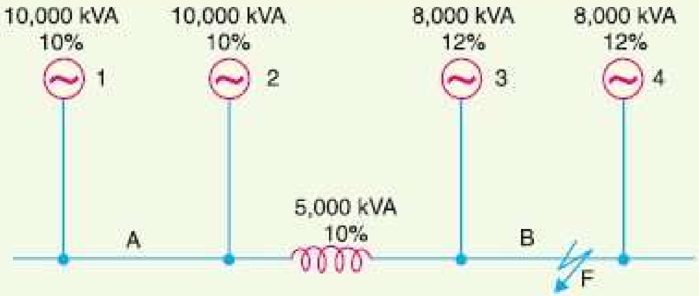


Fig. 17.14

Solution. Fig. 17.14 shows the single line diagram of the network.

Let 10,000 kVA be the base kVA.

% Reactance of generator 1 or 2 on the base kVA

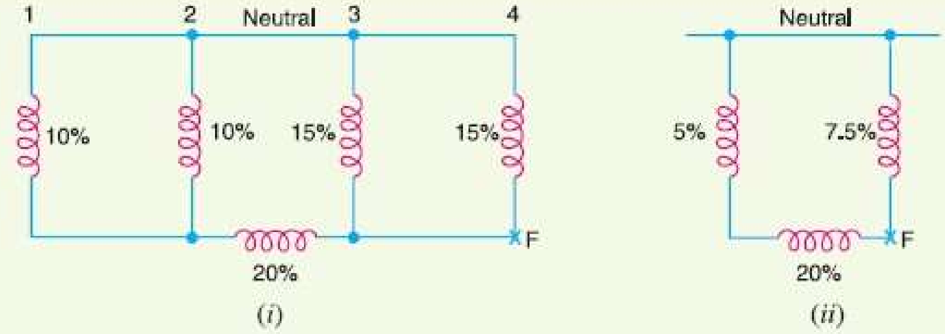
$$= 10 \times 10{,}000/10{,}000 = 10\%$$

% Reactance of generator 3 or 4 on the base kVA

$$= 12 \times 10{,}000/8000 = 15\%$$

% Reactance of bus-bar reactor on the base kVA

$$= 10 \times 10{,}000/5000 = 20\%$$



(*i*) (*ii*)

Fig. 17.15

When fault occurs on section *B* (point *F* in Fig. 17.14), the reactance diagram at the selected base kVA will be as shown in Fig. 17.15 (*i*). This series parallel circuit is further reduced to Fig. 17.15 (*ii*). Referring to Fig. 17.15 (*ii*), it is clear that reactance from generator neutral upto the fault point *F* is (5% + 20%) in parallel with 7·5% *i.e.*

Total % reactance from generator neutral upto fault point *F*

$$= (5\,\% + 20\%) \,||\, 7{\cdot}5\%$$

$$= \frac{25 \times 7\cdot 5}{25 + 7\cdot 5} = 5{\cdot}77\%$$

$$\therefore \quad \text{Fault kVA} = 10{,}000 \times 100/5{\cdot}77 = 1{,}73{,}310$$

$$\text{or} \quad \text{Fault MVA} = \mathbf{173{\cdot}31}$$