2

Faults, types and effects

2.1 The development of simple distribution systems

When a consumer requests electrical power from a supply authority, ideally all that is required is a cable and a transformer, shown physically as in Figure 2.1.

![Figure 2.1](A simple distribution system)

This is called a radial system and can be shown schematically in the following manner (Figure 2.2).

![Figure 2.2](A radial distribution system)

**Advantages**

If a fault occurs at T2 then only the protection on one leg connecting T2 is called into operation to isolate this leg. The other consumers are not affected.
Disadvantages

If the conductor to T2 fails, then supply to this particular consumer is lost completely and cannot be restored until the conductor is replaced/ repaired.
This disadvantage can be overcome by introducing additional/parallel feeders (Figure 2.3) connecting each of the consumers radially. However, this requires more cabling and is not always economical. The fault current also tends to increase due to use of two cables.

![Figure 2.3]
Radial distribution system with parallel feeders

The Ring main system, which is the most favored, then came into being (Figure 2.4). Here each consumer has two feeders but connected in different paths to ensure continuity of power, in case of conductor failure in any section.

![Figure 2.4]
A ring main distribution system

Advantages

Essentially, meets the requirements of two alternative feeds to give 100% continuity of supply, whilst saving in cabling/copper compared to parallel feeders.

Disadvantages

For faults at T1 fault current is fed into fault via two parallel paths effectively reducing the impedance from the source to the fault location, and hence the fault current is much higher compared to a radial path. The fault currents in particular could vary depending on the exact location of the fault.

Protection must therefore be fast and discriminate correctly, so that other consumers are not interrupted.

The above case basically covers feeder failure, since cable tend to be the most vulnerable component in the network. Not only are they likely to be hit by a pick or
alternatively dug-up, or crushed by heavy machinery, but their joints are notoriously weak, being susceptible to moisture, ingress, etc., amongst other things.

Transformer faults are not so frequent, however they do occur as windings are often strained when carrying through-fault current. Also, their insulation lifespan is very often reduced due to temporary or extended overloading leading to eventual failure. Hence interruption or restriction in the power being distributed cannot be avoided in case of transformer failures. As it takes a few months to manufacture a power transformer, it is a normal practice to install two units at a substation with sufficient spare capacity to provide continuity of supply in case of transformer failure.

Busbars on the other hand, are considered to be the most vital component on a distribution system. They form an electrical ‘node’ where many circuits come together, feeding in and sending out power.

On E.H.V. systems where mainly outdoor switchgear is used, it is relatively easy and economical to install duplicate busbar system to provide alternate power paths. But on medium-voltage (11 kV and 6.6 kV) and low-voltage (3.3 kV, 1000 V and 500 V) systems, where indoor metal clad switchgear is extensively used, it is not practical or economical to provide standby or parallel switchboards. Further, duplicate busbar switchgear is not immune to the ravages of a busbar fault.

The loss of a busbar in a network can in fact be a catastrophic situation, and it is recommended that this component be given careful consideration from a protection viewpoint when designing network, particularly for continuous process plants such as mineral processing.

### 2.2 Fault types and their effects

It is not practical to design and build electrical equipment or networks to eliminate the possibility of failure in service. It is therefore an everyday fact that different types of faults occur on electrical systems, however infrequently, and at random locations.

Faults can be broadly classified into two main areas, which have been designated ‘active’ and ‘passive’.

#### 2.2.1 Active faults

The ‘active’ fault is when actual current flows from one phase conductor to another (phase-to-phase), or alternatively from one phase conductor to earth (phase-to-earth). This type of fault can also be further classified into two areas, namely the ‘solid’ fault and the ‘incipient’ fault.

The solid fault occurs as a result of an immediate complete breakdown of insulation as would happen if, say, a pick struck an underground cable, bridging conductors, etc. or the cable was dug up by a bulldozer. In mining, a rockfall could crush a cable, as would a shuttle car. In these circumstances the fault current would be very high resulting in an electrical explosion.

This type of fault must be cleared as quickly as possible, otherwise there will be:

- Increased damage at fault location. Fault energy \( E = I^2 \times R \times t \), where \( t \) is time in seconds.
- Danger to operating personnel (flashes due to high fault energy sustaining for a long time).
- Danger of igniting combustible gas in hazardous areas, such as methane in coal mines which could cause horrendous disaster.
- Increased probability of earth faults spreading to healthy phases.
• Higher mechanical and thermal stressing of all items of plant carrying the fault current, particularly transformers whose windings suffer progressive and cumulative deterioration because of the enormous electromechanical forces caused by multi-phase faults proportional to the square of the fault current.
• Sustained voltage dips resulting in motor (and generator) instability leading to extensive shutdown at the plant concerned and possibly other nearby plants connected to the system.

