1

Definitions: Methods of Calculations

The following terms and definitions correspond largely to those defined in IEC 60909-0. Refer to this standard for all the terms not used in this book.

The terms *short circuit* and *ground fault* describe faults in the isolation of operational equipment, which occur when live parts are shunted out as a result.

1) *Causes*:
   - Overtemperatures due to excessively high overcurrents;
   - Disruptive discharges due to overvoltages; and
   - Arcing due to moisture together with impure air, especially on insulators.
2) *Effects:*
   - Interruption of power supply;
   - Destruction of system components; and
   - Development of unacceptable mechanical and thermal stresses in electrical operational equipment.
3) *Short circuit*: According to IEC 60909-0, a short circuit is the accidental or intentional conductive connection through a relatively low resistance or impedance between two or more points of a circuit that are normally at different potentials.
4) *Short-circuit current*: According to IEC 60909-0, a short-circuit current results from a short circuit in an electrical network.
   It is necessary to differentiate between the short-circuit current at the position of the short circuit and the transferred short-circuit currents in the network branches.
5) *Initial symmetrical short-circuit current*: The effective value of the symmetrical short-circuit current at the moment at which the short circuit arises, when the short-circuit impedance has its value from the time zero.
6) *Initial symmetrical short-circuit apparent power*: The short-circuit power represents a fictitious parameter. During the planning of networks, the short-circuit power is a suitable characteristic number.

Short Circuits in Power Systems: A Practical Guide to IEC 60909-0, Second Edition. Ismail Kasikci.

7) *Peak short-circuit current*: The largest possible momentary value of the short circuit occurring.
8) *Steady-state short-circuit current*: Effective value of the initial symmetrical short-circuit current remaining after the decay of all transient phenomena.
9) *Direct current (d.c.) aperiodic component*: Average value of the upper and lower envelope curve of the short-circuit current, which slowly decays to zero.
10) *Symmetrical breaking current*: The effective value of the short-circuit current that flows through the contact switch at the time of the first contact separation.
11) *Equivalent voltage source*: The voltage at the position of the short circuit, which is transferred to the positive-sequence system as the only effective voltage and is used for the calculation of the short-circuit currents.
12) *Superposition method*: Considers the previous load of the network before the occurrence of the short circuit. It is necessary to know the load flow and the setting of the transformer step switch.
13) *Voltage factor*: Ratio between the equivalent voltage source and the network voltage, U_{n}, divided by $\sqrt{3}$.
14) *Equivalent electrical circuit*: Model for the description of the network by an equivalent circuit.
15) *Far-from-generator short circuit*: The value of the symmetrical alternating current (a.c.) periodic component remains essentially constant.
16) *Near-to-generator short circuit*: The value of the symmetrical a.c. periodic component does not remain constant. The synchronous machine first delivers an initial symmetrical short-circuit current, which is more than twice the rated current of the synchronous machine.
17) *Positive-sequence short-circuit impedance*: The impedance of the positive-sequence system as seen from the position of the short circuit.
18) *Negative-sequence short-circuit impedance*: The impedance of the negative-sequence system as seen from the position of the short circuit.
19) *Zero-sequence short-circuit impedance*: The impedance of the zero-sequence system as seen from the position of the short circuit. Three times the value of the neutral point to ground impedance occurs.
20) *Short-circuit impedance*: Impedance required for the calculation of the short-circuit currents at the position of the short circuit.

1.1 Time Behavior of the Short-Circuit Current

Figure 1.1 shows the time behavior of the short-circuit current for the occurrence of far-from-generator and near-to-generator short circuits.

The d.c. aperiodic component depends on the point in time at which the short circuit occurs. For a near-to-generator short circuit, the subtransient and the transient behaviors of the synchronous machines are important. Following the decay of all transient phenomena, the steady state sets in.

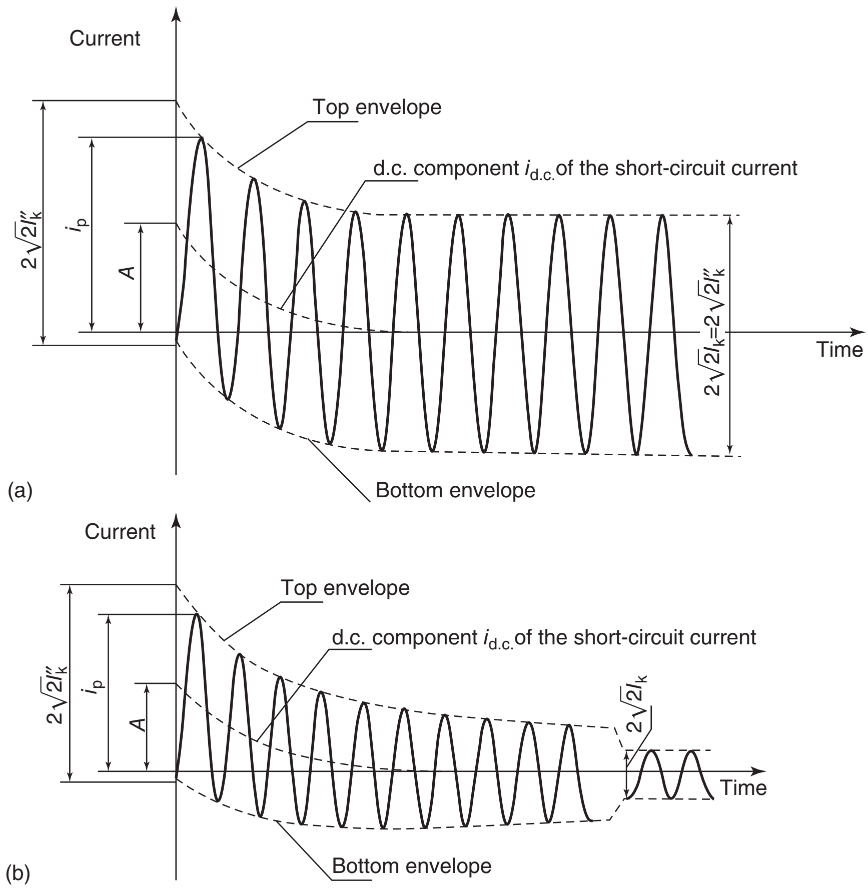

Figure 1.1 Time behavior of the short-circuit current (see Ref. [1]). (a) Far-from-generator short circuit and (b) near-to-generator short circuit. I''_k: initial symmetrical short-circuit current; i_p: peak short-circuit current; $i_{d.c.}$: decaying d.c. aperiodic component; and A: initial value of d.c. aperiodic component.

1.2 Short-Circuit Path in the Positive-Sequence System

For the same external conductor voltages, a three-phase short circuit allows three currents of the same magnitude to develop among the three conductors. Therefore, it is only necessary to consider one conductor in further calculations. Depending on the distance from the position of the short circuit from the generator, it is necessary to consider near-to-generator and far-from-generator short circuits separately. For far-from-generator and near-to-generator short circuits, the short-circuit path can be represented by a mesh diagram with an a.c. voltage source, reactances X, and resistances R (Figure 1.2). Here, X and R replace all components such as cables, conductors, transformers, generators, and motors.

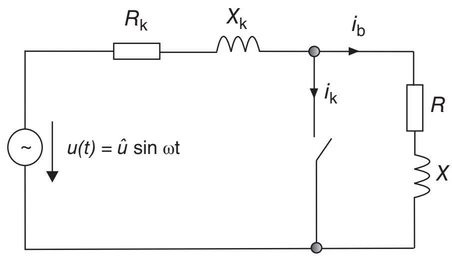

Figure 1.2 Equivalent circuit of the short-circuit current path in the positive-sequence system.

