IEC TR 60909-4

Edition 2.0 2021-06

TECHNICAL REPORT

colour inside

Short-circuit currents in three-phase AC systems –
Part 4: Examples for the calculation of short-circuit currents

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SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –

Part 4: Examples for the calculation of short-circuit currents

FOREWORD

1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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IEC TR 60909-4 has been prepared by IEC technical committee 73: Short-circuit currents. It is a Technical Report.

This second edition cancels and replaces the first edition published in 2000. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) adaption to IEC 60909-0:2016;
b) addition of an example for the calculation of short-circuit currents of wind power station units;
c) correction of errors.

The text of this Technical Report is based on the following documents:

Draft	Report on voting
73/187/DTR	73/193/RVDTR

Full information on the voting for its approval can be found in the report on voting indicated in the above table.

The language used for the development of this Technical Report is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/standardsdev/publications.

A list of all parts in the IEC 60909 series, published under the general title *Short-circuit currents in three-phase AC systems*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under webstore.iec.ch in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –

Part 4: Examples for the calculation of short-circuit currents

1 Scope

This part of IEC 60909, which is a Technical Report, is intended to give help for the application of IEC 60909-0 for the calculation of short-circuit currents in 50 Hz or 60 Hz three-phase AC systems.

This document does not include additional requirements but gives support for the modelling of electrical equipment in the positive-sequence, the negative-sequence and the zero-sequence system (Clause 4), the practical execution of calculations in a low-voltage system (Clause 5), a medium-voltage system with asynchronous motors (Clause 6) and a power station unit with its auxiliary network feeding a large number of medium-voltage asynchronous motors and low-voltage motor groups (Clause 7).

The three examples given in Clauses 5, 6 and 7 are similar to those given in IEC TR 60909-4:2000 but they are revised in accordance with IEC 60909-0, which replaces it. The example given in Clause 8 is new and mirrors the introduction of the new 6.8 of IEC 60909-0:2016.

Clause 9 gives the circuit diagram and the data of a test network and the results for a calculation carried out in accordance with IEC 60909-0, to offer the possibility for a comparison between the results found with a digital program for the calculation of short-circuit currents and the given results for I''_{k}, i_{p}, I_{b}, I_{k}, I''_{k1} and i_{p1} in a high-voltage network with power station units, generators, asynchronous motors and lines in four different voltage levels 380 kV, 110 kV, 30 kV and 10 kV.

2 Normative references

IEC 60038:2009, *IEC standard voltages*

IEC 60909-0:2016, *Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*

3 Terms and definitions, symbols and indices, and formulae

For the purposes of this document, the terms and definitions, symbols and indices, and formulae given in IEC 60909-0 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

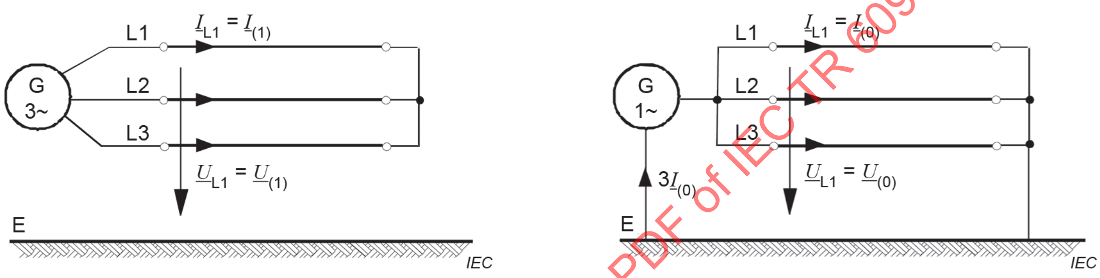
4 Positive-sequence, negative-sequence and zero-sequence impedances of electrical equipment

4.1 General

In addition to Clause 6 of IEC 60909-0:2016, modelling and calculation of the positive-sequence and the zero-sequence impedances of electrical equipment is given. In most cases, the negative-sequence impedances are equal to the positive-sequence impedances when calculating the initial symmetrical short-circuit currents, but see 6.6.1 of IEC 60909-0:2016 and IEC TR 60909-2.

4.2 Overhead lines, cables and short-circuit current-limiting reactors

Figure 1 demonstrates the meaning and the principal measurement of the positive-sequence [Figure 1 a)] and the zero-sequence [Figure 1 b)] impedances of lines with one circuit L1, L2, L3.



a) Positive-sequence **b) Zero-sequence**

NOTE Positive-sequence:

$$\underline{Z}_{(1)} = \underline{U}_{L1}/\underline{I}_{L1} = \underline{U}_{(1)}/\underline{I}_{(1)} \text{ with } \underline{U}_{L1} + \underline{U}_{L2} + \underline{U}_{L3} = 0 \text{ and } U_{L1} = U_{L2} = U_{L3}$$

Zero-sequence:

$$\underline{Z}_{(0)} = \underline{U}_{L1}/\underline{I}_{L1} = \underline{U}_{(0)}/\underline{I}_{(0)} \text{ with } \underline{U}_{L1} = \underline{U}_{L2} = \underline{U}_{L3} = \underline{U}_{(0)} \text{ and } \underline{I}_{L1} = \underline{I}_{L2} = \underline{I}_{L3} = \underline{I}_{(0)}$$

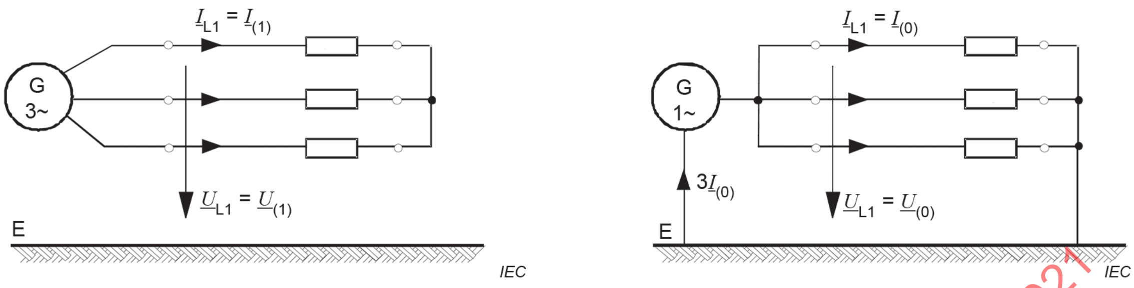
Figure 1 – Positive-sequence and zero-sequence impedances of an overhead line (one circuit) and cable (cross-bonded)

In practice, the measurement of voltage U_{L1} and current I_{L1} leads to the absolute value Z of the impedance. Together with the measurement of the total loss P_V at the current I_{L1}, it is possible to find the complex value $\underline{Z}$ of the impedance:

$$Z = \frac{U_{L1}}{I_{L1}} \qquad R = \frac{P_V}{3I_{L1}^2} \qquad X = \sqrt{Z^2 - R^2} \qquad \underline{Z} = R + jX$$

Formulae for the calculation of the positive-sequence and the zero-sequence system impedances of overhead lines with one or two parallel circuits (double circuit line) and without or with one or two earth wires are given in IEC TR 60909-2. The negative-sequence impedance is equal to the positive-sequence impedance assuming transposed lines and cross-bonded cables, respectively. The measurements to find the positive-sequence and the zero-sequence impedances of cables with sheath, shielding and armouring are similar to those given in Figure 1. Examples are given in IEC TR 60909-2. In the case of the zero-sequence impedance, the earthing of the sheath or the shielding or the armouring is important as well as the number of parallel cables. In the case of low-voltage four-core cables, the cross-section of the earthed core has an influence on the zero-sequence impedance.

Figure 2 demonstrates the meaning and the principal measurement of the positive-sequence [Figure 2 a)] and the zero-sequence impedance [Figure 2 b)] of a three-phase AC short-circuit current-limiting reactor.



a) Positive-sequence **b) Zero-sequence**

NOTE Positive-sequence:

$$\underline{Z}_{(1)} = \underline{U}_{L1}/\underline{I}_{L1} = \underline{U}_{(1)}/\underline{I}_{(1)} \text{ with } \underline{U}_{L1} + \underline{U}_{L2} + \underline{U}_{L3} = 0 \text{ and } U_{L1} = U_{L2} = U_{L3}$$

Zero-sequence:

$$\underline{Z}_{(0)} = \underline{U}_{L1}/\underline{I}_{L1} = \underline{U}_{(0)}/\underline{I}_{(0)} \text{ with } \underline{U}_{L1} = \underline{U}_{L2} = \underline{U}_{L3} = \underline{U}_{(0)} \text{ and } \underline{I}_{L1} = \underline{I}_{L2} = \underline{I}_{L3} = \underline{I}_{(0)}$$

Figure 2 – Positive-sequence and zero-sequence impedance of a short-circuit current-limiting reactor

If the magnetic coupling between the three coils without or with iron core is small, the zero-sequence impedance $\underline{Z}_{(0)}$ is approximately equal to the positive-sequence impedance $\underline{Z}_{(1)}$. When calculating short-circuit currents in high-voltage systems, it is generally sufficient to use the reactance only.

4.3 Transformers

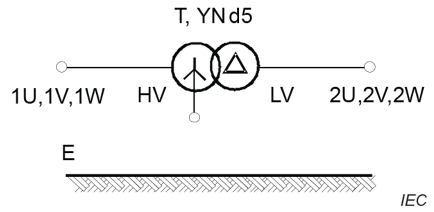
4.3.1 General

Unit transformers of power station units are also dealt with in 4.4.

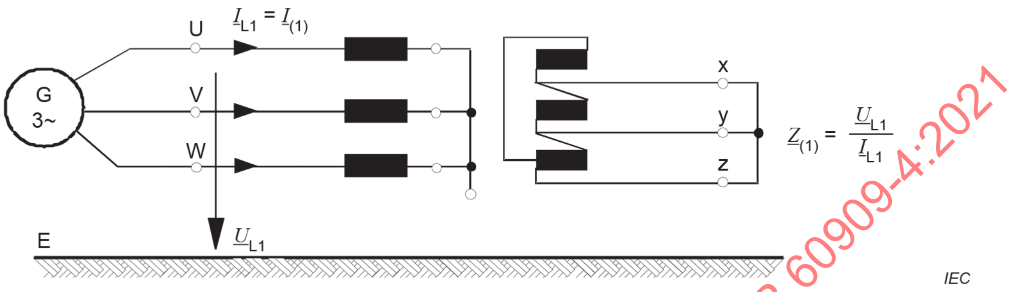
Network transformers have two, or three or even more three-phase windings. Figure 3 gives an example for the positive-sequence [Figure 3 b)] and the zero-sequence system impedances [Figure 3 c)] of a two-winding transformer with the vector group YNd5 [Figure 3 a)].

In the case of three-winding transformers (examples are given in Table 3 of IEC TR 60909-2:2008), it is necessary to measure three different impedances and then to calculate the three impedances of the equivalent circuit in the positive-sequence or the zero-sequence system of the transformer (see 6.3.2 of IEC 60909-0:2016 and the example in 4.3.2 of this document).

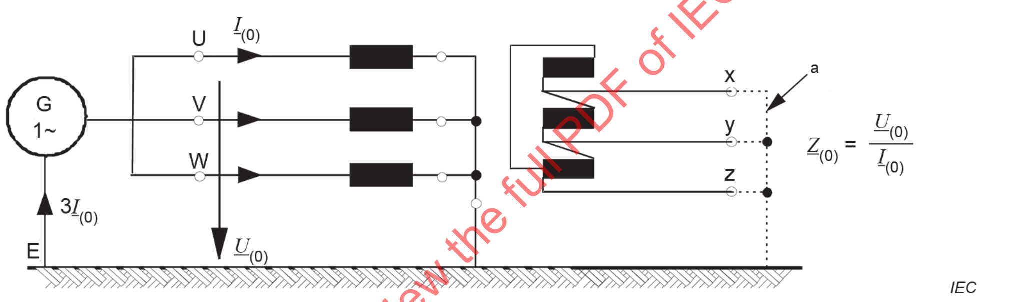
Table 1 gives examples for the equivalent circuits in the positive-sequence and the zero-sequence system of two- and three-winding transformers with different earthing conditions on the HV- and the LV-side. The impedances of Table 1 are related to side A, which may be the HV-side or the LV-side of the transformer.



a) **Two-winding transformer with the terminals 1U,1V,1W at the high-voltage side and 2U,2V,2W at the low-voltage side**



b) **Positive-sequence and negative-sequence impedance $\underline{Z}_{(1)} = \underline{Z}_{(2)}$**



c) **Zero-sequence impedance $\underline{Z}_{(0)}$**

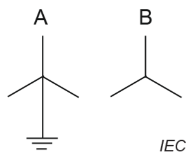
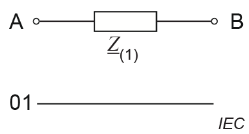
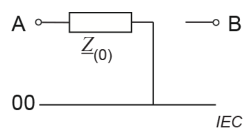
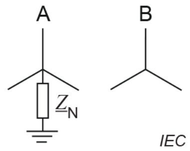
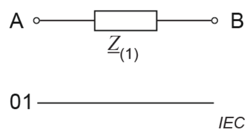
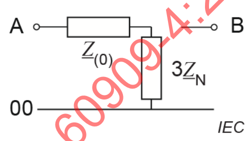
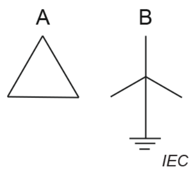
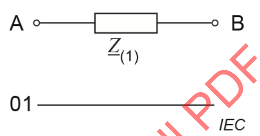
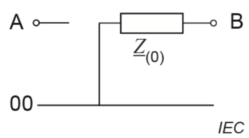
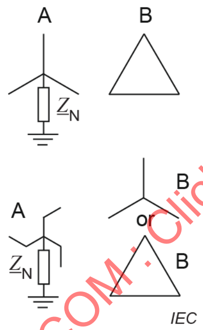
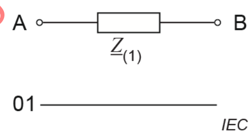
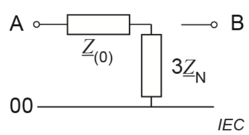
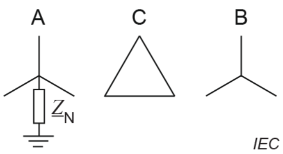
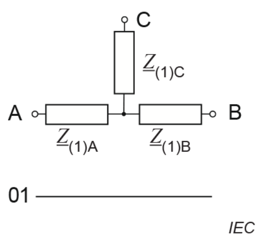
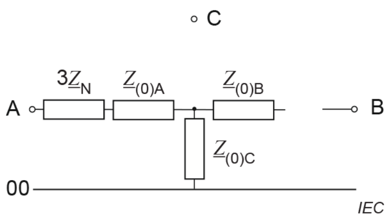
[a] In the case of a delta winding, it is not necessary to introduce the short circuit and the earth connection.

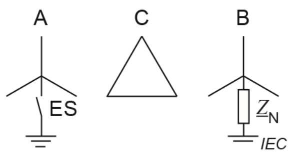
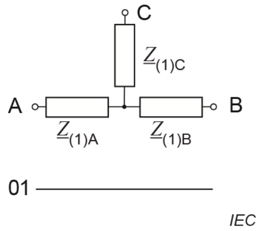
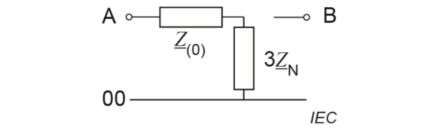
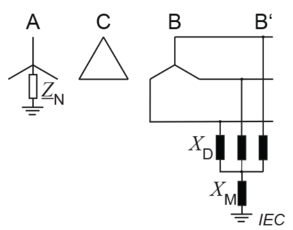
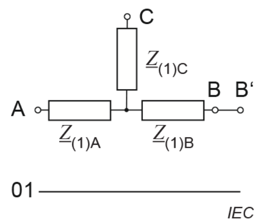
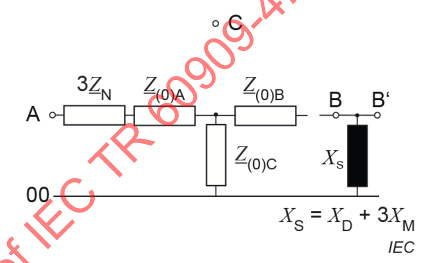
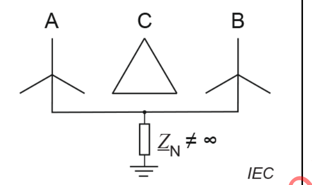
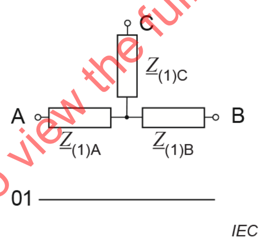
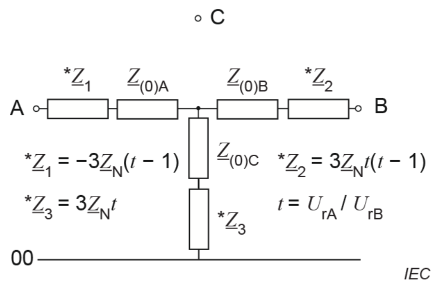
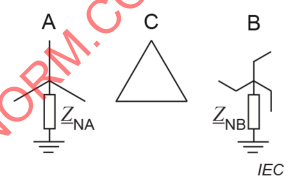
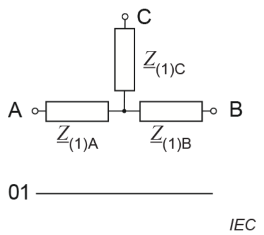
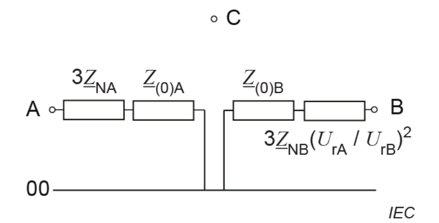
Figure 3 – Positive-sequence and zero-sequence system impedances of a two-winding transformer YNd5

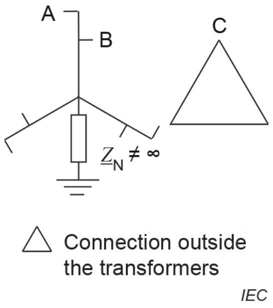
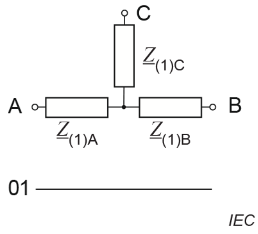
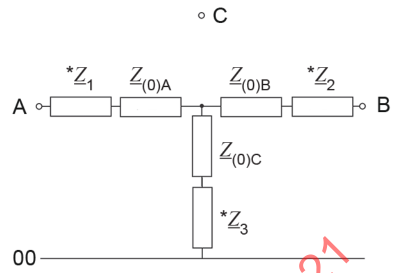
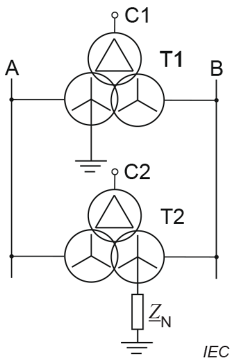
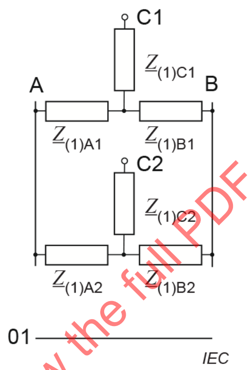
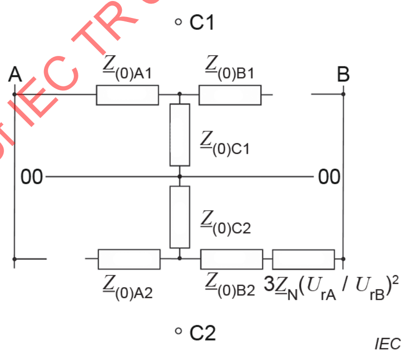
As shown in Table 2, transformers with the vector group Yy should not be used in low-voltage systems with low-impedance earthing on the LV-side (TN-network), because $Z_{(0)}$ may be very high, so that short-circuit protection may fail. For feeding TN-networks, transformers of no. 2 or 3 in Table 1 should be used.