The ‘incipient’ fault, on the other hand, is a fault that starts as a small thing and gets developed into catastrophic failure. Like for example some partial discharge (excessive discharge activity often referred to as Corona) in a void in the insulation over an extended period can burn away adjacent insulation, eventually spreading further and developing into a ‘solid’ fault.

Other causes can typically be a high-resistance joint or contact, alternatively pollution of insulators causing tracking across their surface. Once tracking occurs, any surrounding air will ionize which then behaves like a solid conductor consequently creating a ‘solid’ fault.

2.2.2 Passive faults

Passive faults are not real faults in the true sense of the word, but are rather conditions that are stressing the system beyond its design capacity, so that ultimately active faults will occur. Typical examples are:

• Overloading leading to over heating of insulation (deteriorating quality, reduced life and ultimate failure).
• Overvoltage: Stressing the insulation beyond its withstand capacities.
• Under frequency: Causing plant to behave incorrectly.
• Power swings: Generators going out-of-step or out-of-synchronism with each other.

It is therefore very necessary to monitor these conditions to protect the system against these conditions.

2.2.3 Types of faults on a three-phase system

Largely, the power distribution is globally a three-phase distribution especially from power sources. The types of faults that can occur on a three-phase AC system are shown in Figure 2.5.

![Figure 2.5](attachment:image.png)

*In underground mining applications only*
It will be noted that for a phase-to-phase fault, the currents will be high, because the fault current is only limited by the inherent (natural) series impedance of the power system up to the point of fault (Ohm’s law).

By design, this inherent series impedance in a power system is purposely chosen to be as low as possible in order to get maximum power transfer to the consumer so that unnecessary losses in the network are limited thereby increasing the distribution efficiency. Hence, the fault current cannot be decreased without a compromise on the distribution efficiency, and further reduction cannot be substantial.

On the other hand, the magnitude of earth fault currents will be determined by the manner in which the system neutral is earthed. It is worth noting at this juncture that it is possible to control the level of earth fault current that can flow by the judicious choice of earthing arrangements for the neutral. Solid neutral earthing means high earth fault currents, being limited by the inherent earth fault (zero sequence) impedance of the system, whereas additional impedance introduced between neutral and earth can result in comparatively lower earth fault currents.

In other words, by the use of resistance or impedance in the neutral of the system, earth fault currents can be engineered to be at whatever level desired and are therefore controllable. This cannot be achieved for phase faults.

### 2.2.4 Transient and permanent faults

Transient faults are faults, which do not damage the insulation permanently and allow the circuit to be safely re-energized after a short period.

A typical example would be an insulator flashover following a lightning strike, which would be successfully cleared on opening of the circuit breaker, which could then be automatically closed. Transient faults occur mainly on outdoor equipment where air is the main insulating medium. Permanent faults, as the name implies, are the result of permanent damage to the insulation. In this case, the equipment has to be repaired and recharging must not be entertained before repair/restoration.

### 2.2.5 Symmetrical and asymmetrical faults

A symmetrical fault is a balanced fault with the sinusoidal waves being equal about their axes, and represents a steady-state condition.

An asymmetrical fault displays a DC offset, transient in nature and decaying to the steady state of the symmetrical fault after a period of time, as shown in Figure 2.6.

![Figure 2.6](image)

*An asymmetrical fault*
The amount of offset depends on the $X/R$ (power factor) of the power system and the first peak can be as high as 2.55 times the steady-state level (see Figure 2.7).
3

Simple calculation of short-circuit currents

3.1 Introduction

Before selecting proper protective devices, it is necessary to determine the likely fault currents that may result in a system under various fault conditions. Depending upon the complexity of the system the calculations could also be too much involved. Accurate fault current calculations are normally carried out using an analysis method called symmetrical components. This method is used by design engineers and practicing protection engineers, as it involves the use of higher mathematics. It is based on the principle that any unbalanced set of vectors can be represented by a set of three balanced quantities, namely: positive, negative and zero sequence vectors.

However, for general practical purposes for operators, electricians and men-in-the-field it is possible to achieve a good approximation of three-phase short-circuit currents using some very simple methods, which are discussed below. These simple methods are used to decide the equipment short-circuit ratings and relay setting calculations in standard power distribution systems, which normally have limited power sources and interconnections. Even a complex system can be grouped into convenient parts, and calculations can be made groupwise depending upon the location of the fault.