The following differential equation can be used to describe the short-circuit process:

$$i_k \cdot R_k + L_k \frac{di_k}{dt} = \hat{u} \cdot \sin(\omega t + \psi) \tag{1.1}$$

where ψ is the phase angle at the point in time of the short circuit. The inhomogeneous first-order differential equation can be solved by determining the homogeneous solution i_k and a particular solution I''_k.

$$i_k = i''_{k\sim} + i_{k-} \tag{1.2}$$

The homogeneous solution, with the time constant $\tau_g = L/R$, yields the following:

$$i_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} e^{t/\tau_g} \sin(\psi - \varphi_k) \tag{1.3}$$

For the particular solution, we obtain the following:

$$i''_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} \sin(\omega t + \psi - \varphi_k) \tag{1.4}$$

The total short-circuit current is composed of both the components:

$$i_k = \frac{-\hat{u}}{\sqrt{(R^2 + X^2)}} [\sin(\omega t + \psi - \varphi_k) - e^{t/\tau_g} \sin(\psi - \varphi_k)] \tag{1.5}$$

The phase angle of the short-circuit current (short-circuit angle) is then, in accordance with the above equation,

$$\varphi_k = \psi - \nu = \arctan \frac{X}{R} \tag{1.6}$$

Figure 1.3 shows the switching processes of the short circuit.

For the far-from-generator short circuit, the short-circuit current is, therefore, made up of a constant a.c. periodic component and the decaying d.c. aperiodic component. From the simplified calculations, we can now reach the following conclusions:

1) The short-circuit current always has a decaying d.c. aperiodic component in addition to the stationary a.c. periodic component.
2) The magnitude of the short-circuit current depends on the operating angle of the current. It reaches a maximum at $\gamma = 90°$ (purely inductive load). This case serves as the basis for further calculations.
3) The short-circuit current is always inductive.

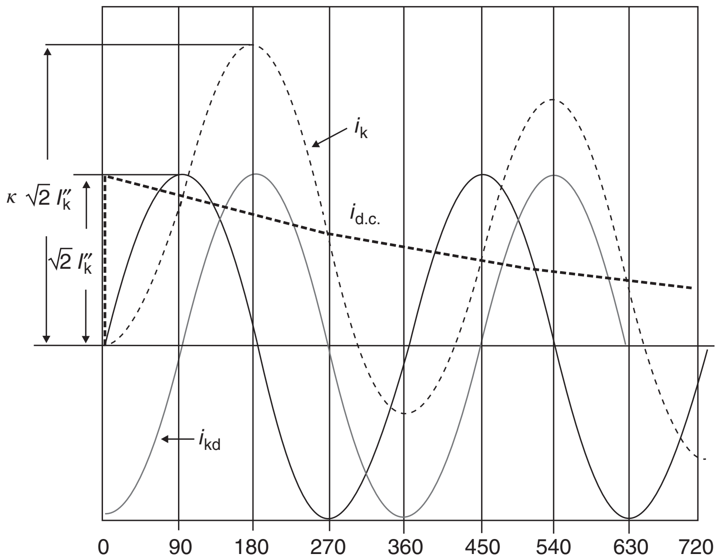

Figure 1.3 Switching processes of the short circuit.

1.3 Classification of Short-Circuit Types

For a three-phase short circuit, three voltages at the position of the short circuit are zero. The conductors are loaded symmetrically. Therefore, it is sufficient to calculate only in the positive-sequence system. The two-phase short-circuit current is less than that of the three-phase short circuit, but largely close to synchronous machines. The single-phase short-circuit current occurs most frequently in low-voltage (LV) networks with solid grounding. The double ground connection occurs in networks with a free neutral point or with a ground fault neutralizer grounded system.

For the calculation of short-circuit currents, it is necessary to differentiate between the far-from-generator and the near-to-generator cases.

1) Far-from-generator short circuit
   When double the rated current is not exceeded in any machine, we speak of a far-from-generator short circuit.

$$I_k'' < 2 \cdot I_{rG} \tag{1.7}$$

   or when

$$I_k'' = I_a = I_k \tag{1.8}$$

2) Near-to-generator short circuit
   When the value of the initial symmetrical short-circuit current I_k'' exceeds double the rated current in at least one synchronous or asynchronous machine at the time the short circuit occurs, we speak of a near-to-generator short circuit.

$$I_k'' 2 > I_{rG} \tag{1.9}$$

or when

$$I''_k > I_a > I_k \tag{1.10}$$

Figure 1.4 schematically illustrates the most important types of short circuits in three-phase networks.

1) Three-phase short circuits:
   - connection of all conductors with or without simultaneous contact to ground;
   - symmetrical loading of the three external conductors;
   - calculation only according to single phase.
2) Two-phase short circuits:
   - unsymmetrical loading;
   - all voltages are nonzero;
   - coupling between external conductors;
   - for a near-to-generator short circuit $I''_{k2} > I''_{k3}$
3) Single-phase short circuits between phase and PE:
   - very frequent occurrence in LV networks.
4) Single-phase short circuits between phase and N:
   - very frequent occurrence in LV networks.
5) Two-phase short circuits with ground:
   - in networks with an insulated neutral point or with a suppression coil grounded system $I''_{kEE} < I''_{k2E}$.

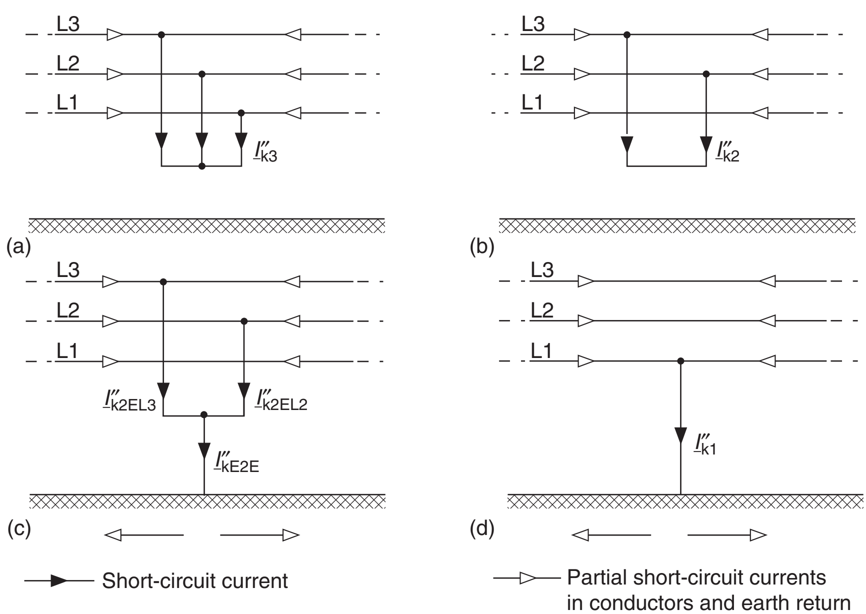

Figure 1.4 Types of short-circuit currents in three-phase networks [1].

With a suppression coil grounded system, a residual ground fault current I_{Rest} occurs. I_C and I_{Rest} are special cases of I''_k.

1.4 Methods of Short-Circuit Calculation

The measurement or calculation of short-circuit current in LV networks on final circuits is very simple. In meshed and extensive power plants, the calculation is more difficult because of the short-circuit current of several partial short-circuit currents in conductors and earth return.

The short-circuit currents in three-phase systems can be determined by three different calculation procedures:

1) superposition method for a defined load flow case;
2) calculating with the equivalent voltage source $\frac{c \cdot U_n}{\sqrt{3}}$ at the fault location; and
3) transient calculation.