Transformers with the vector group YNyn,d are typical in high-voltage networks, with neutral point earthing normally only on one side (A or B). The examples no. 4b and 6 of Table 1 show that the zero-sequence system of both networks are coupled, if both the neutral points A and B are earthed (earthing switch ES in case no. 4b closed). In these cases, additional considerations are necessary, especially if the transformation ratio is high, to find out if this coupling is admissible. Case no. 5 of Table 1 gives an example how to avoid this coupling in the zero-sequence system. Case no. 9 of Table 1 gives a further example to avoid the coupling in the zero-sequence system if two parallel transformers at the same place or at different places are present.

Table 1 – Examples for equivalent circuit-diagrams of transformers in the positive-sequence and the zero-sequence system

No.	Vector group	Transformer	Positive-sequence system	Zero-sequence system
1a	YNy		a) 	b) 
1b	YNy		a) 	b) 
2	Dyn		a) 	b) 
3	YNd ZNy ZNd		a) 	b) 
4a	YNdy		c) 	d) 

No.	Vector group	Transformer	Positive-sequence system	Zero-sequence system
4b	YNdyn	e) 	c) 	d) 
5	YNdz		c) 	d) 
6	YNdyn		f) 	g) 
7	YNdzn		f) 	g) 

No.	Vector group	Transformer	Positive-sequence system	Zero-sequence system
8	YNa+d	Auto-transformer with three separate units 	f) 	g)  $^*\underline{Z}_1$, $^*\underline{Z}_2$, $^*\underline{Z}_3$ as in case No. 6 $\underline{Z}_{(0)A} = \underline{Z}_{(1)A}$; $\underline{Z}_{(0)B} = \underline{Z}_{(1)B}$; $\underline{Z}_{(0)C} = \underline{Z}_{(1)C}$ IEC
9	YNdy Ydyn	h) 	f) 	g) 

a) $\underline{Z}_{(1)K} = K_T\, \underline{Z}_{(1)}$; K_T from Formula (12a) or (12b) of IEC 60909-0:2016.

b) $\underline{Z}_{(0)K} = K_T\, \underline{Z}_{(0)}$, K_T from Formula (12a) or (12b) of IEC 60909-0:2016; ZN without correction factor.

c) K_{TAB}, K_{TAC}, K_{TBC} from Formula (13) of IEC 60909-0:2016.

d) Correction factors as indicated under 3); $\underline{Z}_N$ and X_S without correction factor.

e) Earthing switch.

f) K_{TAB}, K_{TAC}, K_{TBC} from Formula (13) of IEC 60909-0:2016.

g) Corrections factors as indicated under 3); $\underline{Z}_N$ without correction factor.

h) Two parallel three-winding transformers with an earthing pattern to separate the zero-sequence systems of the networks A and B.

In case no. 8 for auto-transformers with neutral point earthing $\underline{Z}_N \neq \infty$, three separate units and an additional auxiliary winding in delta connection, the coupling between the zero-sequence systems of the networks connected to both sides of the transformer cannot be avoided. To find the impedances $^*\underline{Z}_1$, $^*\underline{Z}_2$ and $^*\underline{Z}_3$ as a function of $\underline{Z}_N \neq \infty$, special calculations are necessary as given under case no. 6 in Table 1.

Booster transformers (or regulating transformers for voltage and/or phase-angle control) are represented as network transformers with an equivalent generally of form no. 6 in Table 1. The construction and connection arrangement of shunt transformers will determine whether $\underline{Z}_{(0)C}$ has a finite low value and, in this case, it will be necessary to measure three different impedances, as with three-winding transformers, in order to calculate the impedances of the equivalent circuit.

Table 2 gives some approximations for the ratios $X_{(0)T}/X_T$ of transformers, if one neutral point of the transformer is earthed. In the case of three-winding transformers (cases no. 4 to 7 and 9 of Table 1), the reactance $X_T = X_{(1)T}$ is given by $X_{(1)T} = X_{(1)A} + X_{(1)B}$.

Table 2 – Approximations for the ratios $X_{(0)T}/X_T$ of two- and three-winding transformers

Construction of transformers	Vector group			
	YNd or Dyn	Yzn	YNynd	YNy [c] or YNz
Three cores	0,7...1,0 [a]	0,1...0,15	1...3,5 [b]	3...10
Five cores	1,0			10...100
Three single-core transformers	1,0			10...100

[a] Transformers with small apparent power: $X_{(0)T}/X_T \approx 1{,}0$ (for instance distribution transformers Dyn5 with S_{rT} = 400 kVA, U_{rTHV}/U_{rTLV} = 10 kV/0,4 kV).

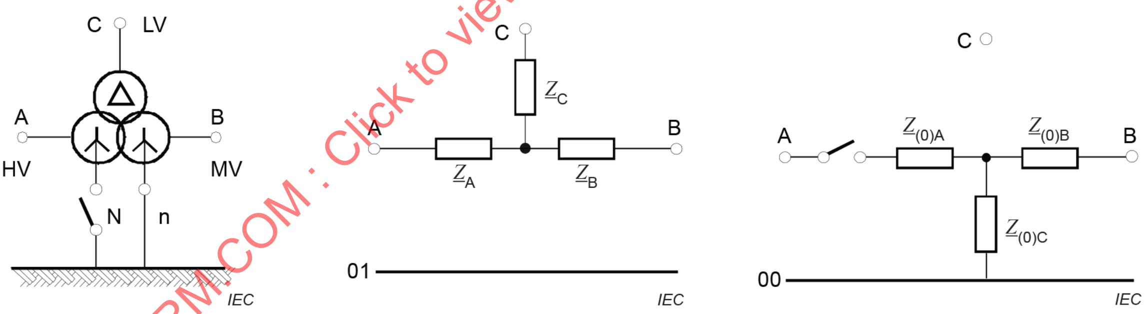
[b] The ratio $X_{(0)T}/X_T$ depends on the construction of the transformer, see IEC TR 60909-2.

[c] Transformers Yy should not be used in networks with low impedance earthing, for instance in low-voltage TN-networks (see IEC 60364-4-41).

4.3.2 Example

The following is an example for the impedances and equivalent circuits of a three-winding network transformer YNynd5, S_{rTHVMV} = 350 MVA.

Figure 4 gives the equivalent circuits of a three-winding network transformer [Figure 4 a)] in the positive-sequence [Figure 4b)] and the zero-sequence system [Figure 4c)]. The negative-sequence system is equal to the positive-sequence system (see no. 4b in Table 1 with $Z_N = 0$).



a) Vector group and terminals of the transformer YNynd5

b) Positive-sequence system

c) Zero-sequence system

Figure 4 – Equivalent circuits of a three-winding network transformer

The following data are given from measurements:

U_{rTHV} = 400 kV	U_{rTMV} = 120 kV	U_{rTLV} = 30 kV
S_{rTHV} = 350 MVA	S_{rTMV} = 350 MVA	S_{rTLV} = 50 MVA
u_{krHVMV} = 21 %; u_{RrHVMV} = 0,26 %;	referred to S_{rTHVMV} = 350 MVA	U_{rTHV} = 400 kV
u_{krHVLV} = 10 %; u_{RrHVLV} = 0,16 %	referred to S_{rTHVLV} = 50 MVA	U_{rTHV} = 400 kV
u_{krMVLV} = 7 %; u_{RrMVLV} = 0,16 %	referred to S_{rTMVLV} = 50 MVA	U_{rTMV} = 120 kV

From Formula (10) of IEC 60909-0:2016, the following impedances of the positive-sequence system are found, related to the MV-side B:

$$\underline{Z}_{AB} = \left(\frac{u_{RrHVMV}}{100\ \%} + j\,\frac{u_{XrHVMV}}{100\ \%} \right) \frac{U_{rTMV}^2}{S_{rTHVMV}} = (0{,}106\,971 + j8{,}639\,338)\ \Omega$$

$$\underline{Z}_{AC} = \left(\frac{u_{RrHVLV}}{100\ \%} + j\,\frac{u_{XrHVLV}}{100\ \%} \right) \frac{U_{rTMV}^2}{S_{rTHVLV}} = (0{,}460\,800 + j28{,}796\,313)\ \Omega$$

$$\underline{Z}_{BC} = \left(\frac{u_{RrMVLV}}{100\ \%} + j\,\frac{u_{XrMVLV}}{100\ \%} \right) \frac{U_{rTMV}^2}{S_{rTMVLV}} = (0{,}460\,800 + j20{,}154\,733)\ \Omega$$

The calculations are carried out here with six-figure numbers following the decimal comma, because this example is used also for the test network in Clause 9 (transformers T3 = T4).

With the rated relative reactances x_T found from the reactive short-circuit voltage $u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2}$ according to Formula (10d) and Table 1 of IEC 60909-0:2016, the following impedance correction factors (Formula (13) of IEC 60909-0:2016) are found:

$$K_{TAB} = 0{,}95 \frac{c_{max}}{1 + 0{,}6\,x_{TAB}} = 0{,}95 \frac{1{,}1}{1 + 0{,}6 \cdot 0{,}209\,984} = 0{,}928\,072$$

$$K_{TAC} = 0{,}95 \frac{c_{max}}{1 + 0{,}6\,x_{TAC}} = 0{,}95 \frac{1{,}1}{1 + 0{,}6 \cdot 0{,}099\,987} = 0{,}985\,856$$

$$K_{TBC} = 0{,}95 \frac{c_{max}}{1 + 0{,}6\,x_{TBC}} = 0{,}95 \frac{1{,}1}{1 + 0{,}6 \cdot 0{,}069\,982} = 1{,}002\,890$$

Together with these correction factors, for instance $\underline{Z}_{ABK} = K_{TAB}\,\underline{Z}_{AB}$, the following corrected impedances (index K) are found:

$$\underline{Z}_{ABK} = (0{,}099\,277 + j8{,}017\,927)\,\Omega$$

$$\underline{Z}_{ACK} = (0{,}454\,283 + j28{,}389\,024)\,\Omega$$

$$\underline{Z}_{BCK} = (0{,}462\,132 + j20{,}212\,973)\,\Omega$$

The corrected equivalent positive-sequence impedances in Figure 4 b), related to the MV-side, are calculated with Formulae (11a), (11b), (11c) of IEC 60909-0:2016.

$$\underline{Z}_{AK} = (0{,}045\,714 + j8{,}096\,989)\,\Omega$$

$$\underline{Z}_{BK} = (0{,}053\,563 - j0{,}079\,062)\,\Omega$$

$\underline{Z}_{CK} = (0{,}408\,568 + j20{,}292\,035)\,\Omega$

For the equivalent model of the transformer in the zero-sequence system [Figure 4 c)], the following reactances are known, related to the medium-voltage side B:

$X_{(0)A} = 8{,}555\,1\ \Omega$ $X_{(0)B} = -0{,}688\,1\ \Omega$ $X_{(0)C} = 18{,}830\,71\ \Omega$

If only the medium-voltage neutral point of the transformer is earthed, the effective zero-sequence reactance is the sum of $X_{(0)B}$ and $X_{(0)C}$ leading to $X_{(0)MVK}$ when introducing the impedance correction factor K_{TBC}:

$$X_{(0)MVK} = K_{TBC}(X_{(0)B} + X_{(0)C}) = 18{,}195\,036\ \Omega$$

4.4 Generators and power station units

4.4.1 General

For synchronous generators without unit transformers in low- and medium-voltage networks, the positive-sequence reactances are X_d'', X_d' and X_d (see IEC TR 60909-2). In the first moment of short circuit, the subtransient reactance X_d'' leads to I_k''.

In this case $X_q'' \approx X_d''$ and therefore the reactance of the negative-sequence system is approximately equal to the subtransient reactance: $X_{(2)} \approx X_d''$. If X_q'' is considerably different from X_d'', then $X_{(2)} = 0{,}5\left(X_d'' + X_q''\right)$ should be used (see Formula (19) of IEC 60909-0:2016).

The zero-sequence reactance $X_{(0)}$ is smaller than the subtransient reactance and depends on the winding configuration of the synchronous machine (see 2.2 of IEC TR 60909-2:2008). If the neutral point of the generator is earthed by an additional impedance (preferably a reactance between neutral point and earth to limit the line-to-earth short-circuit current $I_{k1}'' \leq I_k''$ and/or to suppress third-order currents in the case of generators in parallel to transformers with neutral points, which are earthed in the same part of the network), the impedance correction factor K_G shall be used in the positive-sequence, the negative-sequence, and the zero-sequence system. But K_G shall not be used for the additional neutral point impedance (see 6.6.1 of IEC 60909-0:2016).

The zero-sequence impedance [Figure 5 c)] at the high-voltage side of the power station unit is given by the zero-sequence impedance of the unit transformer and the threefold value of the impedance Z_N between the neutral point of the transformer (HV-side) and earth, in the case of a power station unit (S) with on-load tap changer [Figure 5 a)] (see 6.7.1 of IEC 60909-0:2016) or without on-load tap changer (see 6.7.2 of IEC 60909-0:2016). The positive-sequence and the negative-sequence impedance [Figure 5 b)] of the power station unit shall be calculated with Formula (21) or Formula (23) of IEC 60909-0:2016 together with the impedance correction factor K_S from Formula (22) or K_{SO} from Formula (24) of IEC 60909-0:2016. The zero-sequence impedance of the power station unit is found with $\underline{Z}_{(0)SK} = K_S \cdot \underline{Z}_{(0)THV} + 3\underline{Z}_N$, respectively $\underline{Z}_{(0)SOK} = K_{SO} \cdot \underline{Z}_{(0)THV} + 3\underline{Z}_N$.

The impedance correction factor shall be used as follows:

a) for the positive-sequence impedance:

$$\underline{Z}_{\text{SK}} = K_{\text{S}} \cdot \left[t_{\text{r}}^{2} \cdot \left(R_{\text{G}} + \text{j} X_{\text{d}}^{"} \right) + \underline{Z}_{\text{THV}} \right] \qquad \underline{Z}_{\text{SOK}} = K_{\text{SO}} \cdot \left[t_{\text{r}}^{2} \cdot \left(R_{\text{G}} + \text{j} X_{\text{d}}^{"} \right) + \underline{Z}_{\text{THV}} \right]$$

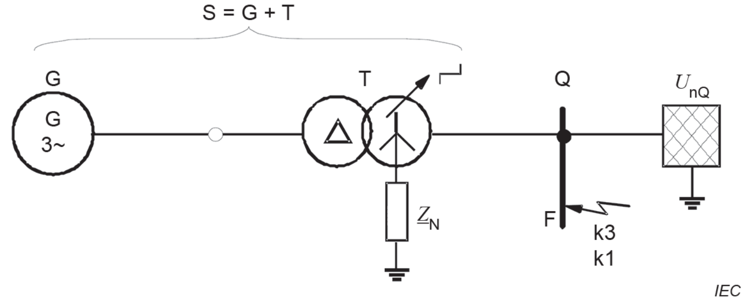
d) for the negative-sequence impedance:

$$\underline{Z}_{(2)\text{SK}} = K_{\text{S}} \cdot \left[t_{\text{r}}^{2} \cdot \left(R_{\text{G}} + \text{j} X_{(2)\text{G}} \right) + \underline{Z}_{\text{THV}} \right] \qquad \underline{Z}_{(2)\text{SOK}} = K_{\text{SO}} \cdot \left[t_{\text{r}}^{2} \cdot \left(R_{\text{G}} + \text{j} X_{(2)\text{G}} \right) + \underline{Z}_{\text{THV}} \right]$$

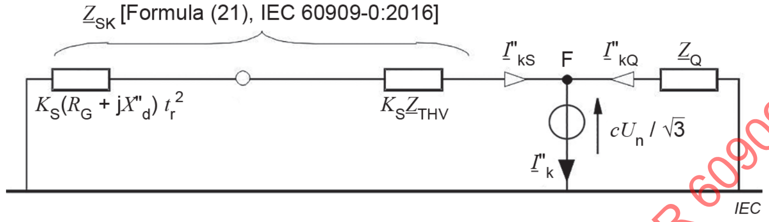
e) for the zero-sequence impedance:

$$\underline{Z}_{(0)\text{SK}} = K_{\text{S}} \cdot \underline{Z}_{(0)\text{THV}} + 3\underline{Z}_{\text{N}} \qquad \underline{Z}_{(0)\text{SOK}} = K_{\text{SO}} \cdot \underline{Z}_{(0)\text{THV}} + 3\underline{Z}_{\text{N}}$$

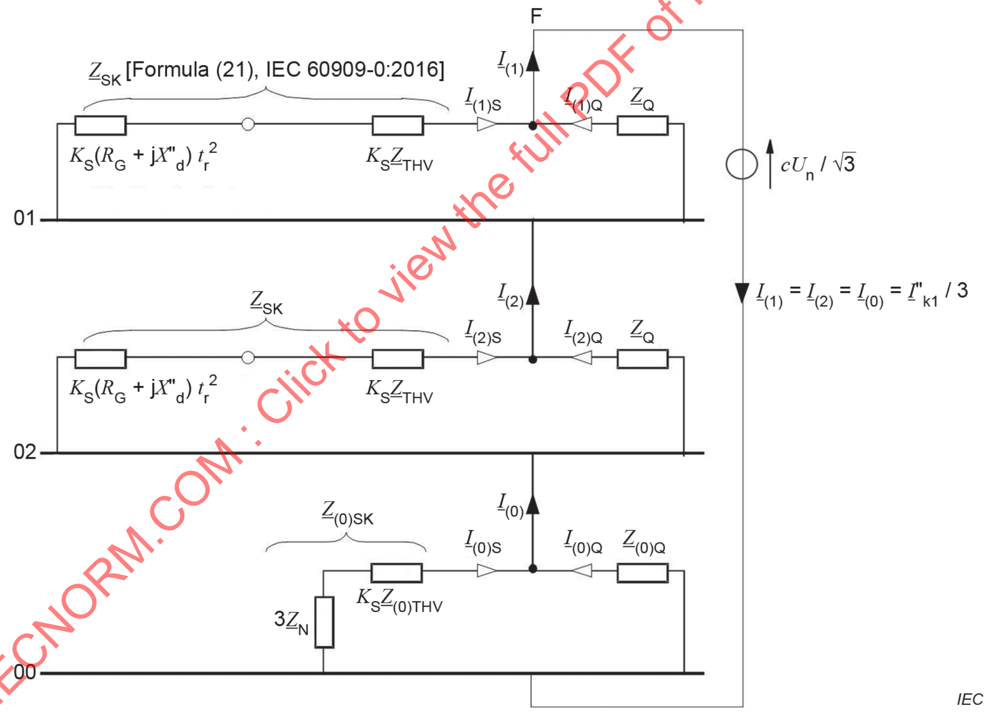
The current $3I_{(0)\text{S}}$ passes from the neutral point of the unit transformer to the impedance $\underline{Z}_{\text{N}}$, if this exists; the earthing arrangement of the power station hence leads to a potential rise of the touch and step voltages.



a) Circuit diagram



b) Positive-sequence system for the calculation of I_{k}''



c) Positive-, negative- and zero-sequence system for the calculation of I_{k1}'' **and the partial short-circuit currents** $I_{(1)Q}$, $I_{(2)Q}$, $I_{(0)Q}$, $I_{(1)S}$, $I_{(2)S}$, **and** $I_{(0)S}$, $X_{(2)G} = X_{d}''$

Figure 5 – Short circuit at the high-voltage side of a power station unit with on-load tap changer

If the partial short-circuit currents $I_{(1)S}$, $I_{(2)S}$ and $I_{(0)S}$ are calculated, the impedance correction factor according to Formula (22) of IEC 60909-0:2016 for power station units with on-load tap-changer shall be introduced, depending on the possible operating range of the generator (see IEC 60909-0). In the case of power station units without on-load tap-changer, the correction factor K_{SO} from Formula (24) of IEC 60909-0:2016 can be used when calculating $I_{(1)SO}$, $I_{(2)SO}$ and $I_{(0)SO}$.