3.2 Revision of basic formulae

It is interesting to note that nearly all problems in electrical networks can be understood by the application of its most fundamental law viz., Ohm’s law, which stipulates,

For DC systems

\[ I = \frac{V}{R} \quad \text{i.e. Current} = \frac{\text{Voltage}}{\text{Resistance}} \]

For AC systems

\[ I = \frac{V}{Z} \quad \text{i.e. Current} = \frac{\text{Voltage}}{\text{Impedance}} \]
3.2.1 Vectors

Vectors are a most useful tool in electrical engineering and are necessary for analyzing AC system components like voltage, current and power, which tends to vary in line with the variation in the system voltage being generated.

The vectors are instantaneous ‘snapshots’ of an AC sinusoidal wave, represented by a straight line and a direction. A sine wave starts from zero value at 0°, reaches its peak value at 90°, goes negative after 180° and again reaches back zero at 360°. Straight lines and relative angle positions, which are termed vectors, represent these values and positions. For a typical sine wave, the vector line will be horizontal at 0° of the reference point and will be vertical upwards at 90° and so on and again comes back to the horizontal position at 360° or at the start of the next cycle. Figure 3.1 gives one way of representing the vectors in a typical cycle.

![Figure 3.1](image1)

*Figure 3.1: Vectors and an AC wave*

In an AC system, it is quite common to come across many voltages and currents depending on the number of sources and circuit connections. These are represented in form of vectors in relation to one another taking a common reference base. Then these can be added or subtracted depending on the nature of the circuits to find the resultant and provide a most convenient and simple way to analyze and solve problems, rather than having to draw numerous sinusoidal waves at different phase displacements.

3.2.2 Impedance

This is the AC equivalent of resistance in a DC system, and takes into account the additional effects of reactance. It is represented by the symbol $Z$ and is the vector sum of resistance and reactance (see Figure 3.2).

![Figure 3.2](image2)

*Figure 3.2: Impedance relationship diagram*

It is calculated by the formula:

$$Z = R + jX$$

Where $R$ is resistance and $X$ is reactance.
It is to be noted that $X$ is positive for inductive circuits whereas it is negative in capacitive circuits. That means that the $Z$ and $X$ will be the mirror image with $R$ as the base in the above diagram.

### 3.2.3 Reactance

Reactance is a phenomenon in AC systems brought about by inductance and capacitance effects of a system. Energy is required to overcome these components as they react to the source and effectively reduce the useful power available to a system. The energy, which is spent to overcome these components in a system is thus not available for use by the end user and is termed ‘useless’ energy though it still has to be generated by the source.

Inductance is represented by the symbol $L$ and is a result of magnetic coupling which induces a back emf opposing that which is causing it. This ‘back-pressure’ has to be overcome and the energy expended is thus not available for use by the end user and is termed ‘useless’ energy, as it still has to be generated. $L$ is normally measured in Henries.

The inductive reactance is represented using the formula:

$$\text{Inductive reactance} = 2\pi f L$$

Capacitance is the electrostatic charge required when energizing the system. It is represented by the symbol $C$ and is measured in farads.

To convert this to ohms,

$$\text{Capacitive reactance} = \frac{1}{2\pi f C}$$

Where

- $f =$ supply frequency,
- $L =$ system inductance and $C =$ system capacitance.

Inductive reactance and capacitive reactance oppose each other vectorially; so to find the net reactance in a system, they must be arithmetically subtracted.

For example, in a system having resistance $R$, inductance $L$ and capacitance $C$, its impedance

$$Z = R + (j \times 2\pi f L) - \left(\frac{j}{2\pi f C}\right)$$

When a voltage is applied to a system, which has an impedance of $Z$, vectorally the voltage is in phase with $Z$ as per the above impedance diagram and the current is in phase with the resistive component. Accordingly, the current is said to be leading the voltage vector in a capacitive circuit and is said to be lagging the voltage vector in an inductive circuit.

### 3.2.4 Power and power factor

In a DC system, power dissipated in a system is the product of volts $\times$ amps and is measured in watts.

$$P = V \times I$$

For AC systems, the power input is measured in volt amperes, due to the effect of reactance and the useful power is measured in watts. For a single-phase AC system, the VA is the direct multiplication of volt and amperes, whereas it is necessary to introduce
a $\sqrt{3}$ factor for a three-phase AC system. Hence VA power for the standard three-phase system is:

$$VA = \sqrt{3} \times V \times I$$

Alternatively;

$$kVA = \sqrt{3} \times V \times I$$

Where

$V$ is in kV
$I$ is in amps, or

$$MVA = \sqrt{3} \times V \times I$$

Where

$V$ is in kV and
$I$ is in kA.