1.4.1 Superposition Method

The superposition method is an exact method for the calculation of the short-circuit currents. The method consists of three steps. The voltage ratios and the loading condition of the network must be known before the occurrence of the short circuit. In the first step, the currents, voltages, and internal voltages for steady-state operation before onset of the short circuit are calculated (Figure 1.5b). The calculation considers the impedances, power supply feeders, and node loads of the active elements. In the second step, the voltage applied to the fault location before the occurrence of the short circuit and the current distribution at the fault location are determined with a negative sign (Figure 1.5b). This is the only voltage source in the network. The internal voltages are short-circuited. In the third step, both the conditions are superimposed. We then obtain a zero voltage at the fault location. The superposition of the currents also leads to the value zero. The disadvantage of this method is that the steady-state condition must be specified. The data for the network (effective and reactive power, node voltages, and the step settings of the transformers) are often difficult to determine. The question also arises: Which operating state leads to the greatest short-circuit current?

The superposition method assumes that the power flow is known of the network before the fault inception and the setting of the tap changer of the transformer and the voltage set points of the generators.

By the superposition method, the power state is superimposed with an amendments state before the short circuit occurs. For this condition, the consideration of positive sequence is sufficient.

The network consists of $i = 1,\ldots,n$ load nodes and $j = 1,\ldots,m$ generators and power supply applications. With a suitable program, the load flow can be calculated for a network condition. After the changes in the network through the short circuit, there are other values at each node. For a three-phase short circuit, the voltage at the fault point equals zero. This condition is also fulfilled when the

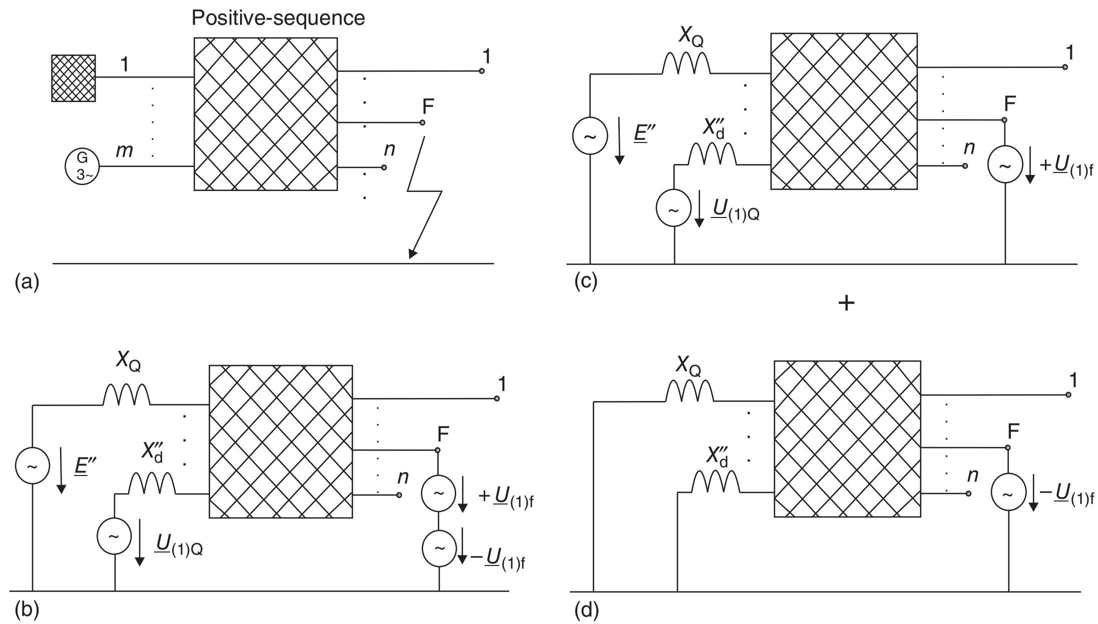

Figure 1.5 Methods for the short-circuit calculation. (a) Single line diagram; (b) voltage source at the fault location; (c) superposition; and (d) equivalent voltage source.

same voltage is given at the fault location but with an opposite voltage sign. All network feeders, synchronous, and asynchronous machines are replaced by their internal impedances (Figure 1.5d).

The calculation of a short-circuit current is a linear problem that can be solved easily with linear equations. There is a linear relationship between the node voltages and node currents.

With the help of nodal admittance matrix systems, linear equations can be solved. All impedances are converted to the LV side of the transformers. In contrast to the load flow calculation, an iteration is not required. The equations are obtained at the short-circuit location ***i*** in matrix notation.

$$\underline{i} = \underline{Y} \cdot \underline{u} \tag{1.11}$$

$$\begin{bmatrix} 0 \\ 0 \\ \vdots \\ I''_{\mathrm{ki}} \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} \underline{Y}_{11} & \underline{Y}_{1\mathrm{n}} \\ \underline{Y}_{21} & \underline{Y}_{2\mathrm{n}} \\ \vdots & \vdots \\ \underline{Y}_{\mathrm{i}1} & \underline{Y}_{\mathrm{in}} \\ \vdots & \vdots \\ \underline{Y}_{\mathrm{n}1} & \underline{Y}_{\mathrm{nn}} \end{bmatrix} \cdot \begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ -c\frac{U_{\mathrm{n}}}{\sqrt{3}} \\ \vdots \\ \underline{U}_{\mathrm{n}} \end{bmatrix} \tag{1.12}$$

After inversion, we obtain the following:

$$\underline{u} = \underline{Y}^{-1} \cdot \underline{i} \tag{1.13}$$

$$\begin{bmatrix} \underline{U}_1 \\ \underline{U}_2 \\ \vdots \\ -c\frac{U_{\mathrm{n}}}{\sqrt{3}} \\ \vdots \\ \underline{U}_{\mathrm{n}} \end{bmatrix} = \begin{bmatrix} \underline{Z}_{11} & \underline{Z}_{1\mathrm{n}} \\ \underline{Z}_{21} & \underline{Z}_{2\mathrm{n}} \\ \vdots & \vdots \\ \underline{Z}_{\mathrm{i}1} & \underline{Z}_{\mathrm{in}} \\ \vdots & \vdots \\ \underline{Z}_{\mathrm{n}1} & \underline{Z}_{\mathrm{nn}} \end{bmatrix} \cdot \begin{bmatrix} 0 \\ 0 \\ \vdots \\ I''_{\mathrm{ki}} \\ \vdots \\ 0_{\mathrm{n}} \end{bmatrix} \tag{1.14}$$

From the i^{th} row of the equation results

$$-c\frac{U_{\mathrm{n}}}{\sqrt{3}} = \underline{Z}_{\mathrm{ii}} \cdot \underline{I}''_{\mathrm{ki}} \tag{1.15}$$

The initial short-circuit a.c. can be calculated by redirecting the above equation:

$$\underline{I}''_{\mathrm{ki}} = -\frac{c \cdot U_{\mathrm{n}}}{\sqrt{3} \cdot \underline{Z}_{\mathrm{ii}}} \tag{1.16}$$

For the node voltages, follow:

$$\underline{U}_{\mathrm{k}} = \underline{Z}_{\mathrm{ki}} \cdot \underline{I}''_{\mathrm{ki}} \tag{1.16a}$$

Since the operating voltage $U_{(1)f} = \frac{U_n}{\sqrt{3}}$ is not known at the fault location, for the equivalent voltage source at the fault point can be introduced.

$$-\underline{U}_{(1)f} = \frac{c \cdot U_n}{\sqrt{3}} \tag{1.17}$$

At the short-circuit point, the only active voltage is the Thevenin equivalent voltage source of the system.