4.4.2 Example

Example for the calculation of impedances and short-circuit currents in the case of a short circuit at the high-voltage side of a power station unit with on-load tap-changer.

For this example, the data of the power station S1 = G1 + T1 in Figure 20 shall be used. The neutral point of the unit transformer YNd5 is earthed through a reactance X_{R1} = 22 Ω (R_{R1} << X_{R1}) to reduce the earth-fault factor in the case of load rejection and a simultaneous line-to-earth short circuit at the high-voltage side of the unit transformer (see 9.2.1).

– Generator:

S_{rG} = 150 MVA; U_{rG} = 21 kV; x''_d = 0,14 p.u.; x_{dsat} = 1,8 p.u.; $\cos\varphi_{rG}$ = 0,85; R_G = 0,002 Ω (turbogenerator working only in the overexcited region)

– Unit transformer:

S_{rT} = 150 MVA; U_{rTHV}/U_{rTLV} = 115 kV/21 kV; u_{kr} = 16 %; u_{Rr} = 0,5 %; $X_{(0)T}/X_T$ = 0,95; $R_{(0)T}/R_T$ = 1,0; $\underline{Z}_N = \mathrm{j}X_{R1}$ = j 22 Ω

– Network feeder (found from a network reduction):

U_{nQ} = 110 kV; c_{Qmax} = 1,1; $I''_{kQ} = 13{,}612\,13\ \mathrm{kA}$; R_Q/X_Q = 0,203 28; $X_{(0)Q}/X_Q$ = 3,479 27; $R_{(0)Q}/R_Q$ = 3,033 61

The following results are found for this example (see Figure 5):

$$\underline{Z}_G = R_G + \mathrm{j}X''_d = \left(0{,}002\ \Omega + \mathrm{j}0{,}14\frac{(21\ \mathrm{kV})^2}{150\ \mathrm{MVA}}\right) = (0{,}002 + \mathrm{j}0{,}4116)\Omega$$

$$\underline{Z}_{Gt} = \underline{Z}_G \cdot t_r^2 = (0{,}059\,98 + \mathrm{j}12{,}343\,33)\Omega \quad \text{with} \quad t_r = 115\ \mathrm{kV}/21\ \mathrm{kV}$$

$$\underline{Z}_{THV} = \left(\frac{u_{Rr}}{100\,\%} + \mathrm{j}\frac{u_{Xr}}{100\,\%}\right)\frac{U_{rTHV}^2}{S_{rT}} = (0{,}440\,83 + \mathrm{j}14{,}099\,78)\Omega$$

with $u_{Xr} = \sqrt{u_{kr}^2 - u_{Rr}^2} = 15{,}992\,19\ \%$ $\quad (x_T = 0{,}159\,9219\ \mathrm{p.u.})$

$$K_S = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTLV}^2}{U_{rTHV}^2} \cdot \frac{c_{max}}{1 + \left|x''_d - x_T\right|\sqrt{1 - \cos^2\varphi_{rG}}} = 0{,}995\,97$$ (see Formula (22) of IEC 60909-0:2016):

$$\underline{Z}_{SK} = K_S \cdot \left[t_r^2 \cdot \underline{Z}_G + \underline{Z}_{THV}\right] = (0{,}498\,79 + \mathrm{j}26{,}336\,68)\Omega$$

In the case of a three-phase short circuit (Figure 5) with $U_n = U_{nQ}$:

$$\underline{I}''_{kS} = \frac{cU_n}{\sqrt{3}\underline{Z}_{SK}} = (0{,}050\,22 - \mathrm{j}2{,}651\,60)\mathrm{kA} \qquad I''_{kS} = 2{,}652\,08\ \mathrm{kA}$$

$$\underline{I}''_{kQ} = \frac{cU_n}{\sqrt{3}\,\underline{Z}_Q} = (2{,}711\,61 - j13{,}339\,31)\text{kA} \qquad I''_{kQ} = 13{,}612\,13\ \text{kA}$$

with $Z_Q = \frac{1{,}1\,U_{nQ}}{\sqrt{3}\,I''_{kQ}}$ and $X_Q = \frac{Z_Q}{\sqrt{1+(R_Q\,/\,X_Q)^2}} = 0{,}979\,96\ Z_Q$

$$\underline{I}''_k = \underline{I}''_{kS} + \underline{I}''_{kQ} = (2{,}761\,83 - j15{,}990\,91)\ \text{kA} \qquad I''_k = 16{,}227\,66\ \text{kA}$$

This result is also given in Table 22 for the test network.

Line-to-earth short-circuit current $\underline{I}''_{k1}$ (see Formula (54) of IEC 60909-0:2016):

$$\underline{Z}_{(1)} = \frac{\underline{Z}_{SK}\underline{Z}_Q}{\underline{Z}_{SK}+\underline{Z}_Q} = (0{,}732\,67 + j4{,}242\,15)\Omega \qquad \underline{Z}_{(2)} = \underline{Z}_{(1)}$$

$$\underline{Z}_{(0)} = \frac{\underline{Z}_{(0)SK}\underline{Z}_{(0)Q}}{\underline{Z}_{(0)SK}+\underline{Z}_{(0)Q}} = (2{,}093\,92 + j14{,}398\,90)\Omega$$

with $\underline{Z}_{(0)SK} = K_S\underline{Z}_{(0)THV} + 3\underline{Z}_N$

$= (0{,}440\,83 + j0{,}95 \cdot 14{,}099\,78)\Omega \cdot 0{,}995\,98 + j66\,\Omega = (0{,}439\,06 + j79{,}340\,87)\Omega$

and $\underline{Z}_{(0)Q} = (3{,}101\,42 + j17{,}498\,23)\Omega$

$$\underline{I}''_{k1} = \frac{\sqrt{3}\,c\,U_n}{\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)}} = \frac{\sqrt{3}\,c\,U_n}{2\,\underline{Z}_{(1)} + \underline{Z}_{(0)}} = (1{,}390\,88 - j8{,}942\,26)\text{kA} \qquad I''_{k1} = 9{,}049\,79\ \text{kA}$$

This result is also given in Table 23 for the test network.

Partial short-circuit currents in Figure 5:

$$\underline{I}_{(1)S} = \underline{I}_{(2)S} = \frac{\underline{I}''_{k1}}{3} \cdot \frac{\underline{Z}_Q}{\underline{Z}_{SK} + \underline{Z}_Q} = (0{,}001\,09 - j0{,}493\,00)\text{kA}$$

$$\underline{I}_{(1)Q} = \underline{I}_{(2)Q} = \frac{\underline{I}''_{k1}}{3} \cdot \frac{\underline{Z}_S}{\underline{Z}_{SK} + \underline{Z}_Q} = (0{,}462\,54 - j2{,}487\,76)\text{kA}$$

$$\underline{I}_{(0)S} = \frac{\underline{I}''_{k1}}{3} \cdot \frac{\underline{Z}_{(0)Q}}{\underline{Z}_{(0)SK} + \underline{Z}_{(0)Q}} = (0{,}008\,53 - j0{,}553\,14)\text{kA}$$

$$\underline{I}_{(0)Q} = \frac{\underline{I}''_{k1}}{3} \cdot \frac{\underline{Z}_{(0)SK}}{\underline{Z}_{(0)SK} + \underline{Z}_{(0)Q}} = (0{,}455\,10 - j2{,}427\,61)\text{kA}$$

$$\underline{I}_{L1S} = \underline{I}_{(1)S} + \underline{I}_{(2)S} + \underline{I}_{(0)S} = (0{,}010\,72 - j1{,}539\,14)\text{kA}$$

$$\underline{I}_{L2S} = \underline{a}^2\underline{I}_{(1)S} + \underline{a}\underline{I}_{(2)S} + \underline{I}_{(0)S} = (0{,}007\,44 - j0{,}060\,14)\text{kA}$$

$$\underline{I}_{L3S} = \underline{a}\underline{I}_{(1)S} + \underline{a}^2\underline{I}_{(2)S} + \underline{I}_{(0)S} = (0{,}007\,44 - j0{,}060\,14)\text{kA}$$

Current from the transformer neutral point to the earthing arrangement:

$$\underline{I}_{L1S} + \underline{I}_{L2S} + \underline{I}_{L3S} = 3\underline{I}_{(0)S} = (0{,}025\,60 - j1{,}659\,42)\text{kA}$$

5 Calculation of short-circuit currents in a low-voltage system U_n = 400 V

5.1 Problem

A low-voltage system with U_n = 400 V and f = 50 Hz is given in Figure 6. The short-circuit currents I_k'' and i_p shall be determined at the short-circuit locations F1 to F3. It may be assumed that the short circuits at the locations F1 to F3 are far-from-generator short circuits (see 3.16 of IEC 60909-0:2016).

The equipment data for the positive-sequence, the negative-sequence and the zero-sequence systems are given in Table 3.

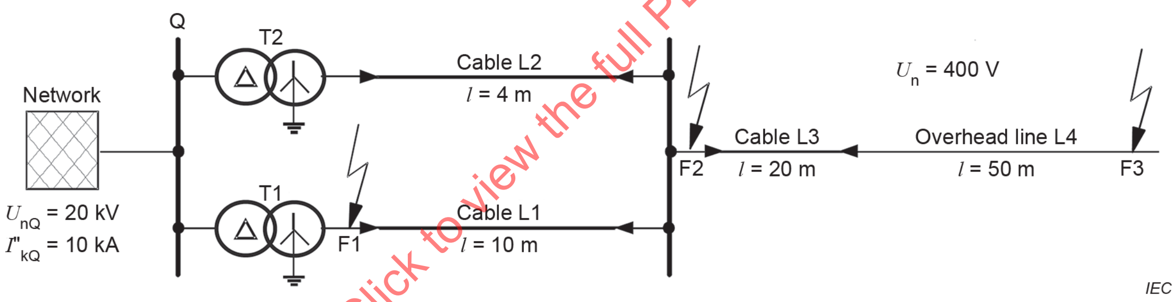


Figure 6 – Low-voltage system U_n = 400 V with short-circuit locations F1, F2, F3

5.2 Determination of the positive-sequence impedances

5.2.1 Network feeder

According to Formula (6) of IEC 60909-0:2016 with $c_Q = c_{Qmax} = 1{,}1$ (see Table 1 of IEC 60909-0:2016), it follows:

$$Z_{Qt} = \frac{c_Q\,U_{nQ}}{\sqrt{3}\,I''_{kQ}} \cdot \frac{1}{t_r^2} = \frac{1{,}1 \cdot 20\ \text{kV}}{\sqrt{3} \cdot 10\ \text{kA}}\left(\frac{0{,}41\ \text{kV}}{20\ \text{kV}}\right)^2 = 0{,}534\ \text{m}\Omega$$

$$X_{Qt} = \frac{Z_{Qt}}{\sqrt{1+(R_{Qt}/X_{Qt})^2}} = \frac{0{,}534}{\sqrt{1+(0{,}1)^2}}\ \text{m}\Omega = 0{,}531\ \text{m}\Omega \qquad R_{Qt} = 0{,}1\,X_{Qt} = 0{,}053\ \text{m}\Omega$$

$$\underline{Z}_{Qt} = (0{,}053 + j0{,}531)\ \text{m}\Omega$$

Table 3 – Data of electrical equipment for the example in Figure 6 – Positive-sequence and zero-sequence impedances ($\underline{Z}_{(2)} = \underline{Z}_{(1)}$)

Equipment	Data	Formulae (IEC 60909-0:2016)	$\underline{Z}_{(1)}$ mΩ	$\underline{Z}_{(0)}$ mΩ
Network feeder Q	U_{nQ} = 20 kV; I''_{kQ} = 10 kA $c_Q = c_{Qmax}$ = 1,1 (Table 1 of IEC 60909-0:2016) $R_Q = 0{,}1\ X_Q$	(6)	0,053 + j0,531	–
Transformers T1 (Dyn 5)	S_{rT} = 630 kVA; U_{rTHV} = 20 kV U_{rTLV} = 410 V; u_{kr} = 4 %; P_{krT} = 6,5 kW; $R_{(0)T}/R_T$ = 1,0; $X_{(0)T}/X_T$ = 0,95.	(7) to (9) K_T from (12a)	2,684 + j10,053	2,684 + j9,550
T2 (Dyn 5)	S_{rT} = 400 kVA; U_{rTHV} = 20 kV U_{rTLV} = 410 V; u_{kr} = 4 %; P_{krT} = 4,6 kW; $R_{(0)T}/R_T$ = 1,0; $X_{(0)T}/X_T$ = 0,95.		4,712 +j15,699	4,712 + j14,914
Lines L1	Two parallel four-core cables; ℓ = 10 m; 4 × 240 mm² Cu $\underline{Z}'_L$ = (0,077 + j0,079) Ω/km $R_{(0)L} = 3{,}7\ R_L$; $X_{(0)L} = 1{,}81\ X_L$.	Data and ratios $R_{(0)L}/R_L$ $X_{(0)L}/X_L$ given by the manufacturer (14), (15)	0,385 + j0,395	1,425 + j0,715
L2	Two parallel three-core cables; ℓ = 4 m; 3 × 185 mm² Al; $\underline{Z}'_L$ = (0,208 + j0,068) Ω/km $R_{(0)L} = 4{,}23\ R_L$; $X_{(0)L} = 1{,}21\ X_L$		0,416 + j0,136	1,760 + j0,165
L3	Four-core cable ℓ = 20 m; 4 × 70 mm² Cu; $\underline{Z}'_L$ = (0,271 + j0,087) Ω/km $R_{(0)L} = 3R_L$; $X_{(0)L} = 4{,}46X_L$.		5,420 + j1,740	16,260 + j7,760
L4	Overhead line; ℓ = 50 m: q_n = 50 mm² Cu; d = 0,4 m; r = 4,55 mm² $\underline{Z}'_L$ = (0,3704 + j0,297) Ω/km $R_{(0)L} = 2R_L$; $X_{(0)L} = 3X_L$.; n = 1		18,519 + j14,850	37,037 + j44,549

5.2.2 Transformers

According to Formulae (7) to (9) and (12a) of IEC 60909-0:2016, it follows:

– Transformer T1:

$$Z_{T1} = \frac{u_{krT1}}{100\%} \cdot \frac{U_{rT1LV}^2}{S_{rT1}} = \frac{4\%}{100\%} \cdot \frac{(410\,\text{V})^2}{630\,\text{kVA}} = 10{,}673\ \text{m}\Omega$$

$$R_{T1} = \frac{P_{krT1}}{3I_{rT1LV}^2} = \frac{P_{krT1}\,U_{rT1LV}^2}{S_{rT1}^2} = \frac{6{,}5\,\text{kW} \cdot (410\,\text{V})^2}{(630\,\text{kVA})^2} = 2{,}753\,\text{m}\Omega$$

$$X_{T1}=\sqrt{Z_{T1}^2-R_{T1}^2}=10{,}312\ \text{m}\Omega \qquad x_{T1}=\frac{X_{T1}}{U_{rT1LV}^2/S_{rT1}}=\frac{10{,}673\ \text{m}\Omega}{(410\,\text{V})^2/630\,\text{kVA}}=0{,}038\ 65\ \text{p.u.}$$

$$\underline{Z}_{T1}=(2{,}753+\text{j}10{,}312)\ \text{m}\Omega$$

$$K_{T1}=0{,}95\cdot\frac{c_{max}}{1+0{,}6x_{T1}}=0{,}95\cdot\frac{1{,}05}{1+0{,}6\cdot 0{,}038\ 65}=0{,}975$$

$$\underline{Z}_{T1K}=K_{T1}\,\underline{Z}_{T1}=(2{,}684+\text{j}10{,}053)\text{m}\Omega$$

– Transformer T2:

$$Z_{T2}=\frac{u_{krT2}}{100\,\%}\cdot\frac{U_{rT2LV}^2}{S_{rT2}}=\frac{4\,\%}{100\,\%}\cdot\frac{(410\ \text{V})^2}{400\ \text{kVA}}=16{,}810\ \text{m}\Omega$$

$$R_{T2}=\frac{P_{krT2}\,U_{rT2LV}^2}{S_{rT2}^2}=\frac{4{,}6\text{k W}\cdot(410\,\text{V})^2}{(400\ \text{kVA})^2}=4{,}833\ \text{m}\Omega$$

$$X_{T2}=\sqrt{Z_{T2}^2-R_{T2}^2}=16{,}100\ \text{m}\Omega \qquad x_{T1}=\frac{X_{T1}}{U_{rT1LV}^2/S_{rT1}}=\frac{16{,}100\ \text{m}\Omega}{(410\,\text{V})^2/400\,\text{kVA}}=0{,}038\ 31\ \text{p.u.}$$

$$\underline{Z}_{T2}=(4{,}833+\text{j}16{,}100)\text{m}\Omega$$

$$K_{T2}=0{,}95\cdot\frac{c_{max}}{1+0{,}6x_{T2}}=0{,}95\cdot\frac{1{,}05}{1+0{,}6\cdot 0{,}038\ 31}=0{,}975$$

$$\underline{Z}_{T2K}=K_{T2}\,\underline{Z}_{T2}=(4{,}712+\text{j}15{,}699)\text{m}\Omega$$

5.2.3 Lines (cables and overhead lines)

– Line L1 (two parallel four-core cables):

$$\underline{Z}_{L1}=0{,}5\cdot(0{,}077+\text{j}0{,}079)\frac{\Omega}{\text{km}}\cdot 10\ \text{m}=(0{,}385+\text{j}0{,}395)\text{m}\Omega$$

– Line L2 (two parallel three-core cables):

$$\underline{Z}_{L2}=0{,}5\cdot(0{,}208+\text{j}0{,}068)\frac{\Omega}{\text{km}}\cdot 4\,\text{m}=(0{,}416+\text{j}0{,}136)\text{m}\Omega$$

– Line L3 (four-core cable):

$$\underline{Z}_{L3}=(0{,}271+\text{j}0{,}087)\frac{\Omega}{\text{km}}\cdot 20\ \text{m}=(5{,}420+\text{j}1{,}740)\text{m}\Omega$$

– Line L4 (overhead line, according to Formulae (14) and (15) of IEC 60909-0:2016):

$$R_{L4}'=\frac{\rho}{q_n}=\frac{\Omega\text{mm}^2}{54\,\text{m}\cdot 50\,\text{mm}^2}=0{,}3704\frac{\Omega}{\text{km}}$$

$$X_{L4}'=2\pi f\frac{\mu_0}{2\pi}\left(\frac{1}{4}+\ln\frac{d}{r}\right)=2\pi\cdot 50\,\text{s}^{-1}\cdot\frac{4\pi\cdot 10^{-4}\,\text{H}}{2\pi\ \text{km}}\left(\frac{1}{4}+\ln\frac{0{,}4\text{m}}{0{,}455\cdot 10^{-2}\ \text{m}}\right)=0{,}297\frac{\Omega}{\text{km}}$$

$$\underline{Z}_{L4}=\left(R_{L4}'+\text{j}X_{L4}'\right)\cdot\ell=(0{,}370+\text{j}0{,}297)\frac{\Omega}{\text{km}}\cdot 50\,\text{m}=(18{,}519+\text{j}14{,}850)\text{m}\Omega$$

5.3 Determination of the zero-sequence impedances

5.3.1 Transformers

For the transformers T1 and T2 with the vector group Dyn5, the following relations are given by the manufacturers:

$R_{(0)T} = R_T$ and $X_{(0)T} = 0{,}95\ X_T$ (see Table 3)

Together with the impedance correction factors K_T from 5.2.2, the following zero-sequence impedances of the transformers are found:

$\underline{Z}_{(0)T1K} = K_{T1}(R_{T1} + \text{j}0{,}95\ X_{T1}) = 2{,}684 + \text{j}9{,}550)$ mΩ