Therefore,

$$I_{amps} = \frac{kVA}{\sqrt{3} \times kV} \quad \text{or} \quad I_{kA} = \frac{MVA}{\sqrt{3} \times kV}$$

From the impedance triangle below, it will be seen that the voltage will be in phase with $Z$, whereas the current will be in phase with resistance $R$ (see Figure 3.3).

![Impedance triangle](image)

**Figure 3.3**

*Impedance triangle*

The cosine of the angle between the two is known as the power factor.

**Examples:**

When angle $= 0^\circ$; cosine $0^\circ = 1$ (unity)
When angle $= 90^\circ$; cosine $90^\circ = 0$.

The useful kW power in a three-phase system taking into account the system reactive component is obtained by introducing the power factor $\cos \phi$ as below:

$$P = \sqrt{3} \times V \times I \times \cos \phi = kVA \times \cos \phi$$

It can be noted that kW will be maximum when $\cos \phi = 1$ and will be zero when $\cos \phi = 0$. It means that the useful power is zero when $\cos \phi = 0$ and will tend to increase as the angle increases. Alternatively it can be interpreted, the more the power factor the more would be the useful power.

Put in another way, it is the factor applied to determine how much of the input power is effectively used in the system or simply it is a measure of the efficiency of the system. The ‘reactive power’ or the so called ‘useless power’ is calculated using the formula

$$p' = \sqrt{3} \times V \times I \times \sin \phi = kVA \times \sin \phi$$
In a power system, the energy meters normally record the useful power kW, which is directly used in the system and the consumer is charged based on total kW consumed over a period of time (KWH) and the maximum demand required over a period of time. However, the $P'$ or the kVAR determines the kVA to be supplied by the source to meet the consumer load after overcoming the reactive components, which will vary depending on the power factor of the system. Hence, it is a usual practice to charge penalties to a consumer whenever the consumer’s system has lesser power factor, since it gives the idea of useless power to be generated by the source.

Obviously, if one can reduce the amount of ‘useless’ power, power that is more ‘useful’ will be available to the consumer, so it pays to improve the power factor wherever possible. As most loads are inductive in nature, adding shunt capacitance can reduce the inductive reactance as the capacitive reactance opposes the inductive reactance of the load.

3.3 Calculation of short-circuit MVA

We have studied various types and effects of faults that can occur on the system in the earlier chapter. It is important that we know how to calculate the level of fault current that will flow under these conditions, so that we can choose equipment to withstand these faults and isolate the faulty locations without major damages to the system.

In any distribution the power source is a generator and it is a common practice to use transformers to distribute the power at the required voltages. A fault can occur immediately after the generator or after a transformer and depending upon the location of fault, the fault current could vary. In the first case, only the source impedance limits the fault current whereas in the second case the transformer impedance is an important factor that decides the fault current.

Generally, the worst type of fault that can occur is the three-phase fault, where the fault currents are the highest. If we can calculate this current then we can ensure that all equipment can withstand (carry) and in the case of switchgear, interrupt this current. There are simple methods to determine short-circuit MVA taking into account some assumptions.

Consider the following system. Here the source generates a voltage with a phase voltage of $E_p$ and the fault point is fed through a transformer, which has a reactance $X_p$ (see Figure 3.4).

![Figure 3.4](image)

Figure 3.4
Short-circuit MVA calculation

Let $I_s$ = r.m.s. short-circuit current

$I$ = Normal full load current

$P$ = Transformer rated power (rated MVA)

$X_p$ = Reactance per phase

$E_p$ = System voltage per phase.

At the time of fault, the fault current is limited by the reactance of the transformer after neglecting the impedances due to cables up to the fault point. Then from Ohm’s law:

$$I_s = \frac{E_p}{X_p}$$
Now,

\[
\text{Short-circuit MVA} = \frac{\sqrt{3}E_p I_s \times 10^6}{\sqrt{3}E_p I \times 10^6} = \frac{E_p}{X_p} \times \frac{X_p \times 100}{E_p}\times \frac{X_p \times 100}{I_p \times E_p} = 100
\]

Multiplying top and bottom by \(X_p/E_p\times 100\)

\[
\left(\frac{E_p}{X_p} \times \frac{X_p}{E_p}\times \frac{X_p \times 100}{E_p}\times \frac{X_p \times 100}{I_p \times E_p}\right) = 100
\]

But,

\[
\frac{IX_p}{E_p} \times 100 = X\% \text{ Reactance per phase}
\]

Therefore,

\[
\text{Short-circuit MVA} = \frac{I_p}{I} = \frac{100}{X}\%
\]

Hence,

\[
\text{Short-circuit MVA} = \frac{100 P}{X}\%
\]

It can be noted above, that the value of \(X\) will decide the short-circuit MVA when the fault is after the transformer. Though it may look that increasing the impedance can lower the fault MVA, it is not economical to choose higher impedance for a transformer. Typical percent reactance values for transformers are shown in the table below.

