Three-phase short-circuit current (Isc) calculation at any point within a LV installation using impedance method

Calculation of Isc by the impedance method

In a 3-phase installation Isc at any point is given by:

\[ Isc = \frac{V_{20}}{\sqrt{3} Z_T} \]

where

\( V_{20} \) (line-to-line voltage) corresponds to the transformer no-load voltage which is 3 to 5% greater than the on-load voltage across the terminals. For example, in 400 V networks, the line-to-line voltage adopted is \( V = 420 \) V and the line-to-neutral voltage is \( V/\sqrt{3} = 242.5 \) V.

Or
\( V_{20} = \) line-to-line voltage of the open circuited secondary windings of the power supply transformer(s).

\( Z_T = \) total impedance per phase of the installation upstream of the fault location (in \( \Omega \))

Method of calculating \( Z_T \)

- Each component of an installation (MV network, transformer, cable, circuit-breaker, bus bar, and so on...) is characterized by its impedance \( Z \), comprising an element of resistance (\( R \)) and an inductive reactance (\( X \)).
- It may be noted that capacitive reactances are not important in short-circuit current calculations.
- The parameters \( R \), \( X \) and \( Z \) are expressed in ohms, and are related by the sides of a right angled triangle, as shown in the impedance diagram of Figure 1.

Fig.1 Impedance diagram
The method consists in dividing the network into convenient sections, and to calculate the R and X values for each. Where sections are connected in series in the network, all the resistive elements in the section are added arithmetically; likewise for the reactances, to give $R_T$ and $X_T$. The impedance ($Z_T$) for the combined sections concerned is then calculated from:

$$Z_T = \sqrt{R_T^2 + X_T^2}$$

Any two sections of the network which are connected in parallel, can, if predominantly both resistive (or both inductive) be combined to give a single equivalent resistance (or reactance) as follows:

Let $R_1$ and $R_2$ be the two resistances connected in parallel, then the equivalent resistance $R_3$ will be given by:

$$R_3 = \frac{R_1 \times R_2}{R_1 + R_2}$$

or for reactances

$$X_3 = \frac{X_1 \times X_2}{X_1 + X_2}$$

It should be noted that the calculation of $X_3$ concerns only separated circuit without mutual inductance. If the circuits in parallel are close together the value of $X_3$ will be higher.

### Determination of the impedance of each component

#### 1- Network upstream of the MV/LV transformer

The 3-phase short-circuit fault level $P_{SC}$, in kA or in MVA$^{(i)}$, is given by the power supply authority concerned, from which an equivalent impedance can be deduced.

A formula which makes this deduction and at the same time converts the impedance to an equivalent value at LV is given, as follows:

$$Z_s = \frac{V_o^2}{P_{SC}}$$

where

- $Z_s$ = impedance of the MV voltage network, expressed in milli-ohms
- $V_o$ = line-to-line no-load LV voltage, expressed in volts
- $P_{SC}$ = MV 3-phase short-circuit fault level, expressed in kVA

- The upstream medium voltage (MV) side resistance $R_a$ is generally found to be negligible compared with the corresponding $X_a$, the latter then being taken as the ohmic value for $Z_a$. If more accurate calculations are
necessary, $X_a$ may be taken to be equal to 0.995 $Z_a$ and $R_a$ equal to 0.1 $X_a$.

- **Table-1** gives values for $R_a$ and $X_a$ corresponding to the most common MV$^{(ii)}$ short-circuit levels in utility power-supply networks, namely, 250 MVA and 500 MVA.