$\underline{Z}_{(0)T2K} = K_{T2}(R_{T2} + \text{j}0{,}95\ X_{T2}) = 4{,}712 + \text{j}14{,}914)$ mΩ

5.3.2 Lines (cables and overhead lines)

– Line L1 (two parallel four-core cables):

  $R_{(0)L} = 3{,}7\ R_L$; $X_{(0)L} = 1{,}81\ X_L$ with return circuit by the fourth conductor and surrounding conductor:

  $\underline{Z}_{(0)L1} = (3{,}7R_{L1} + \text{j}1{,}81\ X_{L1}) = 1{,}425 + \text{j}0{,}715)$ mΩ

– Line L2 (two parallel three-core cables):

  $R_{(0)L} = 4{,}23\ R_L$; $X_{(0)L} = 1{,}21\ X_L$ with return by sheath:

  $\underline{Z}_{(0)L2} = (4{,}23R_{L2} + \text{j}1{,}21\ X_{L2}) = 1{,}760 + \text{j}0{,}165)$ mΩ

– Line L3 (four-core cable):

  $R_{(0)L} = 3\ R_L$; $X_{(0)L} = 4{,}46\ X_L$ with return circuit by the fourth conductor, sheath and earth:

  $\underline{Z}_{(0)L3} = (3R_{L3} + \text{j}4{,}46\ X_{L3}) = 16{,}260 + \text{j}7{,}760)$ mΩ

– Line L4:

  Overhead line with $R_{(0)L} = 2\ R_L$ and $X_{(0)L} = 3\ X_L$ when calculating the maximum short-circuit currents:

  $\underline{Z}_{(0)L4} = (2R_{L4} + \text{j}3\ X_{L4}) = 37{,}037 + \text{j}44{,}549)$ mΩ

5.4 Calculation of I_k'' and i_p for three-phase short circuits

5.4.1 Short-circuit location F1

5.4.1.1 Calculation of I_k''

According to Figure 7, the following short-circuit impedance at the location F1 is found for the positive-sequence system:

$$\underline{Z}_k = \underline{Z}_{Qt} + \frac{\underline{Z}_{T1K}\left(\underline{Z}_{T2K} + \underline{Z}_{L1} + \underline{Z}_{L2}\right)}{\underline{Z}_{T1K} + \underline{Z}_{T2K} + \underline{Z}_{L1} + \underline{Z}_{L2}} = \left(1{,}881 + \text{j}6{,}746\right)\text{m}\Omega$$

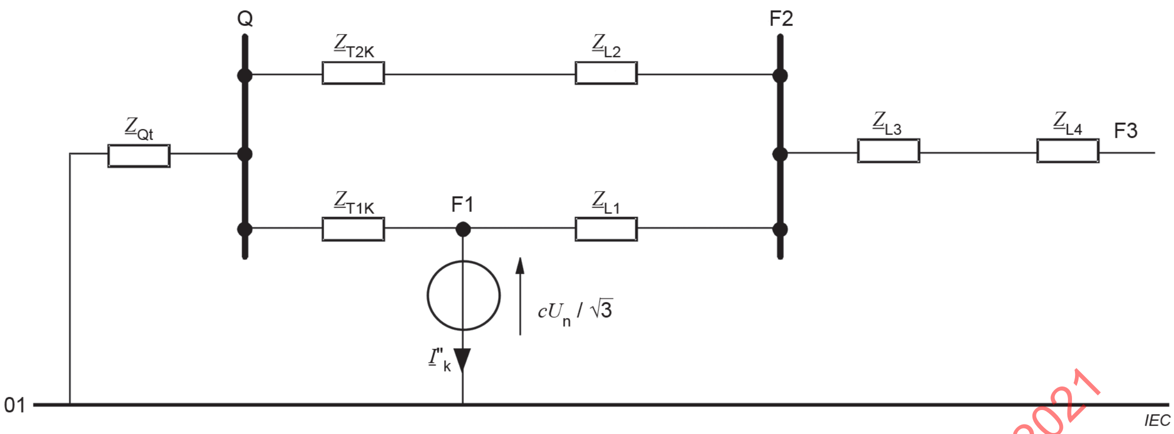


Figure 7 – Positive-sequence system (according to Figure 6) for the calculation of I_k'' at the short-circuit location F1

Maximum initial symmetrical three-phase short-circuit current (Formula (33) of IEC 60909-0:2016) with $c = c_{max}$ = 1,05 (Table 1 of IEC 60909-0:2016):

$$I_k'' = \frac{cU_n}{\sqrt{3}\,Z_k} = \frac{1{,}05 \cdot 400\ \text{V}}{\sqrt{3} \cdot 7{,}003\ \text{m}\Omega} = 34{,}62\ \text{kA}$$

5.4.1.2 Calculation of peak current according to method b) of 8.1.2 of IEC 60909-0:2016

The peak current is calculated according to section 8.1.2 of IEC 60909-0:2016, because the partial currents are not independent and the system has parallel branches, which is the condition for the application of 8.1.1 of IEC 60909-0:2016.

Because the calculation of $\underline{Z}_k$ is carried out with complex quantities, it is easy to find i_p with method b) of 8.1.2 of IEC 60909-0:2016 using the R/X-ratio at the short-circuit location or for higher accuracy method c) of 8.1.2 of IEC 60909-0:2016.

Impedance ratio at the short-circuit location:

$$\frac{R}{X} = \frac{R_k}{X_k} = \frac{1{,}881}{6{,}746} = 0{,}279$$

$$\kappa_b = 1{,}02 + 0{,}98 \cdot e^{-3R/X} = 1{,}445 \qquad \text{(Formula (57) of IEC 60909-0:2016)}$$

Because the R/X-ratio of $\underline{Z}_{T2K} + \underline{Z}_{L1} + \underline{Z}_{L2}$ is higher than 0,3, it is necessary to introduce the factor 1,15 in method b) (see 8.1.2 of IEC 60909-0:2016).

$$i_{pb} = 1{,}15 \cdot \kappa_b \cdot \sqrt{2}\, I_k'' = 1{,}15 \cdot 1{,}445 \cdot \sqrt{2} \cdot 34{,}62\ \text{kA} = 81{,}35\ \text{kA}$$

5.4.1.3 Calculation of peak current according to method c) of 8.1.2 of IEC 60909-0:2016

The impedance $\underline{Z}_c = R_c + jX_c$ is calculated with the equivalent frequency f_c = 20 Hz (f = 50 Hz). The calculation procedure is similar to the calculation of $\underline{Z}_k$ but using the following 20 Hz quantities. In general, the impedances $\underline{Z}$ must be converted to $\underline{Z}_c$ according to:

$$\underline{Z} = R + \mathrm{j}X \quad \rightarrow \quad \underline{Z}_\mathrm{c} = R + \mathrm{j}X \cdot \frac{f_\mathrm{c}}{f} = R + \mathrm{j}X_\mathrm{c}$$

$$\underline{Z}_\mathrm{Qtc} = (0{,}053 + \mathrm{j}0{,}212)\,\mathrm{m\Omega}$$

$$\underline{Z}_\mathrm{T1Kc} = (2{,}684 + \mathrm{j}4{,}021)\,\mathrm{m\Omega} \qquad \underline{Z}_\mathrm{T2Kc} = (4{,}712 + \mathrm{j}6{,}280)\,\mathrm{m\Omega}$$

$$\underline{Z}_\mathrm{L1c} = (0{,}385 + \mathrm{j}0{,}158)\,\mathrm{m\Omega} \qquad \underline{Z}_\mathrm{L2c} = (0{,}416 + \mathrm{j}0{,}054)\,\mathrm{m\Omega}$$

$$\underline{Z}_\mathrm{c} = \underline{Z}_\mathrm{Qtc} + \frac{\underline{Z}_\mathrm{T1Kc}(\underline{Z}_\mathrm{T2Kc} + \underline{Z}_\mathrm{L1c} + \underline{Z}_\mathrm{L2c})}{\underline{Z}_\mathrm{T1Kc} + \underline{Z}_\mathrm{T2Kc} + \underline{Z}_\mathrm{L1c} + \underline{Z}_\mathrm{L2c}} = (1{,}8738 + \mathrm{j}2{,}7076)\,\mathrm{m\Omega}$$

$$\frac{R}{X} = \frac{R_\mathrm{c}}{X_\mathrm{c}} \cdot \frac{f_\mathrm{c}}{f} = \frac{1{,}874\ \mathrm{m\Omega}}{2{,}708\ \mathrm{m\Omega}} \cdot \frac{20\mathrm{Hz}}{50\mathrm{Hz}} = 0{,}277 \qquad \kappa_\mathrm{c} = 1{,}02 + 0{,}98 \cdot \mathrm{e}^{-3R/X} = 1{,}447$$

$$i_\mathrm{pc} = \kappa_\mathrm{c} \cdot \sqrt{2}\, I_\mathrm{k}'' = 1{,}447 \cdot \sqrt{2} \cdot 34{,}62\ \mathrm{kA} = 70{,}86\ \mathrm{kA}$$

Method a) is not adequate in this case (see 8.1.2 a) of IEC 60909-0:2016). This method should be used only as a first approximation, if the short-circuit current calculation is carried out with reactances only. Method a) would lead to κ_a = 1,46, taking the smallest ratios R/X from $\underline{Z}_\mathrm{T1K}$ and $\underline{Z}_\mathrm{T2K}$ + $\underline{Z}_\mathrm{L2}$ + $\underline{Z}_\mathrm{L1}$. If the network feeder with $R_\mathrm{Qt}/X_\mathrm{Qt}$ = 0,1 is also treated as a branch of the network, then a factor κ_a = 1,75 would be found and a peak short-circuit current i_pa = 85,5 kA > i_pc (see 2.4 of IEC TR 60909-1:2002).

5.4.2 Short-circuit location F2

$$\underline{Z}_\mathrm{k} = \underline{Z}_\mathrm{Qt} + \frac{(\underline{Z}_\mathrm{T1K} + \underline{Z}_\mathrm{L1})(\underline{Z}_\mathrm{T2K} + \underline{Z}_\mathrm{L2})}{\underline{Z}_\mathrm{T1K} + \underline{Z}_\mathrm{T2K} + \underline{Z}_\mathrm{L1} + \underline{Z}_\mathrm{L2}} = (1{,}977 + \mathrm{j}6{,}827)\,\mathrm{m\Omega}$$

$$I_\mathrm{k}'' = \frac{cU_\mathrm{n}}{\sqrt{3}\, Z_\mathrm{k}} = \frac{1{,}05 \cdot 400\,\mathrm{V}}{\sqrt{3} \cdot 7{,}108\,\mathrm{m\Omega}} = 34{,}12\mathrm{kA}$$

The calculation with method (c) (see 8.1.2 c) of IEC 60909-0:2016) leads to:

$$\underline{Z}_\mathrm{c} = (1{,}976 + \mathrm{j}2{,}732)\,\mathrm{m\Omega}$$

$$\frac{R}{X} = \frac{R_\mathrm{c}}{X_\mathrm{c}} \cdot \frac{f_\mathrm{c}}{f} = \frac{1{,}976\mathrm{m\Omega}}{2{,}732\mathrm{m\Omega}} \cdot \frac{20\mathrm{Hz}}{50\mathrm{Hz}} = 0{,}289 \qquad \kappa_\mathrm{c} = 1{,}02 + 0{,}98 \cdot \mathrm{e}^{-3R/X} = 1{,}432$$

$$i_\mathrm{pc} = \kappa_\mathrm{c} \cdot \sqrt{2}\, I_\mathrm{k}'' = 1{,}432 \cdot \sqrt{2} \cdot 34{,}12\mathrm{kA} = 69{,}07\mathrm{kA}$$

NOTE The decisive ratio R/X is mostly determined by those of the two branches $\underline{Z}_\mathrm{T1K}$ + $\underline{Z}_\mathrm{L1}$ and $\underline{Z}_\mathrm{T2K}$ + $\underline{Z}_\mathrm{L2}$ with R/X = 0,294 and 0,324. These two ratios are similar to $R_\mathrm{k}/X_\mathrm{k}$ ≈ 0,29 leading to κ_b = 1,431. The calculation with method b) but without the additional factor 1,15 would lead to

$$i_\mathrm{pb} = \kappa_\mathrm{b} \cdot \sqrt{2}\, I_\mathrm{k}'' = 1{,}431 \cdot \sqrt{2} \cdot 34{,}12\mathrm{kA} = 69{,}05\mathrm{kA}$$

5.4.3 Short-circuit location F3

$$\underline{Z}_{\text{k}} = \underline{Z}_{\text{Qt}} + \frac{(\underline{Z}_{\text{T1K}} + \underline{Z}_{\text{L1}})(\underline{Z}_{\text{T2K}} + \underline{Z}_{\text{L2}})}{\underline{Z}_{\text{T1K}} + \underline{Z}_{\text{T2K}} + \underline{Z}_{\text{L1}} + \underline{Z}_{\text{L2}}} + \underline{Z}_{\text{L3}} + \underline{Z}_{\text{L4}} = (25{,}916 + \text{j}23{,}417)\,\text{m}\Omega$$

$$I_{\text{k}}'' = \frac{cU_{\text{n}}}{\sqrt{3}\,Z_{\text{k}}} = \frac{1{,}05 \cdot 400\ \text{V}}{\sqrt{3} \cdot 34{,}928\ \text{m}\Omega} = 6{,}94\ \text{kA}$$

$$\underline{Z}_{\text{c}} = \underline{Z}_{\text{F2c}} + \underline{Z}_{\text{L3c}} + \underline{Z}_{\text{L4c}} = (1{,}976 + \text{j}2{,}732)\,\text{m}\Omega + (23{,}939 + \text{j}6{,}636)\,\text{m}\Omega$$

$$\frac{R}{X} = \frac{R_{\text{c}}}{X_{\text{c}}} \cdot \frac{f_{\text{c}}}{f} = \frac{25{,}914\ \text{m}\Omega}{9{,}368\ \text{m}\Omega} \cdot \frac{20\,\text{Hz}}{50\,\text{Hz}} = 1{,}106 \qquad \kappa_{\text{c}} = 1{,}02 + 0{,}98 \cdot \text{e}^{-3R/X} = 1{,}055$$

$$i_{\text{pc}} = \kappa_{\text{c}} \cdot \sqrt{2}\, I_{\text{k}}'' = 1{,}055 \cdot \sqrt{2} \cdot 6{,}94\ \text{kA} = 10{,}36\ \text{kA}$$

5.5 Calculation of I_{k1}'' and i_{p1} for line-to-earth short circuits

5.5.1 Short-circuit location F1

Figure 8 gives the equivalent circuit in the positive-sequence, the negative-sequence and the zero-sequence system of the network in Figure 6 with a line-to-earth short circuit in F1.

$$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_{\text{k}} = (1{,}881 + \text{j}6{,}746)\,\text{m}\Omega \qquad \text{(see 5.4.1)}$$

$$\underline{Z}_{(0)} = \frac{\underline{Z}_{(0)\text{T1K}}(\underline{Z}_{(0)\text{T2K}} + \underline{Z}_{(0)\text{L1}} + \underline{Z}_{(0)\text{L2}})}{\underline{Z}_{(0)\text{T1K}} + \underline{Z}_{(0)\text{T2K}} + \underline{Z}_{(0)\text{L1}} + \underline{Z}_{(0)\text{L2}}} = (2{,}140 + \text{j}6{,}009)\,\text{m}\Omega$$

$$\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)} = 2\underline{Z}_{(1)} + \underline{Z}_{(0)} == (5{,}902 + \text{j}19{,}501)\,\text{m}\Omega$$

The initial symmetrical line-to-earth short-circuit current is calculated according to Formula (54) of IEC 60909-0:2016. In this case, this current is greater than the three phase initial short-circuit current:

$$I_{\text{k1}}'' = \frac{\sqrt{3} \cdot cU_{\text{n}}}{\left|2\underline{Z}_{(1)} + \underline{Z}_{(0)}\right|} = \frac{\sqrt{3} \cdot 1{,}05 \cdot 400\ \text{V}}{20{,}374\,\text{m}\Omega} = 35{,}71\,\text{kA}$$

The peak short-circuit current i_{p1} is calculated with the factor $\kappa_{(\text{c})}$ = 1,447 found from the positive-sequence system in 5.4.1:

$$i_{\text{p1c}} = \kappa_{\text{c}} \cdot \sqrt{2}\, I_{\text{k1}}'' = 1{,}447 \cdot \sqrt{2} \cdot 35{,}71\,\text{kA} = 73{,}07\ \text{kA}$$

NOTE Taking $\underline{Z}_{\text{c}}$ and $\underline{Z}_{(0)\text{c}}$ in a more detailed calculation to find κ_{c} and i_{p1c}, the following results can be found:

$$\frac{R}{X} = \frac{2R_{\text{c}} + R_{(0)\text{c}}}{2X_{\text{c}} + X_{(0)\text{c}}} \cdot \frac{f_{\text{c}}}{f} = \frac{5{,}827\,\text{m}\Omega}{7{,}876\,\text{m}\Omega} \cdot \frac{20\,\text{Hz}}{50\,\text{Hz}} = 0{,}296$$

$$\kappa_{\text{c}} = 1{,}02 + 0{,}98\,\text{e}^{-3R/X} = 1{,}423 \qquad i_{\text{p1c}} = \kappa_{\text{c}} \cdot \sqrt{2} \cdot I_{\text{k1}}'' = 1{,}423 \cdot \sqrt{2} \cdot 35{,}71\,\text{kA} = 71{,}87\,\text{kA}$$

In this case, the difference is only 1,7 %.