<table>
<thead>
<tr>
<th>MVA Rating</th>
<th>Up to 11 kV</th>
<th>22 kV</th>
<th>33 kV</th>
<th>66 kV</th>
<th>132 kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.25</td>
<td>3.5</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
<td>6.5</td>
</tr>
<tr>
<td>0.5</td>
<td>4.0</td>
<td>4.5</td>
<td>5.0</td>
<td>5.5</td>
<td>6.5</td>
</tr>
<tr>
<td>1.0</td>
<td>5.0</td>
<td>5.5</td>
<td>5.5</td>
<td>6.0</td>
<td>7.0</td>
</tr>
<tr>
<td>2.0</td>
<td>5.5</td>
<td>6.0</td>
<td>6.0</td>
<td>6.5</td>
<td>7.5</td>
</tr>
<tr>
<td>3.0</td>
<td>6.5</td>
<td>6.5</td>
<td>6.5</td>
<td>7.0</td>
<td>8.0</td>
</tr>
<tr>
<td>5.0</td>
<td>7.5</td>
<td>7.5</td>
<td>7.5</td>
<td>8.0</td>
<td>8.5</td>
</tr>
<tr>
<td>10.0 &amp; above</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

It may be noted that these are only typical values and it is always possible to design transformer with different impedances. However, for design purposes it is customary to consider these standard values to design upstream and downstream protective equipment.

In an electrical circuit, the impedance limits the flow of current and Ohm’s law gives the actual current. Alternatively, the voltage divided by current gives the impedance of the system. In a three-phase system which generates a phase voltage of \(E_p\) and where the phase current is \(I_p\),

\[
\text{Impedance in ohms} = \frac{E_p}{1.732 \times I_p}
\]
The above forms the basis to decide the fault current that may flow in a system where the fault current is due to phase-to-phase or phase-to-ground short. In such cases, the internal impedances of the equipment rather than the external load impedances decide the fault currents.

**Example:**
For the circuit shown below calculate the short-circuit MVA on the LV side of the transformer to determine the breaking capacity of the switchgear to be installed (see Figure 3.5).

![Figure 3.5](image)

**Short-circuit MVA example**

**Answer:**

\[
\text{Short-circuit MVA} = \frac{100P}{X\%} = \frac{100 \times 10}{10} = 100 \text{ MVA}
\]

Therefore,

\[
\text{Fault current} = \frac{100}{\sqrt{3} \times 11} = 5.248 \text{ kA}
\]

and

\[
\text{Source impedance} = \frac{11}{\sqrt{3} \times 5.248} = 1.21 \Omega
\]

Calculate the fault current downstream after a particular distance from the transformer with the impedance of the line/cable being 1 Ω (see Figure 3.6).

![Figure 3.6](image)

**Calculation of fault current at end of cable**

\[
\text{Fault current} = \frac{11}{\sqrt{3} \times (1.21 + 1)} = 2.874 \text{ kA}
\]

It should be noted that, in the above examples, a few assumptions are made to simplify the calculations. These assumptions are the following:

- Assume the fault occurs very close to the switchgear. This means that the cable impedance between the switchgear and the fault may be ignored.
- Ignore any arc resistance.
- Ignore the cable impedance between the transformer secondary and the switchgear, if the transformer is located in the vicinity of the substation. If not,
the cable impedance may reduce the possible fault current quite substantially, and should be included for economic considerations (a lower-rated switchgear panel, at lower-cost, may be installed).

- When adding cable impedance, assume the phase angle between the cable impedance and transformer reactance are zero, hence the values may be added without complex algebra, and values readily available from cable manufacturers’ tables may be used.
- Ignore complex algebra when calculating and using transformer internal impedance.
- Ignore the effect of source impedance (from generators or utility).

These assumptions are quite allowable when calculating fault currents for protection settings or switchgear ratings. When these assumptions are not made, the calculations become very complex and computer simulation software should be used for exact answers. However, the answers obtained with making the above assumptions are found to be usually within 5% correct.

### 3.4 Useful formulae

Following are the methods adopted to calculate fault currents in a power system.