(i) Short-circuit MVA: $\sqrt{3} E_L \, I_{sc}$
where:

- $E_L = \text{line-to-line nominal system voltage expressed in kV (r.m.s.)}$
- $I_{sc} = \text{3-phase short-circuit current expressed in kA (r.m.s.)}$

(ii) up to 36 kV

*Table-1 The impedance of the MV network referred to the LV side of the MV/LV transformer.*

<table>
<thead>
<tr>
<th>$P_{sc}$</th>
<th>$V_o$ (V)</th>
<th>$R_a$ (mΩ)</th>
<th>$X_a$ (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250 MVA</td>
<td>420</td>
<td>0.07</td>
<td>0.7</td>
</tr>
<tr>
<td>500 MVA</td>
<td>420</td>
<td>0.035</td>
<td>0.351</td>
</tr>
</tbody>
</table>

2- The Transformer (see Table-2)

The impedance $Z_{tr}$ of a transformer, viewed from the LV terminals, is given by the formula:

$$Z_{tr} = \frac{V_{20}^2}{P_n} \times \frac{V_{sc}}{100}$$

$V_{20} = \text{open-circuit secondary line-to-line voltage expressed in volts.}$
$P_n = \text{rating of the transformer (in kVA).}$
$V_{sc} = \text{the short-circuit impedance voltage of the transformer expressed in \%}.$

The transformer windings resistance $R_{tr}$ can be derived from the total losses as follows:

$$R_{tr} = \frac{P_{cu} \times 10^3}{3I_n^2} \text{ in milli-ohms}$$

where
$P_{cu} = \text{total losses in watts}$
$I_n = \text{nominal full-load current in amps}$
$R_{tr} = \text{resistance of one phase of the transformer in milli-ohms (the LV and}$
corresponding MV winding for one LV phase are included in this resistance value).

\[ X_{tr} = \sqrt{Z_{tr}^2 - R_{tr}^2} \]

For an approximate calculation \( R_{tr} \) may be ignored since \( X \approx Z \) in standard distribution type transformers.

**Table -2 : Resistance, reactance and impedance values for typical distribution 400 V transformers with MV windings ≤20 kV**

<table>
<thead>
<tr>
<th>Rated Power (kVA)</th>
<th>Oil-immersed</th>
<th>Cast-resin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Use (%)</td>
<td>Rtr (mΩ)</td>
</tr>
<tr>
<td>100</td>
<td>4</td>
<td>37.9</td>
</tr>
<tr>
<td>160</td>
<td>4</td>
<td>16.2</td>
</tr>
<tr>
<td>200</td>
<td>4</td>
<td>11.9</td>
</tr>
<tr>
<td>250</td>
<td>4</td>
<td>11.2</td>
</tr>
<tr>
<td>315</td>
<td>4</td>
<td>6.2</td>
</tr>
<tr>
<td>400</td>
<td>4</td>
<td>5.1</td>
</tr>
<tr>
<td>500</td>
<td>4</td>
<td>3.8</td>
</tr>
<tr>
<td>630</td>
<td>4</td>
<td>2.9</td>
</tr>
<tr>
<td>800</td>
<td>6</td>
<td>2.9</td>
</tr>
<tr>
<td>1,000</td>
<td>6</td>
<td>2.3</td>
</tr>
<tr>
<td>1,250</td>
<td>6</td>
<td>1.8</td>
</tr>
<tr>
<td>1,600</td>
<td>6</td>
<td>1.4</td>
</tr>
<tr>
<td>2,000</td>
<td>6</td>
<td>1.1</td>
</tr>
</tbody>
</table>

**3 - Circuit-breakers**

In LV circuits, the impedance of circuit-breakers upstream of the fault location must be taken into account. The reactance value conventionally assumed is 0.15 mΩ per CB, while the resistance is neglected.

**4 - Busbars**

The resistance of bus bars is generally negligible, so that the impedance is practically all reactive, and amounts to approximately 0.15 mΩ / meter length for LV bus bars (doubling the spacing between the bars increases the reactance by about 10% only).
5 - Circuit conductors

The resistance of a conductor is given by the formula: $R_c = \frac{\rho L}{S}$

where

$\rho = $ the resistivity constant of the conductor material at the normal operating temperature being:
- 22.5 mΩ.mm²/m for copper
- 36 mΩ.mm²/m for aluminum

$L = $ length of the conductor in m
$S = $ c.s.a. of conductor in mm²

<table>
<thead>
<tr>
<th></th>
<th>20 °C</th>
<th>EPR/XLPE 90 °C</th>
<th>PVC 70 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>18.51</td>
<td>23.6928</td>
<td>22.212</td>
</tr>
<tr>
<td>Alu</td>
<td>29.41</td>
<td>37.6448</td>
<td>35.292</td>
</tr>
</tbody>
</table>

$L = $ length of the conductor in m
$S = $ c.s.a. of conductor in mm²

Cable reactance values can be obtained from the manufacturers. For c.s.a. of less than 50 mm² reactance may be ignored. In the absence of other information, a value of 0.08 mΩ/meter may be used (for 50 Hz systems) or 0.096 mΩ/meter (for 60 Hz systems). For prefabricated bus-trunking and similar pre-wired ducting systems, the manufacturer should be consulted.