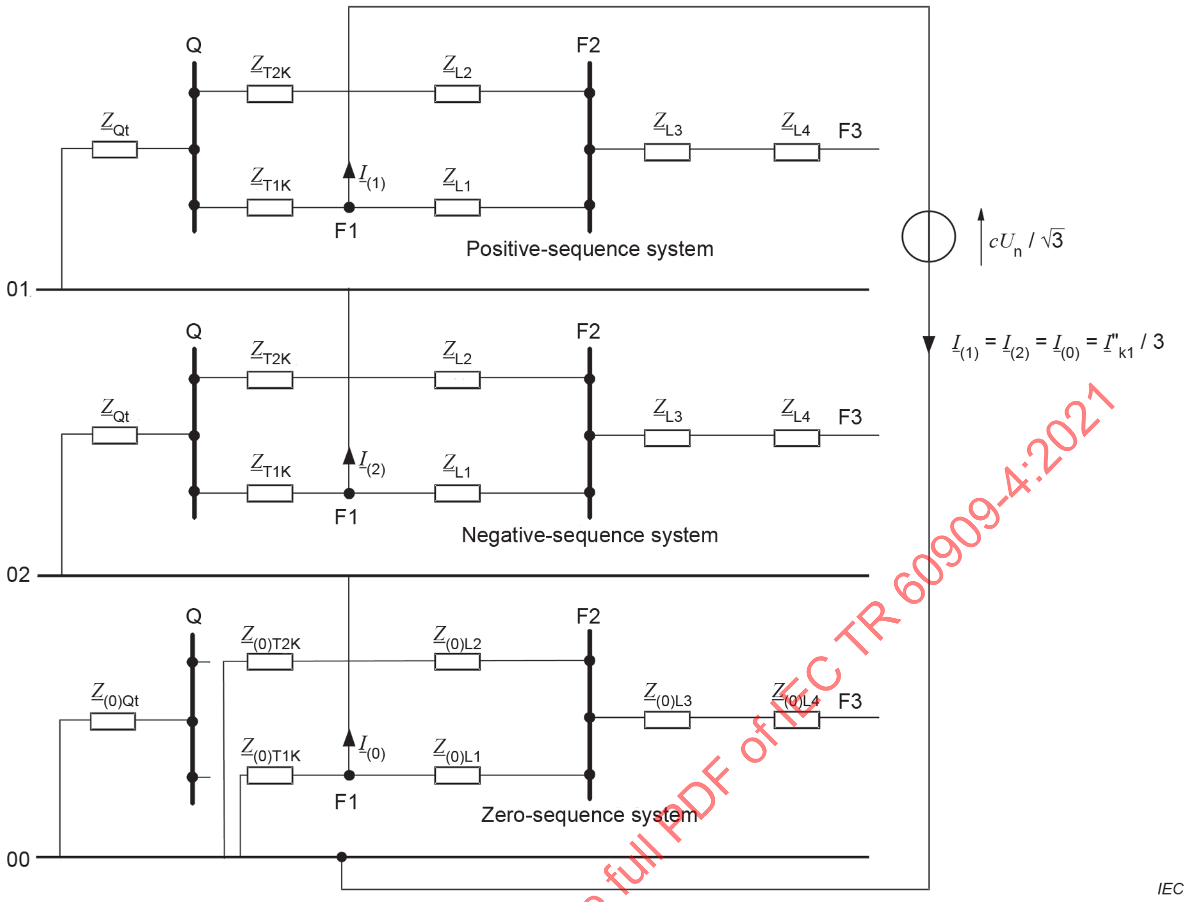


Figure 8 – Positive-sequence, negative-sequence and zero-sequence system with connections at the short-circuit location F1 for the calculation of I''_{k1}

5.5.2 Short-circuit location F2

$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_k = (1{,}977 + j6{,}827)\,\text{m}\Omega$ (see 5.4.2)

$$\underline{Z}_{(0)} = \frac{\left(\underline{Z}_{(0)T1K} + \underline{Z}_{(0)L1}\right)\left(\underline{Z}_{(0)T2K} + \underline{Z}_{(0)L2}\right)}{\underline{Z}_{(0)T1K} + \underline{Z}_{(0)T2K} + \underline{Z}_{(0)L1} + \underline{Z}_{(0)L2}} = (2{,}516 + j6{,}109)\,\text{m}\Omega$$

$$I''_{k1} = \frac{\sqrt{3} \cdot cU_n}{\left|2\underline{Z}_{(1)} + \underline{Z}_{(0)}\right|} = \frac{\sqrt{3} \cdot 1{,}05 \cdot 400\,\text{V}}{20{,}795\,\text{m}\Omega} = 34{,}98\,\text{kA}$$

$$i_{p1c} = \kappa_c \cdot \sqrt{2}\, I''_{k1} = 1{,}432 \cdot \sqrt{2} \cdot 34{,}98\,\text{kA} = 70{,}82\ \text{kA}$$

5.5.3 Short-circuit location F3

$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_k = (25{,}916 + j23{,}417)\,\text{m}\Omega$ (see 5.4.3)

$$\underline{Z}_{(0)} = \underline{Z}_{(0)F2} + \underline{Z}_{(0)L3} + \underline{Z}_{(0)L4} = (55{,}813 + j58{,}418)\,\text{m}\Omega$$

$$I''_{k1} = \frac{\sqrt{3} \cdot cU_n}{\left|2\underline{Z}_{(1)} + \underline{Z}_{(0)}\right|} = \frac{\sqrt{3} \cdot 1{,}05 \cdot 400\,\text{V}}{150{,}549\,\text{m}\Omega} = 4{,}83\,\text{kA}$$

$$i_{p1c} = \kappa_c \cdot \sqrt{2}\, I''_{k1} = 1{,}055 \cdot \sqrt{2} \cdot 4{,}83\,\text{kA} = 7{,}21\,\text{kA}$$

5.6 Collection of results

The collection of results for the example in Figure 6 is given in Table 4 for short-circuit impedances and currents and in Table 5 for the Joule integral (Formula (108) of IEC 60909-0:2016).

Table 4 – Short-circuit impedances and short-circuit currents

Short-circuit location	$Z_k = Z_{(1)}$ mΩ	$Z_{(0)}$ mΩ	I''_k kA	$i_{p(c)}$ kA	I''_{k1} kA	$i_{p1(c)}$ kA	I''_{k1}/I''_k
F1	7,003	6,378	34,62	70,86	35,71	73,07	1,03
F2	7,108	6,606	34,12	69,07	34,98	70,82	1,03
F3	34,928	80,79	6,94	10,36	4,83	7,21	0,70

The Joule integral is calculated at the short-circuit locations F2 and F3 in Figure 6 using the factors m and n given in Figure 18 and Figure 19 of IEC 60909-0:2016. The factor m is calculated with the formula for m given in Annex A of IEC 60909-0:2016. The cut-off times (short-circuit times T_k) for the fuse are found from a given characteristic of a low-voltage fuse of 250 A.

Table 5 – Joule integral depending on T_k at the short-circuit location F2 and F3

Short-circuit location	I''_k kA	Protection type	T_k s	κ	m[a]	n[b]	Joule integral[c] $(\text{kA})^2\text{s}$
F2	34,12	Circuit-breaker 250 A	0,06	1,43	0,198	1	83,68
F3	6,94		0,06	1,06	0,058	1	3,06
F3 [e)]	4,83		0,06	1,06	0,058	1	1,48
F2	34,12	Fuse 250 A	< 0,005	–	–	–	< 0,56 [d]
`F3	6,94		0,02	1,06	0,173	1	1,13
F3 [e)]	4,83		0,07	1,06	0,049	1	1,72

[a] Calculated with formula for m (see annex A of IEC 60909-0:2016).

[b] Far-from-generator short circuit: $I_k = I''_k$; n = 1.

[c] Formula (108) of IEC 60909-0:2016.

[d] Cut-off characteristic of the fuse.

[e] Line-to-earth short circuit.

NOTE With a certain short-circuit duration T_k like that of the example circuit-breaker, the maximum Joule integral occurs for the largest short-circuit current. Whereas with an extremely inverse characteristic like that of the example fuse, the largest Joule integral occurs with the smallest short-circuit current, which can be a single line-to-earth short circuit, as in the example at the short-circuit location F3.

6 Calculation of three-phase short-circuit currents in a medium-voltage system – Influence of asynchronous motors

6.1 Problem

A medium-voltage system 33 kV/6 kV (50 Hz) is given in Figure 9. The short-circuit current calculation shall be carried out without and with asynchronous motors fed from the 6 kV busbar, to show their contribution to the short-circuit currents at the short-circuit location F. Figure 9 gives the circuit diagram of the three-phase AC system 33 kV/6 kV and the data of the electrical equipment. The neutral points of the medium-voltage system are isolated.

The substation 33 kV/6 kV with two network transformers S_{rT} = 15 MVA each is fed through two three-core 30 kV cables from a network feeder with U_{nQ} = 33 kV and $I''_{\mathrm{kQ}} = 13{,}12\,\mathrm{kA}$ ($S''_{\mathrm{kQ}} = \sqrt{3}U_{\mathrm{nQ}}I''_{\mathrm{kQ}} = 750\,\mathrm{MVA}$ (see 3.6 of IEC 60909-0:2016). The distribution system operator gives this information about the network feeder calculated in accordance with IEC 60909-0.

The calculations are carried out with complex impedances (see 6.2). In addition, a calculation is performed with quantities of the per-unit system (see 6.3).

A short-circuit current calculation with the superposition method is presented in 6.4 to show that the results for the short-circuit currents depend on the load flow, the voltage at the short-circuit location before the short circuit and the position of on-load tap-changers of transformers (see Figure 9).

6.2 Complex calculation with absolute quantities

The complex short-circuit impedances in Table 6 are calculated with the data in Figure 9 and with the formulae given in IEC 60909-0.

The short-circuit current $\underline{I}''_{\mathrm{k}}$ at the short-circuit location F is found from a complex addition of the partial short-circuit currents in Figure 9 (see 7.1.1 of IEC 60909-0:2016).

$$\underline{I}''_{\mathrm{k}} = \underline{I}''_{\mathrm{kT1}} + \underline{I}''_{\mathrm{kT2}} + \underline{I}''_{\mathrm{kM1}} + \underline{I}''_{\mathrm{kM2}}$$

where

$\underline{I}''_{\mathrm{kM2}}$ is the partial short-circuit current from the three parallel motors with P_{rM} = 1 MW each (Figure 9), dealt with as one equivalent motor M2.

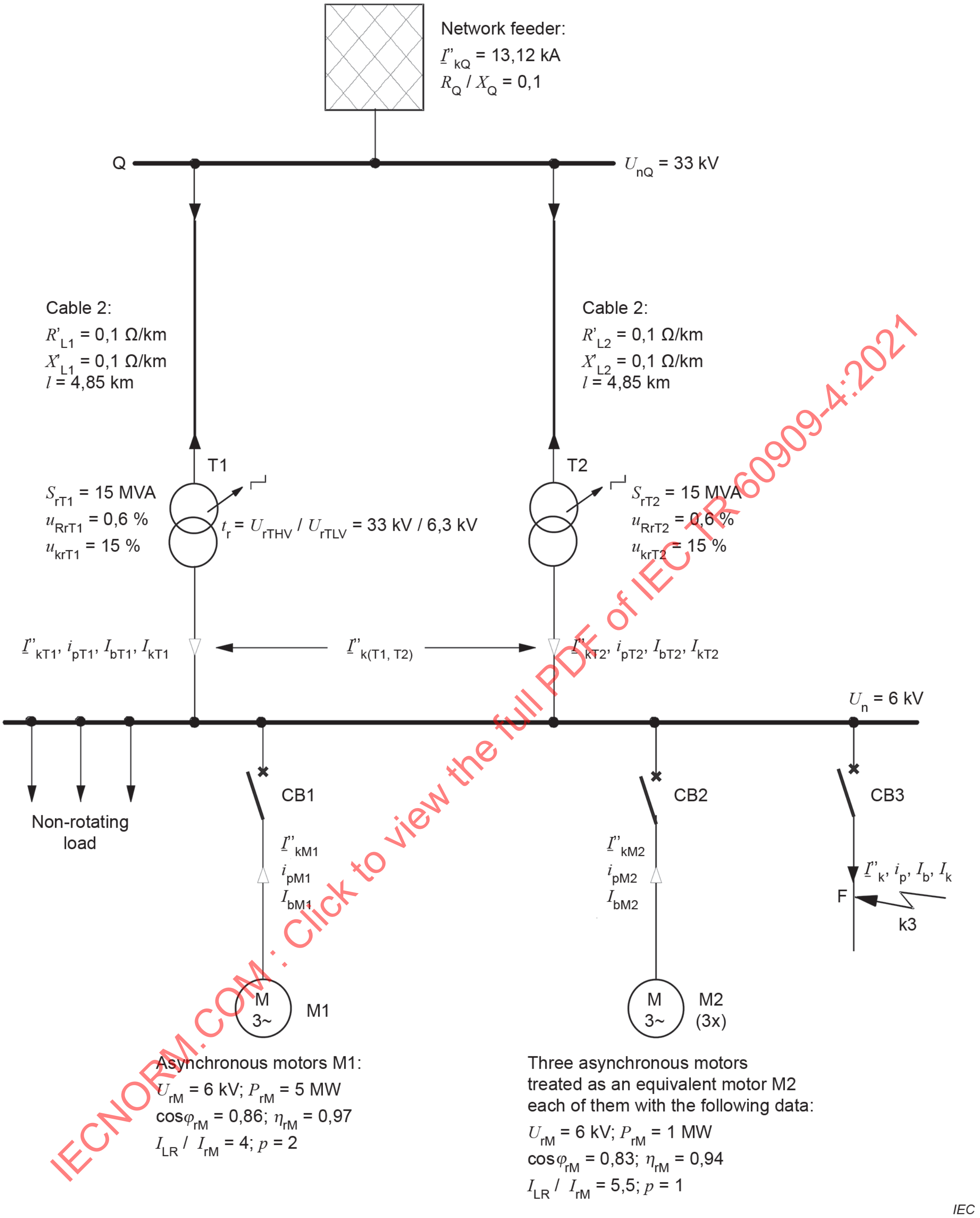


Figure 9 – Medium-voltage network 33 kV/6 kV: data

Table 6 – Calculation of the short-circuit impedances of electrical equipment and $\underline{Z}_{k(T1,T2)}$ at the short-circuit location F, without motors (circuit-breakers CB1 and CB2 are open)

No.	Equipment	Formulae (IEC 60909-0:2016) and calculation	Impedance Ω
1	Network feeder	(6) $Z_{Qt} = \frac{cU_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{t_r^2} = \frac{1{,}1 \cdot 33\,\text{kV}}{\sqrt{3} \cdot 13{,}12\,\text{kA}} \cdot \left(\frac{6{,}3\,\text{kV}}{33\,\text{kV}}\right)^2$	0,058 2
		$X_{Qt} = 0{,}995\, Z_{Qt}$; $R_{Qt} = 0{,}1\, X_{Qt}$;	
		$\underline{Z}_{Qt} = R_{Qt} + \text{j}X_{Qt}$	0,005 9 + j0,057 9
2	Cable L1 (= cable L2)	$R_{L1t} = R'_{L1} \cdot \ell \cdot \frac{1}{t_r^2} = 0{,}1 \frac{\Omega}{\text{km}} \cdot 4{,}85\,\text{km} \cdot \left(\frac{6{,}3\,\text{kV}}{33\,\text{kV}}\right)^2$	
		$X_{L1t} = X'_{L1} \cdot \ell \cdot \frac{1}{t_r^2} = 0{,}1 \frac{\Omega}{\text{km}} \cdot 4{,}85\,\text{km} \cdot \left(\frac{6{,}3\,\text{kV}}{33\,\text{kV}}\right)^2$	
		$\underline{Z}_{L1t} = R_{L1t} + \text{j}X_{L1t}$	0,017 7 + j0,017 7
3	Transformer T1 (= transformer T2)	(7) $Z_{T1} = \frac{u_{kr}}{100\,\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} = \frac{15\,\%}{100\,\%} \cdot \frac{(6{,}3\,\text{kV})^2}{15\,\text{MVA}}$	0,396 9
		(8) $R_{T1} = \frac{u_{Rr}}{100\,\%} \cdot \frac{U_{rTLV}^2}{S_{rT}} = \frac{0{,}6\,\%}{100\,\%} \cdot \frac{(6{,}3\,\text{kV})^2}{15\,\text{MVA}}$	0,015 9
		(9) $X_{T1} = \sqrt{Z_{T1}^2 - R_{T1}^2}$	0,396 6
		(12a) $K_T = 0{,}95 \frac{c_{max}}{1 + 0{,}6 \cdot 0{,}149\,9} = 0{,}958\,8$	
		$\underline{Z}_{T1K} = K_T \left(R_{T1} + \text{j}X_{T1}\right)$	0,015 2 + j0,380 2
4	L1 + T1 = L2 + T2	$\underline{Z}_{L1t} + \underline{Z}_{T1K} = \underline{Z}_{L2t} + \underline{Z}_{T2K}$	0,032 9 + j0,398 0
5	(L1 + T1) || (L2 + T2) in parallel	$\frac{\underline{Z}_{L1t} + \underline{Z}_{T1K}}{2}$	0,016 4 + j0,199 0
6	Short-circuit impedance without motors	$\underline{Z}_{k(T1,T2)} = \underline{Z}_{Qt} + \frac{\underline{Z}_{L1t} + \underline{Z}_{T1K}}{2}$	0,022 3 + j0,257 5
7	Motor M1	(30) $Z_{M1} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} = \frac{1}{4} \cdot \frac{(6\,\text{kV})^2}{6\,\text{MVA}}$	1,501
		with $S_{rM} = \frac{P_{rM}}{\eta_{rM} \cos \varphi_{rM}} \approx 6\,\text{MVA}$	
	Motor M2 (three units 1 MW)	(30) $Z_{M2} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} = \frac{1}{3} \cdot \frac{1}{5{,}5} \cdot \frac{(6\,\text{kV})^2}{1{,}28\,\text{MVA}}$	1,702
		with $S_{rM} = \frac{P_{rM}}{\eta_{rM} \cos \varphi_{rM}} = 1{,}28\,\text{MVA}$	

The sum $\underline{I}''_{kT1} + \underline{I}''_{kT2} = \underline{I}''_{k(T1,T2)}$ at the secondary side of the transformers is found with $\underline{Z}_{k(T1,T2)}$ from Table 6.

$$\underline{I}''_{kT1} + \underline{I}''_{kT2} = \frac{cU_n}{\sqrt{3} \cdot \underline{Z}_{k(T1,T2)}} = \frac{1{,}1 \cdot 6\,\text{kV}}{\sqrt{3} \cdot (0{,}022\,3 + \text{j}0{,}257\,5)\,\Omega} = (1{,}27 - \text{j}14{,}69)\,\text{kA} \qquad I''_{k(T1,T2)} = 14{,}74\,\text{kA}$$

The partial short-circuit currents of the motors are found with $\underline{Z}_{M1}$ and $\underline{Z}_{M2}$ using $R_M = 0{,}1\ X_M$ and $X_M = 0{,}995\ Z_M$ (see 6.10 of IEC 60909-0:2016) for asynchronous motors with $P_{rM}/p \geq 1$ MW.

$$\underline{I}''_{kM1} = \frac{cU_n}{\sqrt{3} \cdot \underline{Z}_{M1}} = \frac{1{,}1 \cdot 6\,\text{kV}}{\sqrt{3} \cdot (0{,}149 + \text{j}1{,}494)\,\Omega} = (0{,}25 - \text{j}2{,}53)\,\text{kA} \qquad I''_{kM1} = 2{,}54\,\text{kA}$$

$$\underline{I}''_{kM2} = \frac{cU_n}{\sqrt{3} \cdot \underline{Z}_{M2}} = \frac{1{,}1 \cdot 6\,\text{kV}}{\sqrt{3} \cdot (0{,}170 + \text{j}1{,}694)\,\Omega} = (0{,}22 - \text{j}2{,}23)\,\text{kA} \qquad I''_{kM2} = 2{,}24\,\text{kA}$$

The addition of the partial short-circuit currents $\underline{I}''_{kT1} + \underline{I}''_{kT2}$, $\underline{I}''_{kM1}$ and $\underline{I}''_{kM2}$ leads to

$$\underline{I}''_k = (1{,}75 - \text{j}19{,}44)\,\text{kA} \qquad I''_k = 19{,}52\,\text{kA}$$

According to 6.10, 8.1.1 and Formula (59) of IEC 60909-0:2016, the peak short-circuit current is found as follows:

$$i_p = i_{p(T1,T2)} + i_{pM1} + i_{pM2} = (37{,}03 + 6{,}27 + 5{,}53)\,\text{kA} = 48{,}82\ \text{kA}$$

with the partial peak short-circuit currents

$$i_{p(T1,T2)} = \kappa\sqrt{2}\ I''_{k(T1,T2)} = 1{,}78 \cdot \sqrt{2} \cdot 14{,}74\,\text{kA} = 37{,}03\ \text{kA}$$

with R/X = 0,022 3/0,257 5 and κ = 1,78 (Formula (57) of IEC 60909-0:2016)

$$i_{pM1} = \kappa\sqrt{2}\ I''_{kM1} = 1{,}75 \cdot \sqrt{2} \cdot 2{,}54\ \text{kA} = 6{,}27\ \text{kA}$$

with R_{M1}/X_{M1} = 0,1 and κ = 1,75 (Table 4 of IEC 60909-0:2016)

$$i_{pM2} = \kappa\sqrt{2}\ I''_{kM2} = 1{,}75 \cdot \sqrt{2} \cdot 2{,}23\ \text{kA} = 5{,}53\ \text{kA}$$

with R_{M2}/X_{M2} = 0,1 and κ = 1,75 (Table 4 of IEC 60909-0:2016)

According to 9.1.6 and Formulae (67), (68), and (69) of IEC 60909-0:2016, the symmetrical short-circuit breaking current for a minimum time delay t_{min} = 0,1s is found as follows:

$$I_b = I_{b(T1,T2)} + I_{bM1} + I_{bM2} = I''_{k(T1,T2)} + \mu_{M1} q_{M1} I''_{kM1} + \mu_{M2} q_{M2} I''_{kM2}$$

$$I_b = (14{,}74 + 0{,}80 \cdot 0{,}68 \cdot 2{,}54 + 0{,}72 \cdot 0{,}57 \cdot 2{,}24)\,\text{kA} = 17{,}04\,\text{kA}$$

with $\mu_{M1} = 0{,}62 + 0{,}72 \cdot e^{-0{,}32 \cdot 4{,}4} = 0{,}80$

$$q_{\text{M1}} = 0{,}57 + 0{,}12 \cdot \ln(2{,}5) = 0{,}68$$

$$\mu_{\text{M2}} = 0{,}62 + 0{,}72 \cdot \text{e}^{-0{,}32 \cdot 6{,}05} = 0{,}72$$

$$q_{\text{M2}} = 0{,}57 + 0{,}12 \cdot \ln(1{,}0) = 0{,}57$$

The maximum DC component i_{DC} of the short-circuit current at t = t_{min} = 0,1 s can be estimated with Formula (81) of IEC 60909-0:2016.

$$i_{\text{DC}} = i_{\text{DC(T1,T2)}} + i_{\text{DCM1}} + i_{\text{DCM2}} = (1{,}372 + 0{,}155 + 0{,}137)\,\text{kA} = 1{,}66 \text{ kA}$$

with $i_{\text{DC(T1,T2)}} = \sqrt{2}\, I''_{\text{k(T1,T2)}} \cdot \text{e}^{-2\pi f t (R/X)} = 1{,}372\,\text{kA}$

$$i_{\text{DCM1}} = \sqrt{2}\, I''_{\text{kM1}} \cdot \text{e}^{-2\pi f t (R_{\text{M1}}/X_{\text{M1}})} = 0{,}155\,\text{kA}$$

$$i_{\text{DCM2}} = \sqrt{2}\, I''_{\text{kM2}} \cdot \text{e}^{-2\pi f t (R_{\text{M2}}/X_{\text{M2}})} = 0{,}137\,\text{kA}$$

Because the asynchronous motors do not contribute to the steady-state short-circuit current (I_{kM1} = 0, I_{kM2} = 0) in the case of a terminal short circuit, the steady-state short-circuit current in F becomes:

$$I_{\text{k}} = I_{\text{k(T1,T2)}} + I_{\text{kM1}} + I_{\text{kM2}} = I''_{\text{k(T1,T2)}} = 14{,}74\,\text{kA}$$

6.3 Calculation with per-unit quantities

It is sufficient in this case to consider only the reactances, when calculating the short-circuit currents; therefore this calculation, using per-unit quantities, shall be carried out with the reactances of electrical equipment.