1.4.2 Equivalent Voltage Source

Figure 1.6 shows an example of the equivalent voltage source at the short-circuit location F as the only active voltage of the system fed by a transformer with or without an on-load tap changer. All other active voltages in the system are short-circuited. Thus, the network feeder is represented by its internal impedance, $\underline{Z}_{Qt}$, transferred to the LV side of the transformer and the transformer by its impedance referred to the LV side. The shunt admittances of the line, the transformer, and the nonrotating loads are not considered. The impedances of the network feeder and the transformer are converted to the LV side.

The transformer is corrected with K_T, which will be explained later.

The voltage factor c (Table 1.1) will be described briefly as follows:

If there are no national standards, it seems adequate to choose a voltage factor c, according to Table 1.1, considering that the highest voltage in a normal

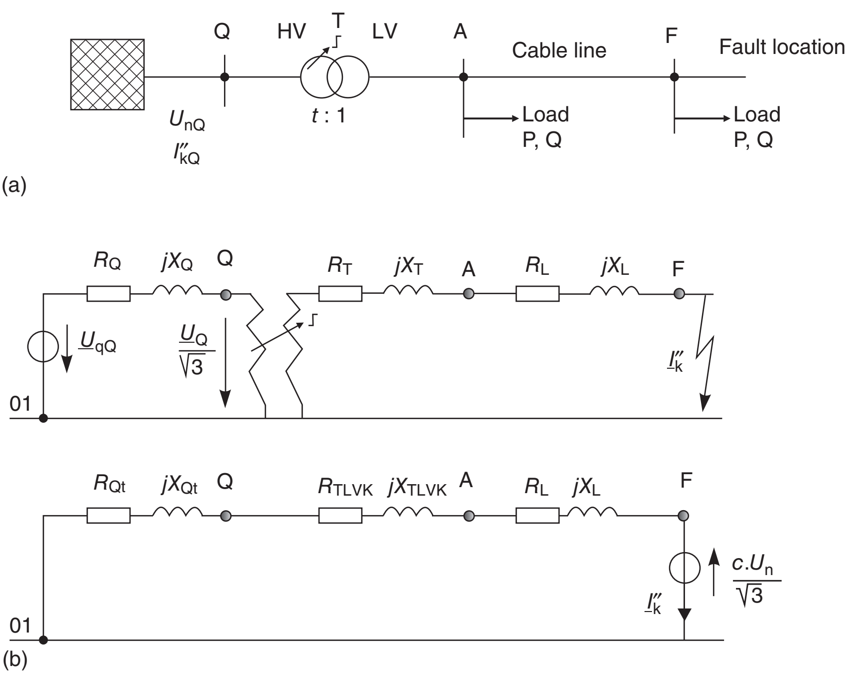

Figure 1.6 Network circuit with equivalent voltage source [2]. (a) System diagram and (b) equivalent circuit diagram of the positive-sequence system.

Table 1.1 Voltage factor *c*, according to IEC 60909-0: 2016-10 [1].

Nominal voltage, U_n	Voltage factor *c* for calculation of	
	Maximum short-circuit currents (c_{max})[a)]	Minimum short-circuit currents (c_{min})
Low voltage		
100–1000 V	1.05[b)]	0.95[b)]
(IEC 38, Table I)	1.10[c)]	0.9[c)]
High voltage[d)]		
>1–35 kV	1.10	1.00
(IEC 38, Tables III and IV)		

a) $c_{max}\,U_n$ should not exceed the highest voltage U_m for equipment of power systems.
b) For LV systems with a tolerance of ±6%, for example, systems renamed from 380 to 400 V.
c) For LV systems with a tolerance of ±10%.
d) If no nominal voltage is defined, $c_{max}\,U_n = U_m$ or $c_{min}\,U_n = 0.90\,U_m$ should be applied.

(undisturbed) system does not differ, on average, by more than approximately +5% (some LV systems) or +10% (some high-voltage, HV, systems) from the nominal system voltage U_n [3].

1) The different voltage values depending on time and position
2) The step changes of the transformer switch
3) The loads and capacitances in the calculation of the equivalent voltage source can be neglected
4) The subtransient behavior of generators and motors must be considered.

This method assumes the following conditions:

1) The passive loads and conductor capacitances can be neglected
2) The step setting of the transformers need not be considered
3) The excitation of the generators need not be considered
4) The time and position dependence of the previous load (loading state) of the network need not be considered.

1.4.3 Transient Calculation

With the transient method, the individual operating equipment and, as a result, the entire network are represented by a system of differential equations. The calculation is very tedious. The method with the equivalent voltage source is a simplification relative to the other methods. Since 1988, it has been standardized internationally in IEC 60909-0. The calculation is independent of a current operational state. Therefore, in this book, the method with the equivalent voltage source will be dealt with and discussed.

1.4.4 Calculating with Reference Variables

There are several methods for performing short-circuit calculations with absolute and reference impedance values. A few methods are summarized here, and examples are calculated for comparison. To define the relative values, there are two possible reference variables.

For the characterization of electrotechnical relationships, we require the four parameters:

1) voltage U in V;
2) current I in A;
3) impedance Z in Ω; and
4) apparent power S in VA.

Three methods can be used to calculate the short-circuit current:

1) The Ohm system: units – kV, kA, V, and MVA.
2) *The per-unit (pu) system*: this method is used predominantly for electrical machines; all four parameters u, i, z, and s are given as per unit (unit = 1). The reference value is 100 MVA. The two reference variables for this system are U_B and S_B. Example: The reactances of a synchronous machine X_d, X'_d, and X''_d are given in pu or in %pu, multiplied by 100%.
3) The %/MVA system: this system is especially well suited for the quick determination of short-circuit impedances. As a formal unit, only the % symbol is added.

1.4.4.1 The Per-Unit Analysis

Today, the power system consists of complex and complicated mesh, ring, and radial networks with many transformers, generators, and cables. The calculation of such a circuit can be very tedious and incorrect. The use of sophisticated computer programs is a big help for engineers. On the other hand, for a quick calculation a simple method, per unit system also can be used. However, this method is not accepted worldwide and is not standardized by IEC, EN, or IEEE committees.

The pu method uses the electrical variables $\underline{U}$, $\underline{I}$, $\underline{Z}$, and $\underline{S}$. They are based on a dimensionless same references, namely, U_{base}, I_{base}, Z_{base}, or S_{base}. The resulting dimensionless quantities are described with the lowercase $\underline{u}$, $\underline{i}$, $\underline{z}$, or $\underline{s}$.

A pu system is defined as follows:

$$\text{Per unit value (pu)} = \frac{\text{the actual value (in any unit)}}{\text{the base or reference value (in the same unit)}}$$

$$\underline{u}_{\text{pu}} = \frac{\underline{U}}{U_{\text{base}}}$$

A reference voltage and a reference apparent power are selected and then reference current and impedance are calculated as follows:

$$Z_{\text{base}} = \frac{U_{\text{base}}^2}{S_{\text{base}}}$$

$$I_{\text{base}} = \frac{S_{\text{base}}}{U_{\text{base}}}$$

Only a single global base value is selected in the short-circuit current calculation. This reference value is then used for all other networks. The choice of reference values can be carried out arbitrarily in principle. However, it is appropriate to select the rated voltage at the short-circuit location as a reference voltage. For example, as reference apparent power is the rated apparent power of the largest transformer in the network or a power of the same selected magnitude (e.g., 100 MVA). The best choice of base can be achieved when the impedances and currents in easily handled orders of magnitude.