6 - Motors

At the instant of short-circuit, a running motor will act (for a brief period) as a generator, and feed current into the fault.

In general, this fault-current contribution may be ignored. However, if the total power of motors running simultaneously is higher than 25% of the total power of transformers, the influence of motors must be taken into account.

Their total contribution can be estimated from the formula:
$I_{scm} = 3.5 \times I_n$ from each motor i.e. $3.5(m \times I_n)$ for $m$ similar motors operating concurrently.

The motors concerned will be the 3-phase motors only; single-phase-motor contribution being insignificant.
7 - Fault-arc resistance

Short-circuit faults generally form an arc which has the properties of a resistance. The resistance is not stable and its average value is low, but at low voltage this resistance is sufficient to reduce the fault-current to some extent. Experience has shown that a reduction of the order of 20% may be expected. This phenomenon will effectively ease the current-breaking duty of a CB, but affords no relief for its fault-current making duty.

Example 1: For the installation network shown in Fig. 2 make short circuit calculation from MV take-off point to the final distribution board. Assume all cables are XLPE type.

Solution:
The short circuit current
Is given by

$$I_{sc} = \frac{420}{\sqrt{3}\sqrt{R_T^2 + X_T^2}}$$

1-To calculate the short circuit current at LV B/B -1, The total Impedance $Z_T$ from point A to point B must be found.

- Network upstream of the MV/LV transformer
  From Table – 1, for short-circuit level of 500MVA.

Fig. 2
$Ra = 0.035 \ (m\Omega) , \ Xa = 0.351 \ (m\Omega)$

- The Transformer : from table -2 , for 1000kVA rating ,

$Rtr = 2.24 \ (m\Omega) , \ Xtr = 8.10 \ (m\Omega)$

- For the single-core cables 5 m copper 4 x 240 mm$^2$/phase : $Rc = \frac{L}{\rho S}$

From Table -3: Let the cable type XLPE , $\rho = 23.7$ approx., hence,

$L = 5 \ m \ and \ S = 4 \times 240 \ mm^2$, therefore ,

$$Rc = \frac{23.7}{4} \times \frac{5}{240} = 0.12 \ (m\Omega)$$

$Xc = 0.08 \times 5 = 0.40 \ (m\Omega)$  [Cable reactance values can be obtained from the manufacturers. For c.s.a. of less than 50 mm$^2$ reactance may be ignored. In the absence of other information, a value of 0.08 m$\Omega$ / metre may be used (for 50 Hz systems)]

- For the main circuit breaker: R and X are Not considered in practice.

Now from point A to point B ,

$RT1 = Ra + Rtr + Rc = 0.035 + 2.24 + 0.12 = 2.4 \ (m\Omega)$

$XT1 = Xa + Xtr + Xc = 0.351 + 8.10 + 0.4 = 8.85 (m\Omega)$

$$I_{sc1} = \frac{420}{\sqrt{3}\sqrt{R_{T1}^2 + X_{T1}^2}} = \frac{420}{\sqrt{3}\sqrt{2.4^2 + 8.85^2}} = 26 \ kA$$

2 – Short circuit calculation at point C: Bus bar  B/B1,10 m , Not considered in practice .