For the calculation with per-unit (p.u.) quantities, two reference values shall be chosen. These reference quantities (index R) shall be:

$$U_{\text{R}} = U_{\text{n}} = 6 \text{ kV or } 33 \text{ kV and } S_{\text{R}} = 100 \text{ MVA.}$$

Per-unit quantities (with asterisks [*] as a superscript before the symbol) therefore are defined as follows:

$$^{*}U = \frac{U}{U_{\text{R}}} \qquad ^{*}U = \frac{I \cdot U_{\text{R}}}{S_{\text{R}}} \qquad ^{*}Z = \frac{Z \cdot S_{\text{R}}}{U_{\text{R}}^2} \qquad ^{*}S = \frac{S}{S_{\text{R}}}$$

If the system is not coherent, that means $U_{\text{rTHV}}/U_{\text{rTLV}} \neq U_{\text{nHV}}/U_{\text{nLV}}$, the rated transformation ratio related to p.u. voltages becomes:

$$^{*}t = \frac{U_{\text{rTHV}}}{U_{\text{rTHV}}} \cdot \frac{U_{\text{R,6kV}}}{U_{\text{R,33kV}}} = \frac{33\text{kV}}{6{,}3\text{kV}} \cdot \frac{6\text{kV}}{33\text{kV}} = 0{,}9524$$

The procedure for the calculation of the short-circuit reactance $^{*}X_{\text{k(T1,T2)}}$ without the influence of motors is given in Table 7 (similar to Table 6).

Table 7 – Calculation of the per-unit short-circuit reactances of electrical equipment and $^*X_{k(T1,T2)}$ at the short-circuit location F

No.	Equipment	Formulae (IEC 60909-0:2016) and calculation	Reactance p.u.
1	Network feeder [a]	(6) $^*X_{Qt} \approx \frac{c_Q \cdot {}^*U_{nQ}}{\sqrt{3} \cdot {}^*I''_{kQ}} \cdot \frac{1}{{}^*t_r^2} = \frac{1{,}1 \cdot 1\text{p.u.}}{\sqrt{3} \cdot 4{,}33\text{p.u.}} \cdot \frac{1}{0{,}9524^2}$	0,161 7
2	Cable L1 [b]	$^*X_{L1t} = X'_{L1} \cdot \ell \cdot \frac{S_R}{U_R^2} \cdot \frac{1}{{}^*t_r^2} = 0{,}1\frac{\Omega}{\text{km}} \cdot 4{,}85\text{ km} \cdot \frac{100\text{ MVA}}{(33\text{ kV})^2} \cdot \frac{1}{0{,}9524^2}$	0,049 1
3	Transformer T1 [c]	(7) $^*X_{T1} = \frac{u_{krT1}}{100\ \%} \cdot \frac{U_{rT1LV}^2}{S_{rT1}} \cdot \frac{S_R}{U_R^2} = \frac{15\%}{100\%} \cdot \frac{(6{,}3\text{kV})^2}{15\text{ MVA}} \cdot \frac{100\text{ MVA}}{(6\text{ kV})^2}$ (12a) $K_T = 0{,}9588$ (see table 6) $^*X_{T1K} = K_T \cdot {}^*X_{T1}$	(1,102 5) 1,057 3
4	L1 + T1 = L2 + T2	$^*X_{L1t} + {}^*X_{T1K} = {}^*X_{L2t} + {}^*X_{T2K}$	1,106 4
5	(L1 + T1) | | (L2 + T2)	$\left({}^*X_{L1t} + {}^*X_{T1K}\right)/2$	0,553 2
6	Short-circuit reactance (p.u.) without motors	$^*X_{k(T1,T2)} = {}^*X_{Qt} + \left({}^*X_{L1t} + {}^*X_{T1K}\right)/2$	0,714 9

[a] $^*I''_k = I''_{kQ} \cdot U_R / S_R = 13{,}12\text{ kA} \cdot 33\text{ kV}/100\text{ MVA} = 4{,}33\text{ p.u.}$

[b] U_R = 33 kV;

[c] U_R = 6 kV

Short-circuit current $^*I''_{k(T1,T2)}$ without motors:

$$^*I''_{k(T1,T2)} = \frac{c \cdot {}^*U_n}{\sqrt{3} \cdot {}^*X_{k(T1,T2)}} = \frac{1{,}1 \cdot 1\text{p.u.}}{\sqrt{3} \cdot {}^*0{,}714\,9\text{ p.u.}} = 0{,}888\,4\text{ p.u.}$$

$$I''_{k(T1,T2)} = {}^*I''_{k(T1,T2)} \cdot \frac{S_R}{U_R} = 0{,}888\,4\text{p.u.} \cdot \frac{100\text{ MVA}}{6\text{ kV}} = 14{,}81\text{kA}$$

The reactances and the short-circuit currents of the asynchronous motors in p.u. are (U_{rM} = U_R = 6 kV):

$$^*X_{M1} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{S_R}{S_{rM}} = \frac{1}{4} \cdot \frac{100\text{ MVA}}{6\text{ MVA}} = 4{,}167\text{ p.u.}$$

$$^*X_{M2} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{S_R}{S_{rM}} = \frac{1}{3} \cdot \frac{1}{5{,}5} \cdot \frac{100\text{ MVA}}{1{,}28\text{ MVA}} = 4{,}735\text{ p.u.}$$

$$^*I''_{kM1} = \frac{c \cdot {}^*U_R}{\sqrt{3} \cdot {}^*X_{M1}} = \frac{1{,}1 \cdot 1\text{ p.u.}}{\sqrt{3} \cdot 4{,}167\text{p.u.}} = 0{,}152\,4\text{p.u.} \qquad I''_{kM1} = {}^*I''_{kM1} \cdot \frac{S_R}{U_R} = 2{,}54\text{kA}$$

$$^{*}I''_{\mathrm{kM2}} = \frac{c \cdot {}^{*}U_{\mathrm{R}}}{\sqrt{3} \cdot {}^{*}X_{\mathrm{M2}}} = \frac{1{,}1 \cdot 1\ \text{p.u.}}{\sqrt{3} \cdot 4{,}735\ \text{p.u.}} = 0{,}134\ \text{p.u.} \quad I''_{\mathrm{kM2}} = {}^{*}I''_{\mathrm{kM2}} \cdot \frac{S_{\mathrm{R}}}{U_{\mathrm{R}}} = 2{,}23\ \text{kA}$$

If the asynchronous motors contribute to the short-circuit current in F, then

$$^{*}I''_{\mathrm{k}} = {}^{*}I''_{\mathrm{k(T1,T2)}} + {}^{*}I''_{\mathrm{kM1}} + {}^{*}I''_{\mathrm{kM2}} = (0{,}888\ 4 + 0{,}152\ 4 + 0{,}134)\ \text{p.u.} = 1{,}174\ 8\ \text{p.u.}$$

$$I''_{\mathrm{k}} = {}^{*}I''_{\mathrm{k}} \cdot \frac{S_{\mathrm{R}}}{U_{\mathrm{R}}} = 1{,}174\,8\ \text{p.u.} \cdot \frac{100\ \text{MVA}}{6\ \text{kV}} = 19{,}58\ \text{kA}$$

The results from this p.u.-calculation are nearly the same as those found in 6.2.

6.4 Calculation with the superposition method

The principal procedure to find short-circuit currents and partial short-circuit currents with the superposition method is given in IEC TR 60909-1.

The short-circuit currents depend on the load flow before the short circuit, the operating voltage of the 33 kV and 6 kV system and the position of the on-load tap-changer of the transformers (Figure 9). The following information in addition to that already given in 6.1 and Figure 9 shall be applied for the superposition method:

a) Transformer T1, T2:

   On-load tap-changer p_{T} = ±18 %; $u_{\mathrm{k+}}$ = 16,5 % at + p_{T} and $u_{\mathrm{k-}}$ = 14,0 % at $-p_{\mathrm{T}}$.

b) Load currents at the 6 kV busbar before (superscript b) the short circuit:

   I^{b} = (0...2,75) kA with cos φ^{b} = 0,8 or cos φ^{b} = 0,9 found from $\underline{S}^{\mathrm{b}} = 3 \cdot \underline{U}_1^{\mathrm{b}} \cdot \underline{I}^{\mathrm{b}*}$

c) Operating voltages before the short circuit:

   U^{b} = (6...6,6) kV; U_{n} = 6 kV; U_{m} = 7,2 kV (according to IEC 60038:2009)

   U^{b} = (30...36) kV; U_{n} = 33 kV; U_{m} = 36 kV (according to IEC 60038:2009)

The partial short-circuit current $\underline{I}''_{\mathrm{k(T1,T2)S}}$ fed from both the transformers calculated with the superposition method (index S) is found from the superposition of the load current $\underline{I}^{\mathrm{b}}_{\mathrm{(T1,T2)}}$ before the short circuit and the current $\underline{I}''_{\mathrm{k(T1,T2)Ub}}$ depending on the voltage U^{b}:

$$\underline{I}''_{\mathrm{k(T1,T2)S}} = \underline{I}^{\mathrm{b}}_{\mathrm{(T1,T2)}} + \underline{I}''_{\mathrm{k(T1,T2)Ub}} = \underline{I}^{\mathrm{b}}_{\mathrm{(T1,T2)}} + \frac{U^{\mathrm{b}}}{\sqrt{3} \cdot \left[0{,}5 \cdot \underline{Z}_{\mathrm{T}}(t) + \left(\underline{Z}_{\mathrm{Q}} + 0{,}5 \cdot \underline{Z}_{\mathrm{L}}\right)/t^2\right]} \qquad (1)$$

The impedance $\underline{Z}_{\mathrm{T}}(t) = \underline{Z}_{\mathrm{T1}}(t) = \underline{Z}_{\mathrm{T2}}(t)$ of the transformers (without correction factor) depends on the actual transformation ratio t ($u_{\mathrm{k+}} \geq u_{\mathrm{k}}(t) \geq u_{\mathrm{k-}}$).

The relation between the voltages $U^{\mathrm{b}}_{\mathrm{Q}}$ and U^{b} at the later short-circuit location is given by the following formula:

$$U_{Q}^{b} = \sqrt{3}\, t \left| \frac{U^{b}}{\sqrt{3}} + \frac{0{,}5\underline{Z}_{T}(t) + 0{,}5\underline{Z}_{L}}{t^{2}} \underline{I}^{b} \right| \tag{2}$$

Figure 10 gives in a first case the results according to Formula (1) and Formula (2) if the tap-changer is in the main position ($t = t_r$ = 33 kV/6,3 kV = 5,238 and $u_k(t) = u_{kr}$ = 15 %; u_{Rr} = 0,6 %), depending on $\underline{S}^b$ ($\cos\varphi^b$ = 0,8) and the voltage U^b as a parameter. In addition, the influence of $\cos\varphi^b$ is indicated for the example U^b = 6,0 kV. It is anticipated that the voltage U_Q^b has values between 33 kV (U_{nQ}) and 36 kV (U_{mQ}).

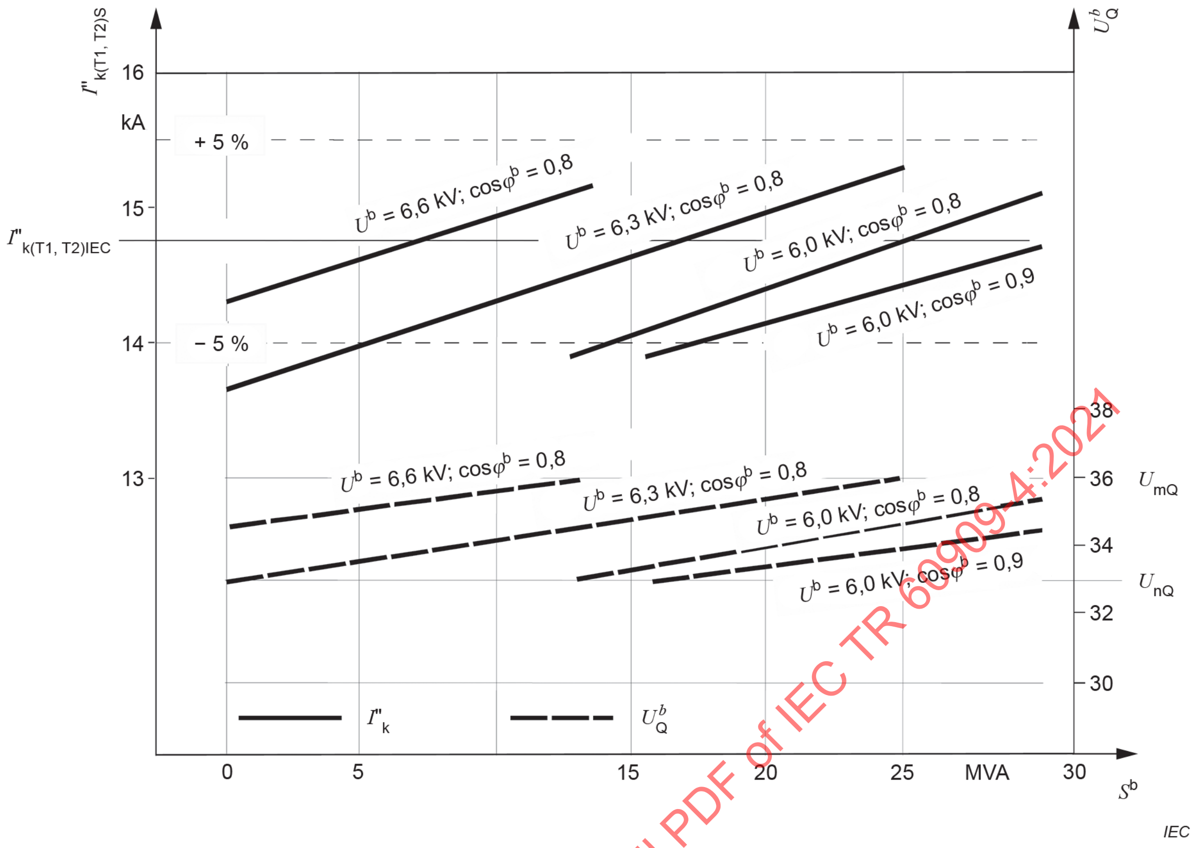
Figure 11 gives the results for the short-circuit currents I''_{kS} found with the superposition method at the short-circuit location F (Figure 11) if the motors (M1 and M2) are included and the on-load tap-changers have different positions. In addition, $u_k(t)$ is given in the lower part of the figure. In the short circuit, the current before the short circuit is zero, therefore the total short-circuit current at the short-circuit location is found as follows:

$$\underline{I}''_{kS} = \underline{I}''_{k(T1,T2)Ub} + \underline{I}''_{k(M1,M2)Ub} \tag{3}$$

with

$$\underline{I}''_{k(M1,M2)Ub} = \frac{U^{b}}{\sqrt{3}\,\dfrac{\underline{Z}_{M1}\,\underline{Z}_{M2}}{\underline{Z}_{M1} + \underline{Z}_{M2}}} \tag{4}$$

and $\underline{I}''_{k(T1,T2)Ub}$ according to Formula (1).

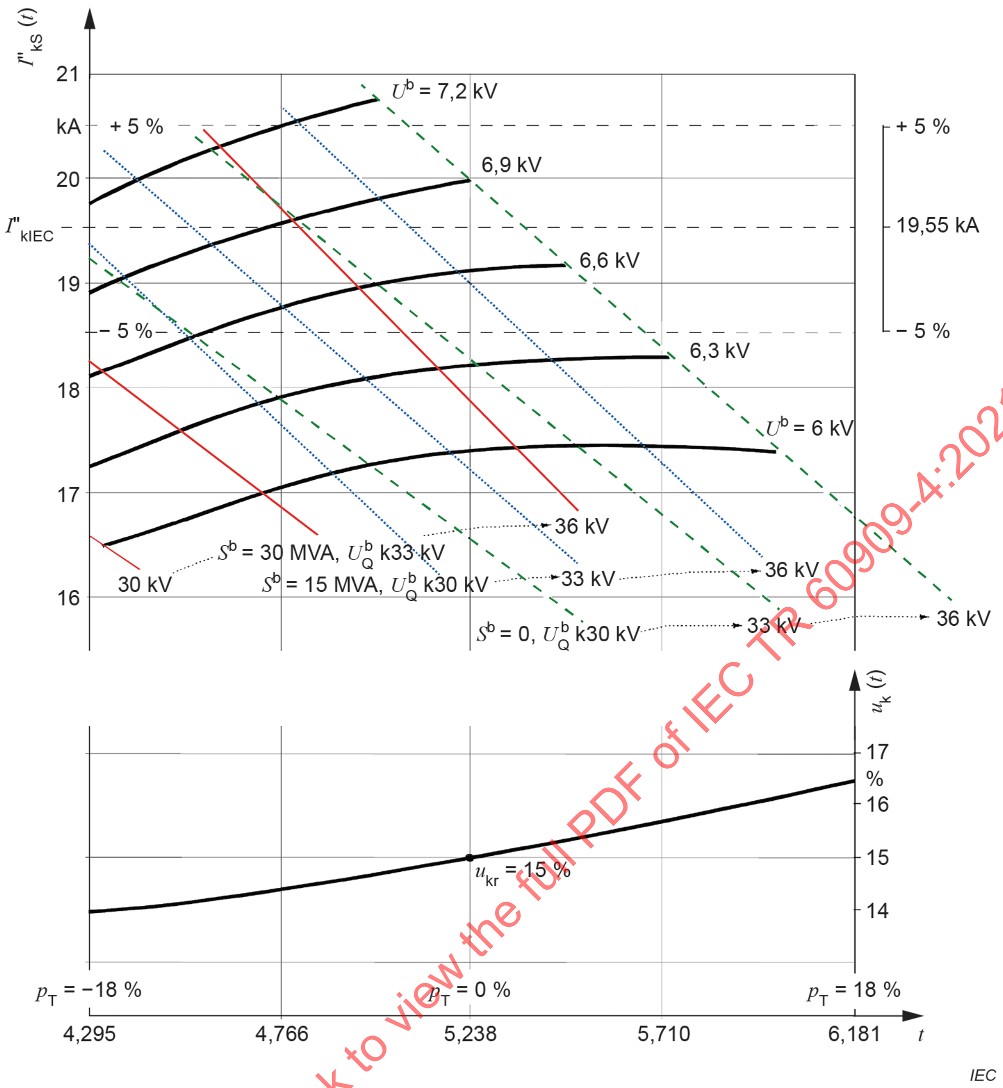


NOTE Tap-changer is in the main position.