- **Ohmic method**: All the impedances are expressed in Ω.
- **Percentage impedance methods**: The impedances are expressed in percentage with respect to a base MVA.
- **Per unit method**: Is similar to the percentage impedance method except that the percentages are converted to equivalent decimals and again expressed to a common base MVA. For example, 10% impedance on 1 MVA is expressed as 0.1 pu on the same base.

### 3.4.1 Ohmic reactance method

In this method, all the reactance’s components are expressed in actual ohms and then it is the application of the basic formula to decide fault current at any location. It is known that when fault current flows it is limited by the impedance to the point of fault. The source can be a generator in a generating station whereas transformers in a switching station receive power from a remote station. In any case, to calculate source impedance at HV in Ω:

$$\text{Source } Z\Omega = \frac{kV}{\sqrt{3} \times \text{HV fault current}}$$

Transformer impedance is expressed in terms of percent impedance voltage and is defined as the percentage of rated voltage to be applied on the primary of a transformer for driving a full load secondary current with its secondary terminals shorted. Hence, this impedance voltage forms the main factor to decide the phase-to-phase or any other fault currents on the secondary side of a transformer (see Figure 3.7).

![Figure 3.7](image)

*Calculation of total impedance and fault currents*
To convert transformer impedance in Ω:

$$\text{Transformer } Z \Omega = \frac{Z\% \times \text{kV}}{\text{kA}}$$

Where
kV is the rated voltage and
kA is the rated current.

Multiplying by kV on both numerator and denominator, we get:

$$\text{Transformer } Z \text{ in } \Omega = \frac{Z \times \text{kV}^2}{100 \times \text{MVA}}$$

Where Z is expressed in percentage impedance value.

In a case consisting of a generator source and a transformer, total impedance at HV including transformer:

$$\text{Total } Z \Omega \text{ HV} = \text{Source } Z \Omega + \text{Transformer } Z \Omega$$

To convert Z Ω from HV to LV:

$$Z \Omega \text{ HV } L V = \frac{\text{Total } Z \Omega \text{ HV } L V^2}{\text{HV}^2}$$

To calculate LV fault current:

$$\text{LV fault current} = \frac{L V}{\sqrt{3} \times Z \Omega \text{ } L V}$$

*Note:* All voltages to be expressed in kV.

*Example:*
In the following circuit calculate:

(a) Total impedance in Ω at 1000 V
(b) Fault current at 1000 V.

\[ Z \Omega \text{ source } = \frac{11}{1.732 \times 2.5} = 2.54 \text{ Ω} \]

\[ Z \Omega \text{ transformer } = \frac{5.5 \times 11^2}{100 \times 1.25} = 5.324 \text{ Ω} \]

\[ Z \Omega \text{ total } = 2.54 + 5.324 = 7.864 \text{ Ω} \]

\[ Z \Omega \text{ total at 1000 V } = \frac{7.864 \times 1^2}{11^2} = 0.065 \text{ Ω} \]

Fault current at 1000 V
\[ \frac{1}{1.732 \times 0.065} = 8.883 \text{ kA} \]

### 3.4.2 Other formulae in ohmic reactance method

In predominantly inductive circuits, it is usual to neglect the effect of resistant components, and consider only the inductive reactance \( X \) and replace the value of \( Z \) by \( X \).
to calculate the fault currents. Following are the other formulae, which are used in the ohmic reactance method. (These are obtained by multiplying numerators and denominators of the basic formula with same factors.)

1. Fault value MVA = \( \frac{E^2}{X} \)

2. \( X = \frac{E^2}{\text{Fault value in MVA}} \)

3. \( X \text{ at 'B' kV} = \frac{(X \text{ at 'A' kV}) B^2}{A^2} \)

### 3.4.3 Percentage reactance method

In this method, the reactance values are expressed in terms of a common base MVA. Values at other MVA and voltages are also converted to the same base, so that all values can be expressed in a common unit. Then it is the simple circuit analysis to calculate the fault current in a system. It can be noted that these are also extensions of basic formulae.

#### Formulae for percentage reactance method

4. Fault value in MVA = \( \frac{100 \text{ (MVA rating)}}{X \%} \)

5. \( X \% = \frac{100 \text{ (MVA rating)}}{\text{Fault value in MVA}} \)

6. \( X \% \text{ at 'N' MVA} = \frac{N \text{ (X \% at rated MVA)}}{\text{rated MVA}} \)

For ease of mathematics, the base MVA of N may be taken as 100 MVA, so the formula would now read:

\[
X \% \text{ at 100 MVA} = \frac{100 \text{ (X \% at rated MVA)}}{\text{rated MVA}}
\]

However, the base MVA can be chosen as any convenient value depending upon the MVA of equipment used in a system.