It should be noted that related parameters' individual resources, such as the relative short-circuit voltage of a transformer u_{kr} or related subtransient reactance x''_d of the generator, are always relative to a base, which consists of the design parameters of the particular equipment. In a short-circuit current calculation as per pu method, these parameters must first be converted to the selected global basis. If we give an example for voltage and current, the expression is as follows:

$$U_{pu} = \frac{U_{actual}}{U_{base}}$$

$$I_{pu} = \frac{I_{actual}}{I_{base}}$$

Note that the voltage according to the international system of units (SI) is not V, but U. The letter V is a unit in this case. V is used especially in Anglo-Saxon countries.

For other values, we can write for 1 pu impedance (Ω):

$$Z_{base} = \frac{U_{base}}{I_{base}} = \frac{U_{base}}{I_{base}} \quad \text{or in pu} \quad Z_{pu} = \frac{U_{pu}}{I_{pu}}$$

$$I_{base} = \frac{S_{base}}{U_{base}}$$

We convert the values to pu:

$$R_{pu} = \frac{R}{Z_{base}}$$

$$X_{pu} = \frac{X}{Z_{base}}$$

Remember that a symmetrical three-phase system has two voltages, line–line voltage U_L (U_n) and U_{LN} (U_0). By definition:

$$U_{LN} = \frac{U_L}{\sqrt{3}}$$

Now consider:

$$U_{LNpu} = \frac{U_{LN}}{U_{LNbase}}$$

It follows that:

$$U_{LNpu} = \frac{U_{LN}}{U_{LNbase}} = \frac{U_L/\sqrt{3}}{U_{Lbase}/\sqrt{3}} = \frac{U_L}{U_{Lbase}} = U_{Lpu}$$

Consider that the factor $\sqrt{3}$ disappears in the pu equation.

1.4.4.2 The %/MVA Method

The %/MVA method can be considered as a modification of the pu method and designed specifically for the HV network calculation. The impedances of the electrical equipment can be determined easily in %/MVA from the synchronous machine and transformer characteristics. It utilizes the fact that for the pu calculation, apparent power S_{base} is completely arbitrary. Consequently, instead of S_{base}, the dimensionless value 1 is inserted. This has the result that the related sizes of the pu are no longer dimensionless.

The related impedances can be represented in %/MVA. The %/MVA method has the advantage that a conversion with t^2 or $1/t^2$ eliminates the transformation of impedances in the voltage level on the transformers. Furthermore, all impedances of resources and the dimensioning data can be obtained from the nameplate.

$$z = \frac{Z}{U_{base}^2} \times 100\%$$

$$u = \frac{Z}{U_{base}} \times 100\%$$

$$i = I \cdot U_{base}$$

1.4.5 Examples

1.4.5.1 Characteristics of the Short-Circuit Current

The short-circuit current is composed of two parts. The first term describes the a.c. (continuous current) and the second term the compensation process.

$$i_{k(t)} = \hat{i}_k \cdot \sin(\omega t - \Psi + \varphi_u) - \hat{i}_k \cdot \sin(\Psi - \varphi) \cdot e^{-(t/\tau)}$$

The size of the short-circuit current is therefore dependent on the phase angle $\varphi = \text{arc tan} \frac{X}{R}$, the time constant $\tau = \frac{L}{R}$, the time t, and the switching angle Ψ.

Thus we can obtain many shifts by changing the sizes (Figure 1.7).

Example: $R_Q/X_Q = 0.176$, $\varphi = -0°$, $\varphi_u = -90°$, $\tau = \infty$ms, $3 \cdot \tau = \infty$ms, $\kappa = 1.02$.

For further considerations, one can write

$$\sin(\omega t - \varphi) = 1, \quad \frac{R}{X} = \frac{1}{\tan \varphi}, \quad \Psi = 0$$

1.4.5.2 Calculation of Switching Processes

Given are the following sizes of short-circuit current (Figure 1.8):

$$\frac{R_Q}{X_Q} = 0.176, \quad \varphi = -80°, \quad \varphi_u = -170°, \quad \tau = 0.018\,\text{ms},$$
$$3 \cdot \tau = 0.054\,\text{ms}, \quad \kappa = 1.597$$

Draw the switching process of the short circuit.

1.4.5.3 Calculation with pu System

Given is a system with 20/6 kV network (Figure 1.9).

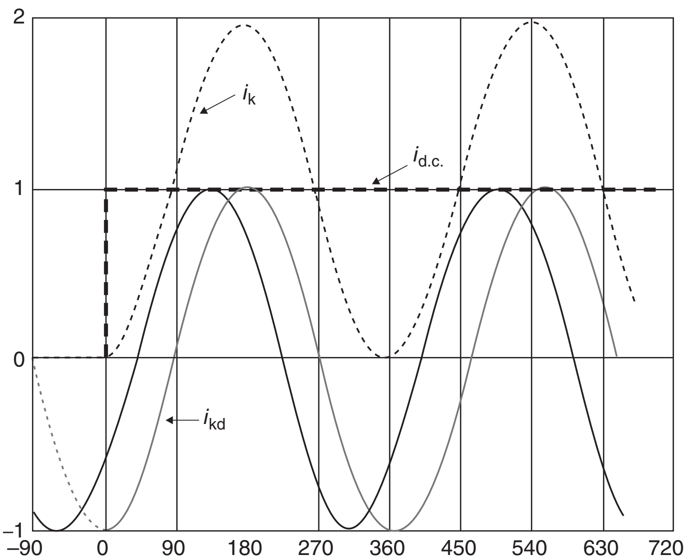

Figure 1.7 Short-circuit current components – switch on.

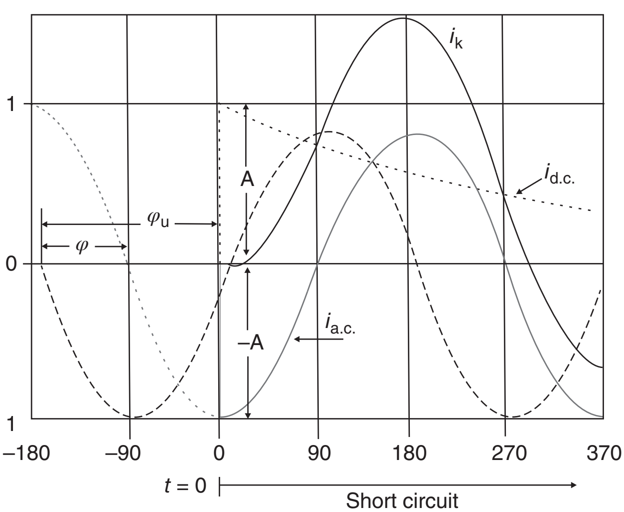

Figure 1.8 Switching process.

Transformer:

$$S_{rT} = 25\,\text{MVA}, \quad u_{krT} = 13\%, \quad 20/6.3\,\text{kV}$$

Motors 1 and 2:

$$2 \times P_{rM} = 2.3\,\text{MW}, \quad U_{rM} = 6\,\text{kV}, \quad cos\varphi_{rM} = 0.86$$
$$p = 2, \quad I_a/I_{rM} = 5, \quad \eta = 0.97$$

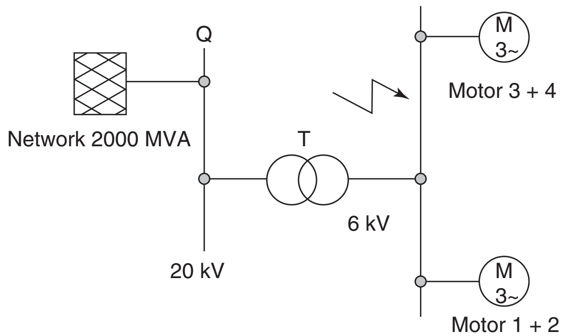

Figure 1.9 Impact of engines on the current.