Figure 10 – Short-circuit current $I''_{k(T1,T2)S}$ calculated by the superposition method (S) compared with $I''_{k(T1,T2)IEC}$ calculated by the IEC method of equivalent voltage source at the short-circuit location, depending on the load S^b and the voltage U^b

As an additional information, the operating voltage is plotted, tap-changer of the transformers in main position.

As examples the following loads: $S^b = 0$, $S^b = 15$ MVA and $S^b = 30$ MVA at $\cos\varphi^b = 0{,}8$ are used for calculations, considering a voltage range between $U_Q^b = 30\,\text{kV}$ and $U_Q^b = 36\,\text{kV} = U_{mQ}$. Especially the maximum voltage $U_Q^b = U_{mQ}$ is limiting the region of possible short-circuit currents in Figure 11.



NOTE Motors are included. The tap-changer position of the transformers is adapted to the voltage U^b and the load S^b ($\cos\varphi^b$ = 0,8).

Figure 11 – Short-circuit current I''_{kS} calculated by the superposition method (S) compared with I''_{kIEC} calculated by the IEC method of equivalent voltage source at the short-circuit location, depending on the transformation ratio *t* before the short circuit

7 Calculation of three-phase short-circuit currents for a power station unit and the auxiliary network

7.1 Problem

Three-phase short-circuit currents at the short-circuit locations F1 to F5 in Figure 12 shall be calculated according to IEC 60909-0.

A power station unit with on-load tap-changer (S) with $S_{rG} = S_{rT}$ = 250 MVA is connected to a network feeder with U_{nQ} = 220 kV. The actual short-circuit current is given as $I''_{kQ} = 21\,\text{kA}$ by the transmission system operator (without the contribution of the power station unit), calculated in accordance with IEC 60909-0, $c = c_{max}$ = 1,1. The unit transformer is equipped with an on-load tap-changer at the high-voltage side (see 6.7.1 of IEC 60909-0:2016). The auxiliary transformer AT is a three-winding transformer (see 6.3.2 of IEC 60909-0:2016) with two secondary windings feeding the two separate auxiliary busbars B and C with $U_{nB} = U_{nC}$ = 10 kV.

The influence of the medium- and low-voltage asynchronous motors shall be taken into account when calculating short-circuit currents in F2 to F5 (see 7.1.3 of IEC 60909-0:2016). The low-voltage motor groups, connected to the busbars D and E, are treated as equivalent motors (see 7.1.3 of IEC 60909-0:2016).

The terminal short-circuit currents of the medium-voltage motors M1 to M14 and the low-voltage motor groups M15 to M26 are calculated in Table 8 and Table 9 using Table 4 of IEC 60909-0:2016. The impedances of the connecting cables between the busbars and the motors are neglected. The results therefore will be on the conservative side.

It is anticipated that all the asynchronous motors are in operation at different loads. This will also lead to results on the conservative side. The sum of the rated apparent power of the asynchronous motors at busbar B reaches $\sum S_{\mathrm{rMB}} \approx 40$ MVA and at busbar C approximately $\sum S_{\mathrm{rMC}} \approx 30$ MVA. Contrary to these rated apparent powers, the maximum auxiliary load during operation of the power station unit will reach approximately 25 MVA $\leq S_{\mathrm{rAT}} = 0{,}1\, S_{\mathrm{rG}}$ in a coal-fired power station.

In 7.3.4 dealing with the short circuit in F4, it can be shown that the motors fed from busbar C only contribute less than 1 % to the initial short-circuit current I''_{kF4}. So the results for the short-circuit currents in F4 are nearly the same, if the motors M8...M14 and the motor groups M21...M26 are not in operation.

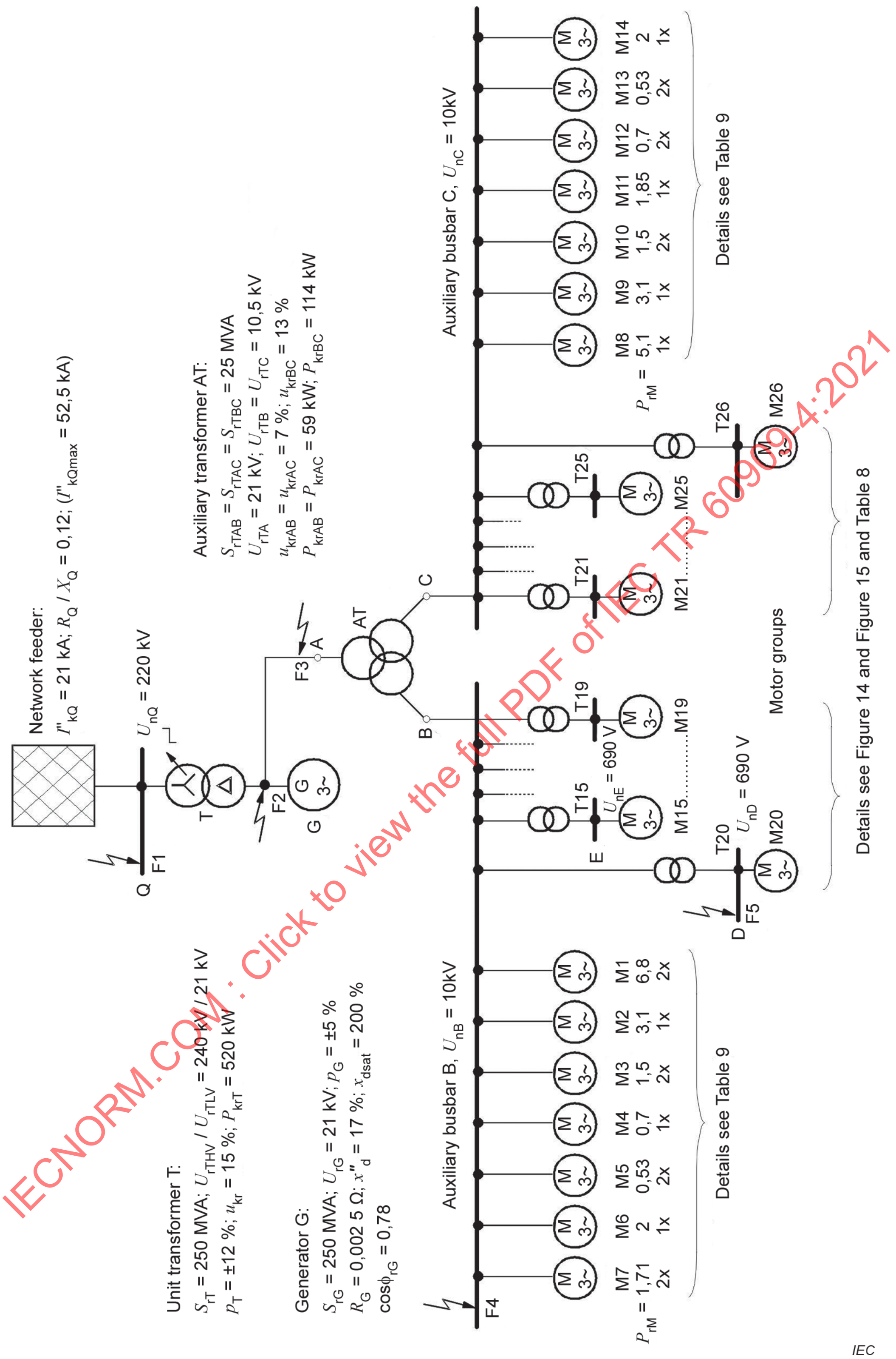


Figure 12 – Power station unit (generator and unit transformer with on-load tap-changer) and auxiliary network with medium- and low-voltage asynchronous motors: data

7.2 Short-circuit impedances of electrical equipment

7.2.1 Network feeder

According to 6.2 and Formula (4) and Formula (5) of IEC 60909-0:2016, the impedance Z_Q of the network feeder at HV side is found with $I''_{kQ} = 21\,\text{kA}$, R_Q/X_Q = 0,12 and $c = c_{max}$ = 1,1 (Table 1 of IEC 60909-0:2016).

$$Z_Q = \frac{cU_{nQ}}{\sqrt{3} \cdot I''_{kQ}} = \frac{1{,}1 \cdot 220\ \text{kV}}{\sqrt{3} \cdot 21\,\text{kA}} = 6{,}653\ \Omega$$

$$X_Q = \frac{Z_Q}{\sqrt{1+(R_Q/X_Q)^2}} = \frac{6{,}653\ \Omega}{\sqrt{1+(0{,}12)^2}} = 6{,}606\ \Omega \qquad R_Q = 0{,}12X_Q$$

$\underline{Z}_Q$ = (0,793 + j6,606) Ω

For the calculation of the maximum short-circuit currents at the short-circuit locations F2 to F5, the value Z_{Qmin} corresponding to $I''_{kQmax} = 52{,}5\,\text{kA}$ shall be used (see 7.2.2 of IEC 60909-0:2016). I''_{kQmax} with R_Q/X_Q = 0,1 is estimated from the future planning of the power system taking into account the lifetime of the power station unit:

$$Z_{Qmin} = \frac{cU_{nQ}}{\sqrt{3}\ I''_{kQmax}} = \frac{1{,}1 \cdot 220\ \text{kV}}{\sqrt{3} \cdot 52{,}5\,\text{kA}} = 2{,}661\,\Omega$$

$\underline{Z}_{Qmin}$ = (0,265 + j2,648) Ω

7.2.2 Power station unit

7.2.2.1 Generator

According to 6.6.1 of IEC 60909-0:2016, the impedance Z_G of the generator is found at LV side with S_{rG} = 250 MVA, U_{rG} = 21 kV, R_G = 0,0025 Ω and $x''_d = 17\,\%$.

$$\underline{Z}_G = R_G + jX''_d = (0{,}0025 + j0{,}2999)\Omega \qquad Z_G = 0{,}2999\Omega$$

with $$X''_d = \frac{x''_d}{100\ \%} \cdot \frac{U_{rG}^2}{S_{rG}} = \frac{17\ \%}{100\ \%} \cdot \frac{(21\ \text{kV})^2}{250\ \text{MVA}} = 0{,}299\,9\ \Omega$$

The fictitious resistance R_{Gf} shall be used (see 8.1.1 of IEC 60909-0:2016), when calculating κ and i_p:

$$R_{Gf} = 0{,}05X''_d \qquad (S_{rG} \geq 100\ \text{MVA})$$

$$\underline{Z}_{Gf} = R_{Gf} + jX''_d = (0{,}015\,0 + j0{,}299\,9)\Omega$$

7.2.2.2 Unit transformer

According to 6.3.1 of IEC 60909-0:2016, the impedance of the unit transformer at the high-voltage and the low-voltage side is found as follows:

$$Z_{THV}=\frac{u_{kr}}{100\,\%}\cdot\frac{U_{rTHV}^2}{S_{rT}}=\frac{15\,\%}{100\,\%}\cdot\frac{(240\,\text{kV})^2}{250\,\text{MVA}}=34{,}56\,\Omega$$

$$R_{THV}=\frac{u_{Rr}}{100\,\%}\cdot\frac{U_{rTHV}^2}{S_{rT}}=\frac{0{,}208\,\%}{100\,\%}\cdot\frac{(240\,\text{kV})^2}{250\,\text{MVA}}=0{,}479\,\Omega$$

with $u_{Rr}=\frac{P_{krT}}{S_{rT}}\cdot 100\,\%=0{,}208\,\%$

$$X_{THV}=\sqrt{Z_{THV}^2-R_{THV}^2}=34{,}557\,\Omega$$

$$\underline{Z}_{THV}=R_{THV}+\text{j}X_{THV}=(0{,}479+\text{j}34{,}557)\,\Omega$$

Short-circuit impedance of the unit transformer referred to the low-voltage side with t_r = 240 kV/21 kV = 11,429:

$$\underline{Z}_{TLV}=\frac{\underline{Z}_{THV}}{t_r^2}=(0{,}0037+\text{j}0{,}265)\,\Omega \qquad Z_{TLV}=\frac{Z_{THV}}{t_r^2}=0{,}265\,\Omega$$

7.2.2.3 Power station unit with on-load tap-changer

According to 6.7.1 of IEC 60909-0:2016 and $U_G = U_{rG}$:

$$K_S=\frac{U_{nQ}^2}{U_{rG}^2}\cdot\frac{U_{rTLV}^2}{U_{rTHV}^2}\cdot\frac{c_{max}}{1+\left|x_d''-x_T\right|\cdot\sqrt{1-\cos^2\varphi_{rG}}}$$

$$K_S=\frac{(220\,\text{kV})^2}{(21\,\text{kV})^2}\cdot\frac{(21\,\text{kV})^2}{(240\,\text{kV})^2}\cdot\frac{1{,}1}{1+|0{,}17-0{,}15|\cdot 0{,}625\,8}=0{,}913$$

$$\underline{Z}_{SK}=K_S\cdot\left(t_r^2\underline{Z}_G+\underline{Z}_{THV}\right)$$

$$\underline{Z}_{SK}=0{,}913\cdot\left[\left(\frac{240\,\text{kV}}{21\,\text{kV}}\right)^2\cdot(0{,}002\,5+\text{j}0{,}299\,9)\,\Omega+(0{,}479+\text{j}34{,}557)\,\Omega\right]=(0{,}736+\text{j}67{,}301)\,\Omega$$

Using the fictitious value R_{Gf}, the following impedance is found:

$$\underline{Z}_{Sf}=(2{,}226+\text{j}67{,}313)\,\Omega \qquad R_{Sf}/X_S=0{,}033$$

7.2.3 Auxiliary transformers

The positive-sequence system impedances of the three-winding transformer AT (Figure 12) referred to side A are found from Formulae (10a), (10b), (10c) of IEC 60909-0:2016:

$$\underline{Z}_{AB} = \left(\frac{u_{RrAB}}{100\,\%} + j\frac{u_{XrAB}}{100\,\%} \right) \cdot \frac{U_{rTA}^2}{S_{rTAB}} = (0{,}0416 + j1{,}234)\,\Omega$$

with $u_{RrAB} = \frac{P_{krTAB}}{S_{rTAB}} \cdot 100\,\%$ and $u_{XrAB} = \sqrt{u_{krAB}^2 - u_{RrAB}^2}$ (Formula (10d) of IEC 60909-0:2016)

$$\underline{Z}_{AC} = \underline{Z}_{AB} = (0{,}0416 + j1{,}234)\,\Omega$$

$$\underline{Z}_{BC} = \left(\frac{u_{RrBC}}{100\,\%} + j\frac{u_{XrBC}}{100\,\%} \right) \cdot \frac{U_{rTA}^2}{S_{rTBC}} = (0{,}0804 + j2{,}292)\,\Omega$$

The impedance correction factors K_T can be found from Formulae (13a), (13b), (13c) of IEC 60909-0:2016 with x_{TAB} = x_{TAC} ≈ 0,070 0 and x_{TBC} ≈ 0,129 9:

$$K_{TAB} = K_{TAC} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 x_{TAB}} = 1{,}003$$

$$K_{TBC} = 0{,}95 \cdot \frac{c_{max}}{1 + 0{,}6 \cdot x_{TBC}} = 0{,}969$$

The corrected $\underline{Z}_{ABK}$ to $\underline{Z}_{BCK}$ lead to the corrected impedances $\underline{Z}_{AK}$, $\underline{Z}_{BK}$ and $\underline{Z}_{CK}$ (Formulae (11a), (11b), (11c) of IEC 60909-0:2016) of the equivalent circuit diagram given in Figure 6b of IEC 60909-0:2016:

$$\underline{Z}_{AK} = \frac{1}{2}\left(K_{TAB}\,\underline{Z}_{AB} + K_{TAC}\,\underline{Z}_{AC} - K_{TBC}\,\underline{Z}_{BC} \right) = (0{,}0028 + j0{,}1268)\,\Omega$$

$$\underline{Z}_{BK} = \underline{Z}_{CK} = \frac{1}{2}\left(K_{TBC}\,\underline{Z}_{BC} + K_{TAB}\,\underline{Z}_{AB} - K_{TAC}\,\underline{Z}_{AC} \right) = (0{,}039\,0 + j1{,}110\,9)\,\Omega$$

7.2.4 Low-voltage transformers 2,5 MVA and 1,6 MVA

7.2.4.1 General

According to Figure 12, there are five transformers (T15...T19) on auxiliary busbar B and five transformers (T21.....T25) on auxiliary busbar C, each with S_{rT} = 2,5 MVA, U_{rTHV}/U_{rTLV} = 10 kV/0,73 kV (Table 8). The transformers (T20) and (T26) with S_{rT} = 1,6 MVA, U_{rTHV}/U_{rTLV} = 10 kV/0,42 kV (Table 8) are connected to the busbars B (T20) and C (T26). Each of these transformers feeds a group of asynchronous motors (Table 8). The impedances of the transformers are calculated with 6.3.1 of IEC 60909-0:2016 and the correction factors K_T from Formula (12a) of IEC 60909-0:2016, taking the data given in Table 8.