Also, \( X \% \text{ at 'B' kV} = \frac{(X \% \text{ at 'A' kV}) B^2}{A^2} \)

To calculate the fault current in the earlier example using percentage reactance method:

\[ 11 \text{ kV} \begin{array}{c} 1250 \text{kVA} \\ Z = 5.5\% \end{array} \quad 722 \text{ A} \quad 1000 \text{ V} \]

\[ I_f = 2.5 \text{ kA} \]
Fault MVA at the source = $1.732 \times 11 \times 2.5 = 47.63$ MVA. Take the transformer MVA (1.25) as the base MVA. Then source impedance at base MVA

$$\frac{1.25 \times 100}{47.63} = 2.624\% \text{ (using (5))}$$

Transformer impedance = 5.5% at 1.25 MVA. Total percentage impedance to the fault = 2.624 + 5.5 = 8.124%. Hence fault MVA after the transformer = $(1.25 \times 100)/8.124 = 15.386$ MVA. Accordingly fault current at 1 kV = $15.386/(1.732 \times 1) = 8.883$ kA. It can be noted that the end answers are the same in both the methods.

Formulae correlating percentage and ohmic reactance values

7. $X\% = \frac{100 \times \text{MVA rating}}{E^2}$

8. $X = \frac{X\% \times E^2}{100 \times \text{(MVA rating)}}$

### 3.4.4 Per unit method

This method is almost same as the percentage reactance method except that the impedance values are expressed as a fraction of the reference value.

Per unit impedance = \frac{\text{Actual impedance in ohms}}{\text{Base impedance in ohms}}

Initially the base kV ($kV_b$) and rated kVA or MVA ($kVA_b$ or $MVA_b$) are chosen in a system. Then,

Base current $I_b = \frac{\text{Base kVA}}{1.732 \times \text{Base kV}}$

Base impedance $Z_b = \frac{\text{Base V}}{1.732 \times \text{Base A}} = \frac{kV_b + 1000}{1.732 \times I_b}$

Multiplying by kV at top and bottom

$$= \frac{kV_b^2 \times 1000}{kVA_b}$$

Per unit impedance of a source having short-circuit capacity of $kVA_{sc}$ is:

$$Z_{pu} = \frac{kVA_b}{kVA_{sc}}$$

Calculate the fault current for the same example using pu method.
Here base kVA is chosen again as 1.25 MVA.
Source short-circuit MVA = 1.732 \times 11 \times 2.5 = 47.63 \text{ MVA}

Source impedance = \frac{1.25}{47.63} = 0.02624 \text{ pu}

Transformer impedance = 0.055 \text{ pu}

Impedance to transformer secondary = 0.02624 + 0.055 = 0.08124 \text{ pu}

Hence short-circuit current at 1 \text{ kV} = \frac{1250}{1.732 \times 1 \times 0.08124} = 8.883 \text{ kA}

Depending upon the complexity of the system, any method can be used to calculate the fault currents.

**General formulae**

It is quite common that the interconnections in any distribution system can be converted or shown in the combination of series and parallel circuits. Then it would be necessary to calculate the effective impedance at the point of fault by combining the series and parallel circuits using the following well-known formulae. The only care to be taken is that all the values should be in same units and should be referred to the same base.

**Series circuits:**

9. \( X_1 = X_1 + X_2 + X_3 + \cdots X_n \) where all values of \( X \) are either:

(a) \( X \% \) at the same MVA base; or

(b) \( X \) at the same voltage.

**Parallel circuits:**

10. \( \frac{1}{X_1} = \frac{1}{X_1} + \frac{1}{X_2} + \frac{1}{X_3} + \cdots + \frac{1}{X_n} \)

**3.5 Cable information**

Though cable impedances have been neglected in the above cases, to arrive at more accurate results, it may be necessary to consider cable impedances in some cases, especially where long distance of transmission lines and cables are involved. Further the cables selected in a distribution system should be capable of withstanding the short-circuit currents expected until the fault is isolated/fault current is arrested.

Cables are selected for their sustained current rating so that they can thermally withstand the heat generated by the current under healthy operating conditions and at the same time, it is necessary that the cables also withstand the thermal heat generated during short-circuit conditions.