Motors 3 and 4:

$$2 \times P_{\mathrm{rM}} = 0.36\,\mathrm{MW}, \quad U_{\mathrm{rM}} = 6\,\mathrm{kV}, \quad \cos\varphi_{\mathrm{rM}} = 0.87$$

$$p = 1, \quad I_{\mathrm{a}}/I_{\mathrm{rM}} = 5.5, \quad \eta = 0.98$$

1.4.5.4 Calculation with pu Magnitudes

Given: $U_{\mathrm{B}} = U_{\mathrm{n}} = 6\,\mathrm{kV}$ bzw. $20\,\mathrm{kV}$, $S_{\mathrm{B}} = 100\,\mathrm{MVA}$. Calculate example 1.4.5.3 using pu magnitude.

$$U_* = \frac{U}{U_{\mathrm{B}}} \quad I_* = \frac{I \cdot U_{\mathrm{B}}}{\mathrm{SB}} \quad Z_* = \frac{Z \cdot S_{\mathrm{B}}}{U_{\mathrm{B}}^2} \quad S_* = \frac{S}{S_{\mathrm{B}}}$$

Transformer translation in pu system:

$$t_{\mathrm{r}}^* = \frac{U_{\mathrm{rTOS}}}{U_{\mathrm{rTUS}}} \cdot \frac{U_{\mathrm{B,6\,kV}}}{U_{\mathrm{B,20\,kV}}} = \frac{20\,\mathrm{kV}}{6.3\,\mathrm{kV}} \cdot \frac{6\,\mathrm{kV}}{20\,\mathrm{kV}} = 0.9524$$

Power supply:

$$Z_{\mathrm{Qt}}^* = \frac{c \cdot U_{\mathrm{nQ}}^{2*}}{S_{\mathrm{kQ}}''^*} \cdot \frac{1}{t_{\mathrm{r}}^{2*}} = \frac{1.1 \cdot (1 \cdot \mathrm{pu})^2}{10\,\mathrm{pu}} \cdot \frac{1}{0.9524^2} = 0.1212\,\mathrm{pu}$$

Transformer:

$$Z_{\mathrm{T}}^* = \frac{u_{\mathrm{krT}}}{100\%} \cdot \frac{U_{\mathrm{rTUS}}^2}{S_{\mathrm{rT}}} \cdot \frac{S_{\mathrm{B}}}{U_{\mathrm{B,6\,kV}}^2} = \frac{13\%}{100\%} \cdot \frac{(6.3\,\mathrm{kV})^2}{25\,\mathrm{MVA}} \cdot \frac{100\,\mathrm{MVA}}{(6\,\mathrm{kV})^2} = 0.5733\,\mathrm{pu}$$

Impedance:

$$Z_{\mathrm{k}}^* = Z_{\mathrm{Qt}}^* + Z_{\mathrm{T}}^* = 0.6945\,\mathrm{pu}$$

$I_{\mathrm{k}}''^*$ without motors.

$$I_{\mathrm{k}}''^* = \frac{c \cdot U_{\mathrm{n}}^*}{\sqrt{3} \cdot Z_{\mathrm{k}}^*} = \frac{1.1 \cdot 1\,\mathrm{pu}}{\sqrt{3} \cdot 0.6945\,\mathrm{pu}} = 0.9144\,\mathrm{pu}$$

Current in kA:

$$I_{\mathrm{k}}'' = I_{\mathrm{k}}^* \cdot \frac{S_{\mathrm{B}}}{U_{\mathrm{B,6\,kV}}} = 0.9144\,\mathrm{pu} \cdot \frac{100\,\mathrm{MVA}}{6\,\mathrm{kV}} = 15.24\,\mathrm{kA}$$

Impedances of motors in pu systems:

$$Z_{\mathrm{m1}}^{*}=\frac{1}{2}\frac{\eta\cdot\cos\varphi}{I_{\mathrm{an}}/I_{\mathrm{rM}}}\cdot\frac{U_{\mathrm{rM}}^{2}}{P_{\mathrm{rM}}}\cdot\frac{S_{\mathrm{B}}}{U_{\mathrm{B,6\,kV}}^{2}}=\frac{1}{2}\frac{\eta\cdot\cos\varphi}{I_{\mathrm{an}}/I_{\mathrm{rM}}}\cdot\frac{S_{\mathrm{B}}}{P_{\mathrm{rM}}}$$

$$=\frac{1}{2}\cdot\frac{0.86\cdot 0.97}{5}\cdot\frac{100\,\mathrm{MVA}}{2.3\,\mathrm{MVA}}=3.63\,\mathrm{pu}$$

$$Z_{\mathrm{m2}}=\frac{1}{2}\cdot\frac{0.87\cdot 0.98}{5.5}\cdot\frac{100\,\mathrm{MVA}}{0.36\,\mathrm{MVA}}=21.5\,\mathrm{pu}$$

Partly current:

$$I_{\mathrm{km1}}^{\prime\prime *}=\frac{c\cdot U_{\mathrm{n}}^{*}}{\sqrt{3}\cdot Z_{\mathrm{m1}}^{*}}=\frac{1.1\cdot 1\ \mathrm{pu}}{\sqrt{3}\cdot 3.63\,\mathrm{pu}}=0.175\,\mathrm{pu}$$

$$I_{\mathrm{km1}}^{\prime\prime}=2.92\,\mathrm{kA}$$

$$I_{\mathrm{km2}}^{\prime\prime *}=0.0295\,\mathrm{pu}$$

$$I_{\mathrm{km2}}^{\prime\prime}=0.492\,\mathrm{kA}$$

1.4.5.5 Calculation with pu System for an Industrial System

Given is Figure 1.10. Calculate the short circuit power and short-circuit currents of an industrial power plant with the pu method.

First, the equivalent circuit diagram is drawn (Figure 1.11).

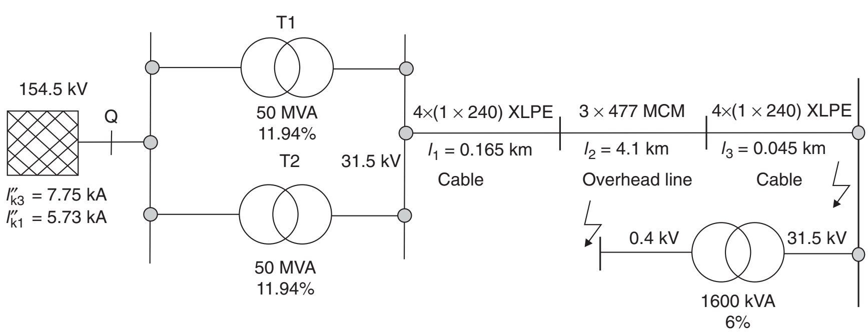

Figure 1.10 Supply for an industrial company.

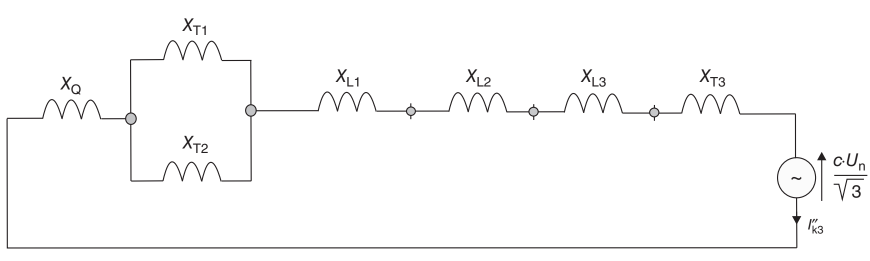

Figure 1.11 Equivalent circuit diagram in positive sequence.