For the three-core XLPE  cable 100 m , 95 mm$^2$ copper

$$Rc_2 = 23.7 \times \frac{100}{95} = 25 \ (m\Omega) \ , \ Xc_2 = 100 \times 0.08 = 8 \ (m\Omega)$$

Hence $RT2 = RT1 + Rc2 = 25 + 2.4 = 27.4 \ (m\Omega)$

$XT2 = XT1 + Xc2 = 8.85 + 8 = 16.85 \ (m\Omega)$

$$I_{sc2} = \frac{420}{\sqrt{3}\sqrt{R_{T2}^2 + X_{T2}^2}} = \frac{420}{\sqrt{3}\sqrt{27.4^2 + 16.85^2}} = 7.54 \ kA$$
3- Short circuit calculation at point D: Bus bar B/B2, Not considered in practice. Only the impedance of the three-core cable, 20 m, 10 mm² copper,

\[ R_{c3} = 23.7 \times \frac{20}{10} = 47.4 \text{ (mΩ)} \]

\[ X_{c3} = 20 \times 0.08 = 1.6 \text{ (mΩ)} \]

Hence \( R_T3 = R_T2 + R_{c3} = 27.4 + 47.4 = 74.8 \text{ (mΩ)} \)

\[ X_T3 = X_T2 + X_{c3} = 16.85 + 1.6 = 18.45 \text{ (mΩ)} \]

\[ I_{sc3} = \frac{420}{\sqrt{3} \sqrt{R_T3^2 + X_T3^2}} = \frac{420}{\sqrt{3} \sqrt{74.8^2 + 18.45^2}} = 3.15 \text{ kA} \]

Summary

Fig.3 gives design table of impedances for different parts of a power-supply system
**Fig. 3:** Recapitulation table of impedances for different parts of a power-supply system

<table>
<thead>
<tr>
<th>Parts of power-supply system</th>
<th>( R ) (mΩ)</th>
<th>( X ) (mΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply network</td>
<td>( \frac{R_a}{X_a} = 0.1 )</td>
<td>( X_a = 0.995 Z_a )</td>
</tr>
<tr>
<td>Transformer</td>
<td>( R_{tr} = \frac{P_{eu} \times 10^3}{3I_n^2} )</td>
<td>( Z_{tr} = \frac{V_{20}^2}{P_n} \times \frac{V_{sc}}{100} )</td>
</tr>
<tr>
<td>Table - 2</td>
<td>Rtr is often negligible compared to Xtr for transformers &gt; 100 kVA</td>
<td></td>
</tr>
<tr>
<td>Circuit-breaker</td>
<td>Not considered in practice</td>
<td></td>
</tr>
<tr>
<td>Busbars</td>
<td>Negligible for ( S &gt; 200 \text{ mm}^2 ) in the formula: ( X_B = 0.15 \text{ mΩ/m} )</td>
<td></td>
</tr>
<tr>
<td>Circuit conductors(^{(1)})</td>
<td>( R = \rho \frac{L}{S} )</td>
<td>Cables: ( X_C = 0.08 \text{ mΩ/m} )</td>
</tr>
<tr>
<td>Motors</td>
<td>See Sub-clause 4.2 Motors (often negligible at LV)</td>
<td></td>
</tr>
<tr>
<td>Three-phase short circuit current in kA</td>
<td>( I_{sc} = \frac{V_{20}}{\sqrt{3} \sqrt{R_T^2 + X_T^2}} )</td>
<td></td>
</tr>
</tbody>
</table>
Symbols for table given in Fig.3:

\( V_{20} \): Phase-to-phase no-load secondary voltage of MV/LV transformer (in volts).
\( P_{sc} \): 3-phase short-circuit power at MV terminals of the MV/LV transformers (in kVA).
\( P_{cu} \): 3-phase total losses of the MV/LV transformer (in watts).
\( P_n \): Rating of the MV/LV transformer (in kVA).
\( V_{sc} \): Short-circuit impedance voltage of the MV/LV transformer (in %).
\( R_T \): Total resistance. \( X_T \): Total reactance

1. \( \rho \) = resistivity at normal temperature of conductors in service
   - \( \rho = 22.5 \text{ m}\Omega \times \text{mm}^2/\text{m} \) for copper
   - \( \rho = 36 \text{ m}\Omega \times \text{mm}^2/\text{m} \) for aluminium

2. If there are several conductors in parallel per phase, then divide the resistance of one conductor by the number of conductors. The reactance remains practically unchanged.