The following table will assist in cable selection, which also states the approximate impedance in \( \Omega/\text{km} \). Current rating and voltage drop of 3 and 4 core PVC insulated cables with stranded copper conductors. Fault current ratings for cables are given in the manufacturers’ specifications and tables, and must be modified by taking into account the fault duration.
### Sustained Current Rating

<table>
<thead>
<tr>
<th>Rated Area (mm²)</th>
<th>Z Approx. (Ω/km)</th>
<th>Ground</th>
<th>Duct</th>
<th>Air</th>
<th>Voltage Drop per Amp. Meter mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5</td>
<td>13.41</td>
<td>23</td>
<td>19</td>
<td>22</td>
<td>23.2</td>
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<tr>
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<td>8.67</td>
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<td>6.0</td>
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<td>51</td>
<td>5.79</td>
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<tr>
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<td>67</td>
<td>55</td>
<td>68</td>
<td>3.46</td>
</tr>
<tr>
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<td>1.253</td>
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<td>72</td>
<td>91</td>
<td>2.17</td>
</tr>
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<td>119</td>
<td>95</td>
<td>115</td>
<td>1.40</td>
</tr>
<tr>
<td>35.0</td>
<td>0.578</td>
<td>140</td>
<td>114</td>
<td>145</td>
<td>1.00</td>
</tr>
<tr>
<td>50.0</td>
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<td>135</td>
<td>180</td>
<td>0.71</td>
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<tr>
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<td>670</td>
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</tbody>
</table>

**Example:**

Reference to Table 3.1 shows that, a 70 mm² copper cable can withstand a short-circuit current of 8.05 kA for 1 s. However, the duration of the fault or the time taken by the protective device to operate has to be considered. This device would usually operate well within 1 s, the actual time being read from the curves showing short-circuit current/tripping time relationships supplied by the protective equipment manufacturer. Suppose the fault is cleared after 0.2 s. We need to determine what short-circuit current the cable can withstand for this time. This can be found from the expression:

\[ I_{sc} = \frac{A \times K}{\sqrt{t}} \]

Where

- \( K = 115 \) for PVC/copper cables of 1000 V rating
- \( K = 143 \) for XLPE/copper cables of 1000 V rating
- \( K = 76 \) for PVC/aluminum (solid or stranded) cables of 1000 V rating
- \( K = 92 \) for XLPE/aluminum (solid or stranded) cables of 1000 V rating.

And where

- \( A \) = the conductor cross-sectional area in mm²
- \( t \) = the duration of the fault in seconds.
So in our example:

\[ I_{SC} = \frac{70 \times 115}{\sqrt{0.2}} = 18 \text{ kA (for 0.2 s)} \]

Cable bursting is not normally a real threat in the majority of cases where armored cable is used since the armoring gives a measure of reinforcement. However, with larger sizes, in excess of 300 mm\(^2\), particularly when these cables are unarmored, cognizance should be taken of possible bursting effects.

When the short-circuit current rating for a certain time is known, the formula \( E = I^2 t \) can also be used to obtain the current rating for a different time. In the above example:

\[ I_1^2 t_1 = I_2^2 t_2 \]

\[ \Rightarrow I_2 = \frac{\sqrt{I_1^2 t_1}}{t_2} \]

\[ I_2 = \frac{\sqrt{(8.05^2 \times 1)}}{0.2} = 18 \text{ kA} \]

Naturally, if the fault is cleared in more than 1 s, the above formula’s can also be used to determine what fault current the cable can withstand for this extended period.

\textit{Note:} In electrical protection, engineers usually cater for failure of the primary protective device by providing back-up protection. It makes for good engineering practice to use the tripping time of the back-up device, which should only be slightly longer than that of the primary device in short-circuit conditions, to determine the short-circuit rating of the cable. This then has a built-in safety margin.
### 3.6 Copper conductors

#### Electrical Properties

<table>
<thead>
<tr>
<th>Cable Size (mm²)</th>
<th>Ground (A)</th>
<th>Ducts (A)</th>
<th>Air (A)</th>
<th>Impedance (Ω/km)</th>
<th>Volt Drop (mV/A/m)</th>
<th>1 s Short-Circuit Rating (kA)</th>
<th>DI–3c (mm)</th>
<th>DI–4c (mm)</th>
<th>d–3c (mm)</th>
<th>d–4c (mm)</th>
<th>D2–3c (mm)</th>
<th>D2–4c (mm)</th>
<th>3c (kg/km)</th>
<th>4c (kg/km)</th>
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<tbody>
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<td>18</td>
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</table>

*Table 3.1*

Electrical and physical properties of 3- and 4-core PVC-insulated PVC-bedded SWA PVC-sheathed 600/1000 V cables