Impedance of the power supply:

$$Z_Q = \frac{U_n}{\sqrt{3} \cdot I''_{k3}} = \frac{154\,\text{kV}}{\sqrt{3} \cdot 7.75\,\text{kA}} = 11.486\,\Omega$$

Short-circuit power of the supply:

$$S''_{kQ} = \sqrt{3} \cdot U_n \cdot I''_{k3} = \sqrt{3} \cdot 154\,\text{kV} \cdot 7.75\,\text{kA} = 2064.75\,\text{MVA}$$

Reactance of the feed:

$$X_Q = \frac{1 \cdot 100}{S''_{kQ}} = \frac{1 \cdot 100}{2064.75\,\text{MVA}} = 0.0484\,\text{pu}$$

Reactance of transformers:

$$X_T = \frac{X_{T1} \cdot X_{T2}}{X_{T1} + X_{T2}} = 5.97\%$$

$$X_T = \frac{100}{50\,\text{MVA} + 50\,\text{MVA}} \cdot 5.97\% = 0.0597\,\text{pu}$$

Total reactance:

$$X_G = X_Q + X_T = 0.0484\,\text{pu} + 0.0597\,\text{pu} = 0.10813\,\text{pu}$$

$$I_{pu} = \frac{U}{X_G} = \frac{1}{0.10813\,\text{pu}} = 9.248\,\text{pu}$$

Short-circuit power:

$$X_{kQ} = 1\,\text{pu} \cdot 100 = 9.248 \cdot 100 = 924.8\,\text{MVA}$$

$$X_{Hpu} = \frac{X_H}{X_B} = \frac{X_F L}{X_B}$$

$$X_B = \frac{U^2}{100} = \frac{31.5\,\text{kV}^2}{100} = 9.922\,\Omega$$

$$X_H = X_{H1} + X_{H1}$$

$$X_T = 0.0161 + 1.5088 = 1.528\,\text{pu}$$

$$X_{H1} = l_1 \cdot X_{H1} = 0.21\,\text{km} \cdot 0.0754\,\Omega/\text{km} = 0.0161\,\Omega$$

$$X_{H2} = l_2 \cdot X_{H2} = 4.1\,\text{km} \cdot 0.368\,\Omega/\text{km} = 1.5088\,\Omega$$

$$X_{Hpu} = \frac{1.526}{9.922} = 0.154\,\text{pu}$$

$$X_{G2} = X_{G1} + X_H = 0.10813 + 0.154 = 0.26213\,\text{pu}$$

$$I_B = \frac{S}{\sqrt{3} \cdot U} = \frac{100 \cdot 10^3}{\sqrt{3} \cdot 31.5\,\text{kV}} = 1835\,\text{A}$$

$$I_{pu} = \frac{1}{X_{G2}} = \frac{1}{0.26213\,\text{pu}} = 3.8\,\text{pu}$$

On distribution transformer:

$$I''_k = I_{pu} \cdot I_B = 3.8\,\text{pu} \cdot 1835\,\text{A} = 6.973\,\text{kA}$$

Short-circuit power on the primary side of the transformer:

$$S''_k = \sqrt{3} \cdot U \cdot I''_k = \sqrt{3} \cdot 31.5\,\text{kV} \cdot 6.973\,\text{kA} = 380\,\text{MVA}$$

Short-circuit power on the secondary side of the transformer:

$$X_{TR} = \frac{100}{1.6} \cdot 0.06 = 3.75\,\text{pu}$$

$$X_{G3} = X_{G2} + X_{G1} = 0.26213 + 3.75 = 4.10213\,\text{pu}$$

$$I_{pu} = \frac{1}{X_{G3}} = \frac{1}{4.10213\,\text{pu}} = 0.24924\,\text{pu}$$

$$I''_{k(0.4\,\text{kV})} = I_{pu} \cdot I_B = 0.24924\,\text{pu} \cdot 1.835\,\text{kA} = 0.457\,\text{kA}$$

1.4.5.6 Calculation with MVA System

Figure 1.12 shows a power plant with auxiliary power system and power supply. Calculate using the %/MVA system at the busbar SS circuit power, the peak short-circuit current and the breaking current.

The total reactance at the fault is calculated with the aid of the equivalent circuit shown in Figure 1.13 by gradual power conversion.

1) Calculation of the reactance of the individual resources

   Network reactance:

$$X_Q = \frac{1.1 \cdot 100}{S''_{kQ}} = \frac{1.1 \cdot 100}{8000\,\text{MVA}} = 0.0138\%/\text{MVA}$$

   Transformer 1:

$$X_{T1} = \frac{u_{kr}}{S_{rT1}} = \frac{13}{100\,\text{MVA}} = 0.1300\%/\text{MVA}$$

   Generator:

$$X_G = \frac{x''_d}{S_{rG}} = \frac{11.5}{93.7\,\text{MVA}} = 0.1227\%/\text{MVA}$$

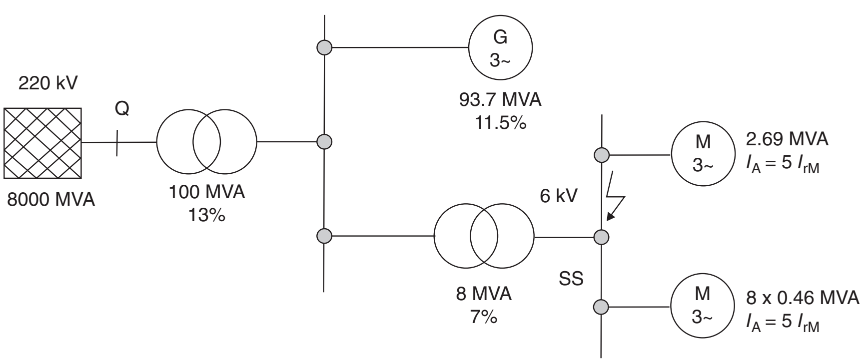

Figure 1.12 Power plant with auxiliary power system.

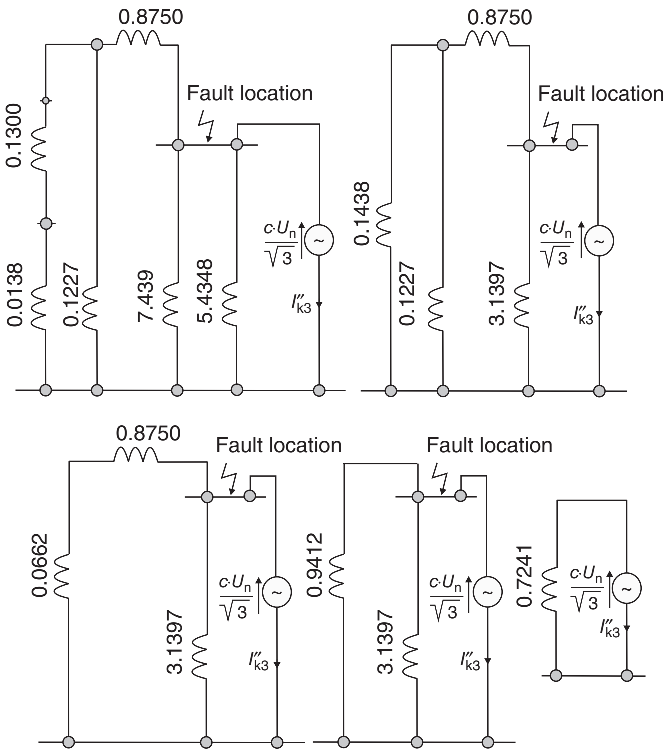

Figure 1.13 Equivalent circuit diagram in positive sequence.

Transformer 2:

$$X_{\mathrm{T2}} = \frac{u_{\mathrm{kr}}}{S_{\mathrm{rT2}}} = \frac{7}{8\,\mathrm{MVA}} = 0.8750\%/\mathrm{MVA}$$

Asynchronous motor:

$$X_{\mathrm{M1}} = \frac{I_{\mathrm{rM}}/I_{\mathrm{A}}}{S_{\mathrm{rM}}} \cdot 100 = \frac{1}{5 \cdot 2.69\,\mathrm{MVA}} \cdot 100 = 7.439\%/\mathrm{MVA}$$

Asynchronous motor group:

$$X_{\mathrm{M2}} = \frac{I_{\mathrm{rM}}/I_{\mathrm{A}}}{S_{\mathrm{rM}}} \cdot 100 = \frac{1}{5 \cdot 8 \cdot 0.46\,\mathrm{MVA}} \cdot 100 = 5.4348\%/\mathrm{MVA}$$

Total reactance at the fault point:

$$S_{\mathrm{k}}'' = \frac{1.1 \cdot 100\%}{X_{\mathrm{k}}} = \frac{1.1 \cdot 100\%}{0.7225\%/\mathrm{MVA}} = 152\,\mathrm{MVA}$$

2) Parts of each feed on the short-circuit power.
With the total reactance, we can determine the circuit power.

$$S_{\mathrm{k}}'' = \frac{1.1 \cdot 100\%}{X_{\mathrm{G}}} = \frac{1.1 \cdot 100\%}{0.7241} = 152\,\mathrm{MVA}$$

Thus, the proportions of the individual feeds to the short-circuit power:

Part of each motor gives:

$$S''_{\text{kM1}} = \frac{0.1345}{1.381} \cdot 152\,\text{MVA} = 14.8\,\text{MVA}$$

Parts of the motor group is then:

$$S''_{\text{kM1}} = \frac{0.184}{1.381} \cdot 152\,\text{MVA} = 20.3\,\text{MVA}$$

Part of transformer 2:

$$S''_{\text{kM1}} = \frac{1.0625}{1.381} \cdot 152\,\text{MVA} = 116.9\,\text{MVA}$$

3) For the 220-kV grid:
Part of the generator:

$$S''_{\text{kG}} = \frac{8.150}{15.104} \cdot 116.9\,\text{MVA} = 63.1\,\text{MVA}$$

Part of the 220-kV network

$$S''_{\text{kQ}} = \frac{6.954}{15.104} \cdot 116.9\,\text{MVA} = 53.8\,\text{MVA}$$

4) Determining the μ and q factors
From Figure 13.3, we get the μ factors for $t_\text{v} = 0.1\,\text{s}$.
For each motor:

$$\frac{S''_{\text{kM1}}}{S_{\text{rM1}}} = \frac{14.8}{2.69} = 5.50 \Rightarrow \mu = 0.77$$

For motor groups:

$$\frac{S''_{\text{kM2}}}{S_{\text{rM2}}} = \frac{20.3}{8 \cdot 0.46} = 5.52 \Rightarrow \mu = 0.76$$

For the generator:

$$\frac{S''_{\text{kG}}}{S_{\text{rG}}} = \frac{63.1}{93.7} = 0.67 \Rightarrow \mu = 1$$

The q factors are determined from the engine power/phase pair, according to Figure 13.3 for $t_\text{v} = 0.1\,\text{s}$.
For each motor:

$$\frac{\text{Rated power}}{\text{Pol-pair}} = \frac{2.3}{2} = 1.15 \Rightarrow q = 0.55$$

For motor groups:

$$\frac{\text{Rated power}}{\text{Pol-pair}} = \frac{0.36}{3} = 0.12 \Rightarrow q = 0.3$$

5) Determination of the individual feeds to the switching capacity
For each motor:

$$S_{\text{aM1}} = \mu \cdot q \cdot S''_{\text{kM1}} = 0.77 \cdot 0.55 \cdot 14.8\,\text{MVA} = 6.3\,\text{MVA}$$

For motor groups:

$$S_{\text{aM2}} = \mu \cdot q \cdot S''_{\text{kM2}} = 0.76 \cdot 0.3 \cdot 20.3\,\text{MVA} = 64.6\,\text{MVA}$$

For the generator:

$$S_{aG} = \mu \cdot S''_{kG} = 1 \cdot 63.1\,\text{MVA} = 63.1\,\text{MVA}$$

220-kV network:

$$S_{aQ} = \mu \cdot S''_{kQ} = 1 \cdot 53.8\,\text{MVA} = 53.8\,\text{MVA}$$

6) Calculation of short-circuit currents
Initial short-circuit a.c.:

$$I''_k = \frac{S''_k}{\sqrt{3} \cdot U_n} = \frac{152\,\text{MVA}}{\sqrt{3} \cdot 6\,\text{kV}} = 14.63\,\text{kA}$$

Peak short-circuit current:

$$i_p = \kappa \cdot \sqrt{3} \cdot I''_k = 1.8 \cdot \sqrt{3} \cdot 14.63\,\text{kA} = 37.2\,\text{kA}$$

Breaking current:

$$I_a = \frac{S_a}{\sqrt{3} \cdot U_n} = \frac{127.8\,\text{MVA}}{\sqrt{3} \cdot 6\,\text{kV}} = 12.3\,\text{kA}$$

The sample was calculated for comparison with NEPLAN. As we can see, the results are the same (Figure 1.14).

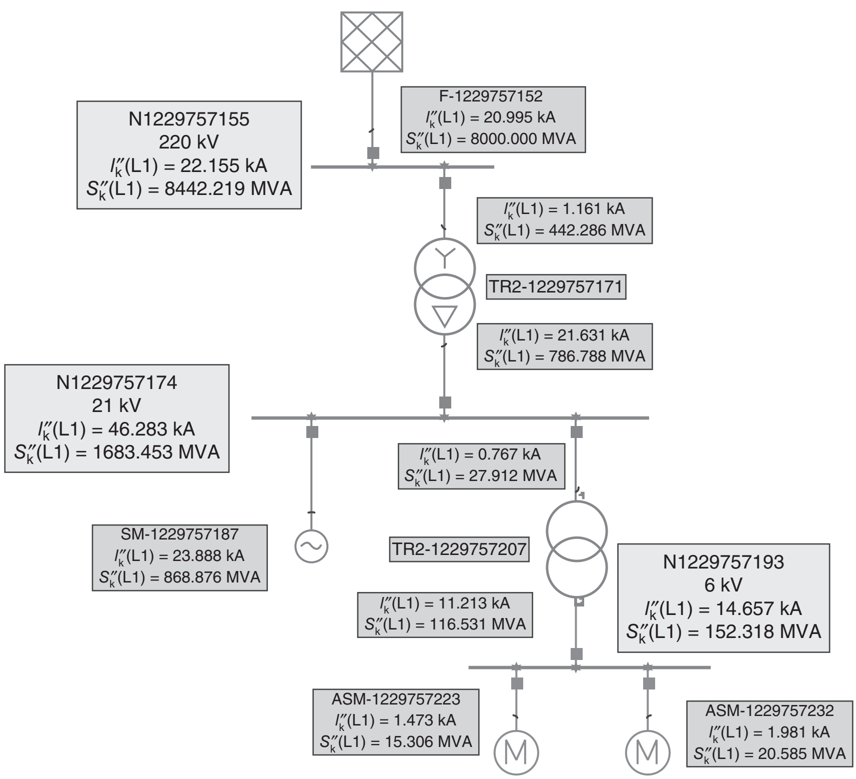

Figure 1.14 Result with NEPLAN.