7.2.4.2 Transformers S_{rT} = 2,5 MVA (T15...T19, T21...T25)

$$Z_{T15HV} = \frac{u_{krT15}}{100\,\%} \cdot \frac{U_{rT15HV}^2}{S_{rT15}} = \frac{6\,\%}{100\,\%} \cdot \frac{(10\,\text{kV})^2}{2{,}5\,\text{MVA}} = 2{,}4\,\Omega$$

$$R_{T15HV} = P_{krT15} \cdot \frac{U_{rT15HV}^2}{S_{rT15}^2} = 0{,}023\,5\,\text{MW} \cdot \frac{(10\,\text{kV})^2}{(2{,}5\,\text{MVA})^2} = 0{,}376\,\Omega \qquad (u_{Rr} = 0{,}94\,\%)$$

$$\underline{Z}_{\text{T15HV}} = (0{,}376 + \text{j}2{,}370)\,\Omega$$

$$K_{\text{T15HV}} = 0{,}95 \cdot \frac{c_{\max}}{1 + 0{,}6 \cdot x_{\text{T15}}} = 0{,}95 \cdot \frac{1{,}1}{1 + 0{,}6 \cdot 0{,}0593} = 1{,}009$$

$$\underline{Z}_{\text{T15HVK}} = (0{,}379 + \text{j}2{,}392)\,\Omega = \underline{Z}_{\text{T21HVK}}$$

$$\underline{Z}_{\text{T15HVK}} = \underline{Z}_{\text{T16HVK}} = \underline{Z}_{\text{T17HVK}} = \underline{Z}_{\text{T18HVK}} = \underline{Z}_{\text{T19HVK}}$$

$$\underline{Z}_{\text{T21HVK}} = \underline{Z}_{\text{T22HVK}} = \underline{Z}_{\text{T23HVK}} = \underline{Z}_{\text{T24HVK}} = \underline{Z}_{\text{T25HVK}}$$

7.2.4.3 Transformers S_{rT} = 1,6 MVA (T20, T26)

$$Z_{\text{T20HV}} = \frac{u_{\text{krT20}}}{100\,\%} \cdot \frac{U_{\text{rT20HV}}^2}{S_{\text{rT20}}} = \frac{6\,\%}{100\,\%} \cdot \frac{(10\,\text{kV})^2}{1{,}6\,\text{MVA}} = 3{,}75\,\Omega$$

$$R_{\text{T20HV}} = P_{\text{krT20}} \cdot \frac{U_{\text{rT20HV}}^2}{S_{\text{rT20}}^2} = 0{,}016\,5\,\text{MW} \cdot \frac{(10\,\text{kV})^2}{(1{,}6\,\text{MVA})^2} = 0{,}645\,\Omega \qquad (u_{\text{Rr}} = 1{,}03\,\%)$$

$$\underline{Z}_{\text{T20HV}} = (0{,}645 + \text{j}3{,}694)\,\Omega$$

$$K_{\text{T20HV}} = 0{,}95 \cdot \frac{c_{\max}}{1 + 0{,}6 \cdot x_{\text{T20}}} = 0{,}95 \cdot \frac{1{,}1}{1 + 0{,}6 \cdot 0{,}059\,1} = 1{,}009$$

$$\underline{Z}_{\text{T20HVK}} = (0{,}650 + \text{j}3{,}728)\,\Omega = \underline{Z}_{\text{T26HVK}}$$

Referred to the low-voltage side:

$$\underline{Z}_{\text{T20LV}} = \underline{Z}_{\text{T20HV}} \cdot \frac{1}{t_{\text{r}}^2} = (1{,}138 + \text{j}6{,}516)\,\text{m}\Omega \qquad (t_{\text{r}} = 10\,\text{kV}/0{,}42\,\text{kV})$$

$$K_{\text{T20LV}} = 0{,}95 \cdot \frac{c_{\max}}{1 + 0{,}6 \cdot x_{\text{T20}}} = 0{,}95 \cdot \frac{1{,}05}{1 + 0{,}6 \cdot 0{,}059\,1} = 0{,}963$$

$$\underline{Z}_{\text{T20LVK}} = (1{,}096 + \text{j}6{,}277)\,\text{m}\Omega = \underline{Z}_{\text{T26LVK}}$$

Table 8 – Data of transformers 10 kV/0,73 kV and 10 kV/0,42 kV, data of low-voltage motor groups and partial short-circuit currents of these motor groups on busbars B and C respectively

Transformer motor groups		T15...T19 T21...T25	Σ T15...T19 Σ T21...T25	T20 T26	Σ T15...T20 Σ T21...T26	Remarks
S_{rT}	MVA	2,5	12,5	1,6	14,1	
U_{rTHV}	kV	10		10		Data given by the manufacturer
U_{rTLV}	kV	0,73		0,42		
u_{kr}	%	6		6		
P_{krT}	kW	23,5		16,5		
P_{rM}	MW	0,9	4,5	1,0	5,5	Data of motor groups
U_{rM}	kV	0,69		0,40		
$\cos\varphi_{rM}\ \eta_{rM}$	–	0,72		0,72		
I_{LR}/I_{rM}	–	5		5		See 7.1.3 of IEC 60909-0:2016
R_M/X_M	–	0,42		0,42		See 7.1.3 of IEC 60909-0:2016
κ_{rM}	–	1,3		1,3		See 7.1.3 of IEC 60909-0:2016
S_{rM}	MVA	1,25	6,25	1,39	7,64	$P_{rM}/(\cos\varphi_{rM}\ \eta_{rM})$
R_{THVK}	Ω	0,379		0,650		See 7.2.4
X_{THVK}	Ω	2,392		3,728		
R_M	Ω	0,029 5		0,008 9		R_M = 0,42 X_M
X_M	Ω	0,070 2		0,021 2		X_M = 0,922 Z_M [a]
I''_{kM}	kA	5,491		10,53 [b]		c = 1,05; U_{nE} = 0,69 kV; U_{nD} = 0,4 kV
$R_{Mt} = R_M \cdot t_r^2$	Ω	5,536		5,054		t_r = 10 kV/0,73 kV or
$X_{Mt} = X_M \cdot t_r^2$	Ω	13,179		12,033		t_r = 10 kV/0,42 kV
$R_{THVK} + R_{Mt}$	Ω	5,915	1,183	5,704	0,980	at the 10 kV side
$X_{THVK} + X_{Mt}$	Ω	15,571	3,114	15,761	2,600	
$\lvert \underline{Z}_{THVK} + \underline{Z}_{Mt} \rvert$	Ω	16,657	3,331	16,761	2,779	
I''_{kTF4}, $\Sigma I''_{kTF4}$	kA	0,381	1,906	0,379	2,285 [c]	U_{nB} = 10 kV, c = 1,1

[a] Z_M from Formula (31) of IEC 60909-0:2016.

[b] Partial short-circuit current in F5.

[c] Partial short-circuit current in F4.

Table 9 – Data of medium-voltage asynchronous motors and their partial short-circuit currents at short-circuit locations on busbars B and C respectively

Auxiliary busbar		B (short-circuit location F4)								C							
Motor no.		1	2	3	4	5	6	7	$\sum(1..7)$	8	9	10	11	12	13	14	$\sum(8...14)$
P_{rM}	MW	6,8	3,1	1,5	0,7	0,53	2	1,71	–	5,1	3,1	1,5	1,85	0,7	0,53	2	–
Quantity	–	2	1	2	1	2	1	2	–	1	1	2	1	2	2	1	–
U_{rM}	kV				10				10				10				10
$\cos\varphi_{rM}$	–	0,89	0,85	0,88	0,85	0,75	0,85	0,85	–	0,87	0,85	0,88	0,85	0,85	0,75	0,85	–
η_{rM}	–	0,976	0,959	0,962	0,952	0,948	0,96	0,96	–	0,973	0,959	0,962	0,959	0,952	0,948	0,96	–
I_{LR}/I_{rM} [a]	–				4				–				4				–
Pair of poles p	–	2	2	1	3	5	3	3	–	3	2	1	3	3	5	3	–
S_{rM}, $\sum S_{rM}$	MVA	15,66	3,80	3,54	0,87	1,49	2,45	4,19	32,0	6,02	3,80	3,54	2,27	1,73	1,49	2,45	21,3
I_{rM}, $\sum I_{rM}$	kA	0,904	0,220	0,205	0,050	0,086	0,142	0,242	1,85	0,348	0,220	0,205	0,131	0,100	0,086	0,142	1,23
P_{rM}/p	–	3,40	1,55	1,50	0,23	0,11	0,67	0,57	–	1,70	1,55	1,50	0,62	0,23	0,11	0,67	–
R_M/X_M	–		0,1			0,15			–		0,1			0,15			–
κ_M	–		1,746			1,645			–		1,746			1,645			–
μ (t_{min} = 0,1s) [b]	–				0,796				–				0,796				–
q (t_{min} = 0,1s) [c]	–	0,72	0,62	0,62	0,40	0,30	0,52	0,50	–	0,63	0,62	0,62	0,51	0,40	0,30	0,52	–
I''_{kM}, $\sum I''_{kM}$	kA	3,98	0,97	0,90	0,22	0,38	0,62	1,06	8,13	1,53	0,97	0,90	0,58	0,44	0,38	0,62	5,41
i_{pM}	kA	9,83	2,39	2,22	0,51	0,88	1,45	2,48	19,75	3,78	2,39	2,22	1,34	1,02	0,88	1,45	13,08
I_{bM}	kA	2,27	0,48	0,44	0,07	0,09	0,26	0,43	4,04	0,77	0,48	0,44	0,24	0,14	0,09	0,26	2,42
Z_M	Ω	1,60	6,57	7,05	28,90	16,77	10,20	5,97	0,781	4,15	6,57	7,05	11,02	14,45	16,77	10,20	1,173
X_M	Ω		0,995 Z_M			0,989 Z_M			0,776		0,995 Z_M			0,989 Z_M			1,165
R_M	Ω		0,1 X_M			0,15 X_M			0,089		0,1 X_M			0,15 X_M			0,138

[a] $I''_{kM} / I_{rM} = 4{,}4$ (see 7.2.5); $I''_{kM} = c \cdot (I_{LR} / I_{rM}) \cdot I_{rM}$.

[b] $\mu(0{,}1\text{s}) = 0{,}62 + 0{,}72 \cdot e^{-0{,}32 I''_{kM}/I_{rM}}$ (Formula (67) of IEC 60909-0:2016).

[c] $q(0{,}1\text{s}) = 0{,}57 + 0{,}12 \ln(P_{rM}/p)$ (Formula (69) of IEC 6090-0:2016).

7.2.5 Asynchronous motors

Data and short-circuit impedances of the medium-voltage motors M1...M7 connected to busbar B and motors M8...M14 connected to busbar C in Figure 12 are given in Table 9. Using Formula (30) and Formula (97) of IEC 60909-0:2016 and bearing in mind that $U_{rM} = U_n$ in this case, the following formula, used in Table 9, can be found for the calculation of I''_{kM}:

$$I''_{kM} = \frac{cU_n}{\sqrt{3}\ Z_M} = \frac{cU_n}{\sqrt{3}} \cdot \frac{I_{LR}}{I_{rM}} \cdot \frac{I_{rM}}{U_{rM}/\sqrt{3}} = c \cdot \frac{I_{LR}}{I_{rM}} \cdot I_{rM}$$

Data and short-circuit impedances of the low-voltage motor groups are given in Table 8. This table gives also the partial short-circuit currents of the motor groups (M15 to M20) at the high-voltage side of the transformers T15 to T20 in the case of a short circuit in F4 (busbar B in Figure 12).

7.3 Calculation of short-circuit currents

7.3.1 Short-circuit location F1

7.3.1.1 General

The short-circuit current $\underline{I}''_k$ in F1 can be calculated as the sum of $\underline{I}''_{kQ}$ and $\underline{I}''_{kS}$. The current $\underline{I}''_{kS}$ shall be calculated with $\underline{Z}_{SK}$ according to Formula (21) of IEC 60909-0:2016 for a power station unit with on-load tap-changer. It is not necessary to take the asynchronous motors of the auxiliary network into account, because their overall contribution is smaller than 1 % of I''_k in this case (see 7.3.3).

7.3.1.2 Initial symmetrical short-circuit current $\underline{I}''_k$

$$\underline{I}''_{kQ} = \frac{cU_{nQ}}{\sqrt{3} \cdot \underline{Z}_Q} = \frac{1{,}1 \cdot 220\,\text{kV}}{\sqrt{3} \cdot (0{,}793 + \text{j}6{,}606)\,\Omega} = (2{,}502 - \text{j}20{,}850)\,\text{kA}$$

$$\underline{I}''_{kS} = \frac{cU_{nQ}}{\sqrt{3} \cdot \underline{Z}_{SK}} = \frac{1{,}1 \cdot 220\,\text{kV}}{\sqrt{3} \cdot (0{,}736 + \text{j}67{,}313)\,\Omega} = (0{,}023 - \text{j}2{,}076)\,\text{kA}$$

$$\underline{I}''_k = \underline{I}''_{kQ} + \underline{I}''_{kS} = (2{,}525 - \text{j}22{,}926)\,\text{kA} \qquad I''_k = 23{,}065\,\text{kA}$$

7.3.1.3 Peak short-circuit current i_p

From the impedance $\underline{Z}_Q$, it follows that R_Q/X_Q = 0,12 and κ_Q = 1,704. From the impedance $\underline{Z}_{Sf}$ (see 7.2.2), the ratio R_{Sf}/X_S = 0,033 is found and κ_S = 1,907.

$$i_p = i_{pQ} + i_{pS} = \kappa_Q \sqrt{2} \cdot I''_{kQ} + \kappa_S \sqrt{2} \cdot I''_{kS} = 1{,}704\sqrt{2} \cdot 21\,\text{kA} + 1{,}908\sqrt{2} \cdot 2{,}075\,\text{kA} = 56{,}20\,\text{kA}$$

7.3.1.4 Symmetrical short-circuit breaking current I_b

$$I_b = I_{bQ} + I_{bS} = I''_{kQ} + \mu \cdot I''_{kS} = 21\,\text{kA} + 0{,}859 \cdot 2{,}075\,\text{kA} = 22{,}782\,\text{kA}$$

with $\mu_{0,1} = 0{,}62 + 0{,}72 \cdot \text{e}^{-0{,}32 \cdot I''_{kG}/I_{rG}}$ (Formula (67) of IEC 60909-0:2016 for t_{min} = 0,1 s)

The ratio I''_{kG}/I_{rG} is found as follows:

$$\frac{I''_{kG}}{I_{rG}} = \frac{I''_{kSt}}{I_{rG}/t_r} = \frac{2{,}076\,\text{kA}\cdot(240\,\text{kV}/21\,\text{kV})}{6{,}873\,\text{kA}} = 3{,}45$$

7.3.1.5 Steady-state short-circuit current I_{kmax}

$$I_k = I_{kQ} + I_{kS} = I''_{kQ} + \lambda_{max}\cdot I_{rGt} = 21\,\text{kA} + 1{,}65\cdot 0{,}601\,\text{kA} = 21{,}992\,\text{kA}$$

The factor λ_{max} = 1,65 is found from Figure 15a) of IEC 60909-0:2016 for x_{dsat} = 2,0, if the highest possible excitation voltage is 1,3 times the rated excitation at rated load and power factor for the turbogenerator S_{rG} = 250 MVA (see also 2.6.2.2 of IEC TR 60909-1:2002).

7.3.2 Short-circuit location F2

7.3.2.1 General

In accordance with Figure 11 and 7.2.2 of IEC 60909-0:2016, both the partial short-circuit currents I''_{kG} (Formula (35) of IEC 60909-0:2016) and I''_{kT} (Formula (37) of IEC 60909-0:2016) shall be calculated, because the highest value of these two currents is used for the dimensioning of the bars between generator and unit transformer and, when present, the circuit-breaker between generator and unit transformer.

7.3.2.2 Initial symmetrical short-circuit currents I''_{kG} and I''_{kT}

$$I''_{kG} = \frac{cU_{rG}}{\sqrt{3}\cdot K_{G,S}Z_G} = \frac{1{,}1\cdot 21\,\text{kV}}{\sqrt{3}\cdot 0{,}994\cdot 0{,}2999\,\Omega} = 44{,}73\,\text{kA}$$

with Formula (36) of IEC 60909-0:2019:

$$K_{G,S} = \frac{c_{max}}{1 + x''_d\sqrt{1-\cos^2\varphi_{rG}}} = \frac{1{,}1}{1+0{,}17\cdot 0{,}626} = 0{,}994$$

and Z_G according to 5.2.2

$$I''_{kT} = \frac{cU_{rG}}{\sqrt{3}\cdot\left|\underline{Z}_{TLV} + \dfrac{\underline{Z}_{Qmin}}{t_r^2}\right|} = \frac{1{,}1\cdot 21\,\text{kV}}{\sqrt{3}\cdot|0{,}005\,7 + \text{j}0{,}285|\,\Omega} = 46{,}81\,\text{kA}$$

with $\underline{Z}_{Qmin}$ = (0,265 + j2,648) Ω from 7.2.1, $\underline{Z}_{TLV}$ = (0,0037 + j0,265) Ω from 7.2.2 and t_r = 240 kV/21kV.

In this case, the highest value of the calculated currents and the contribution of the auxiliary substation have to be used for the dimensioning of the bus bar between generator and the unit transformer: I''_{kT} and I''_{kATHV}, calculated in 7.3.3:

$$I''_{kT} + I''_{kATHV} = (46{,}81 + 6{,}36)\,\text{kA} = 53{,}17\,\text{kA}$$

$$\left|\underline{I}''_{kT} + \underline{I}''_{kATHV}\right| = |1{,}76 - \text{j}53{,}11|\,\text{kA} = 53{,}14\,\text{kA}$$

7.3.2.3 Peak short-circuit currents i_{pG} and i_{pT}

$$i_{pG} = \kappa_G \sqrt{2} \cdot I''_{kG} = 1{,}86\sqrt{2} \cdot 44{,}73\,kA = 117{,}88\,kA$$

with $R/X = R_{Gf}/X''_d = 0{,}05$ and κ_G = 1,86 (Formula (57) of IEC 60909-0:2016).

$$i_{pT} = \kappa_T \sqrt{2} \cdot I''_{kT} = 1{,}94\sqrt{2} \cdot 46{,}81\,kA = 128{,}62\,kA$$

with R/X = 0,0057 Ω / 0,285 Ω = 0,02 and κ_T = 1,94

7.3.2.4 Symmetrical short-circuit breaking currents I_{bG} and I_{bT}

$$I_{bG} = \mu \cdot I''_{kG} = 0{,}71 \cdot 44{,}73\,kA = 31{,}75\,kA$$

with $\mu_{0,1} = 0{,}62 + 0{,}72 \cdot e^{-0{,}32 \cdot I''_{kG}/I_{rG}} = 0{,}71$ t_{min} = 0,1 s

$$I''_{kG}/I_{rG} = 44{,}73\,kA/6{,}87\,kA = 6{,}51$$

$I_{bT} = I''_{kT}$ (far-from-generator short circuit (Formula (73) of IEC 60909-0:2016).

7.3.2.5 Steady-state short-circuit currents I_{kGmax} and I_{kTmax}

$$I_{kGmax} = \lambda_{max} \cdot I_{rG} = 1{,}75 \cdot 6{,}87\,kA = 12{,}03\,kA$$

with λ_{max} = 1,75 from Figure 15a of IEC 60909-0:2016 found with $I''_{kG}/I_{rG} = 6{,}51$.

$I_{kTmax} = I''_{kT}$ (far-from-generator short circuit (Formula (87) of IEC 60909-0:2016).

Taking care of the contribution from the motors fed through the auxiliary transformer AT (see 7.3.3), the following currents for the dimensioning of the bars between generator and unit transformer are found:

$$i_{pT} + i_{pATHV} = (128{,}62 + 15{,}12)\,kA = 143{,}74\,kA$$

$I_{bT} + I_{bATHV} \approx I''_{kT} + I''_{kATHV} = (46{,}81 + 6{,}35)\,kA = 53{,}16\,kA$ at the conservative side.

7.3.3 Short-circuit location F3

7.3.3.1 Initial short-circuit currents I''_{kGT} and I''_{kATHV}

Figure 13 gives the positive-sequence system for the calculation of the short-circuit current in F3 and the partial short-circuit currents $\underline{I}''_{kGT}$ with Z_S (Formula (38) of IEC 60909-0:2016) and $\underline{I}''_{kATHV}$ at the high-voltage side of the auxiliary transformer.

$$\underline{I}''_{kGT} = \frac{c_{max}U_{rG}}{\sqrt{3}} \cdot \left[\frac{1}{K_{G,S}\underline{Z}_{G}} + \frac{1}{K_{T,S}\underline{Z}_{TLV} + \frac{\underline{Z}_{Qmin}}{t_{r}^{2}}} \right] = \frac{c_{max}U_{rG}}{\sqrt{3}\cdot \underline{Z}_{S}}$$

with $K_{G,S} = 0{,}994$ from 7.3.2, $\underline{Z}_{G} = (0{,}002\,5 + j0{,}299\,9)\,\Omega$ from 7.2.2, $\underline{Z}_{TLV} = (0{,}003\,7 + j0{,}265)\,\Omega$ from 7.2.2, $\underline{Z}_{Qmin} = (0{,}265 + j2{,}648)\,\Omega$ from 7.2.1 and

$$K_{T,S} = \frac{c_{max}}{1 - x_{T}\sqrt{1-\cos^{2}\varphi_{rG}}} = \frac{1{,}1}{1 - 0{,}15 \cdot 0{,}626} = 1{,}214$$

from Formula (38) of IEC 60909-0:2016, the following partial short-circuit current is found:

$$\underline{I}''_{kGT} = \frac{1{,}1 \cdot 21\,\text{kV}}{\sqrt{3}} \cdot \left[\frac{1}{(0{,}002\,5 + j0{,}298\,2)\,\Omega} + \frac{1}{(0{,}004\,5 + j0{,}321\,2)\,\Omega + (0{,}002\,0 + j0{,}020\,3)\,\Omega} \right]$$

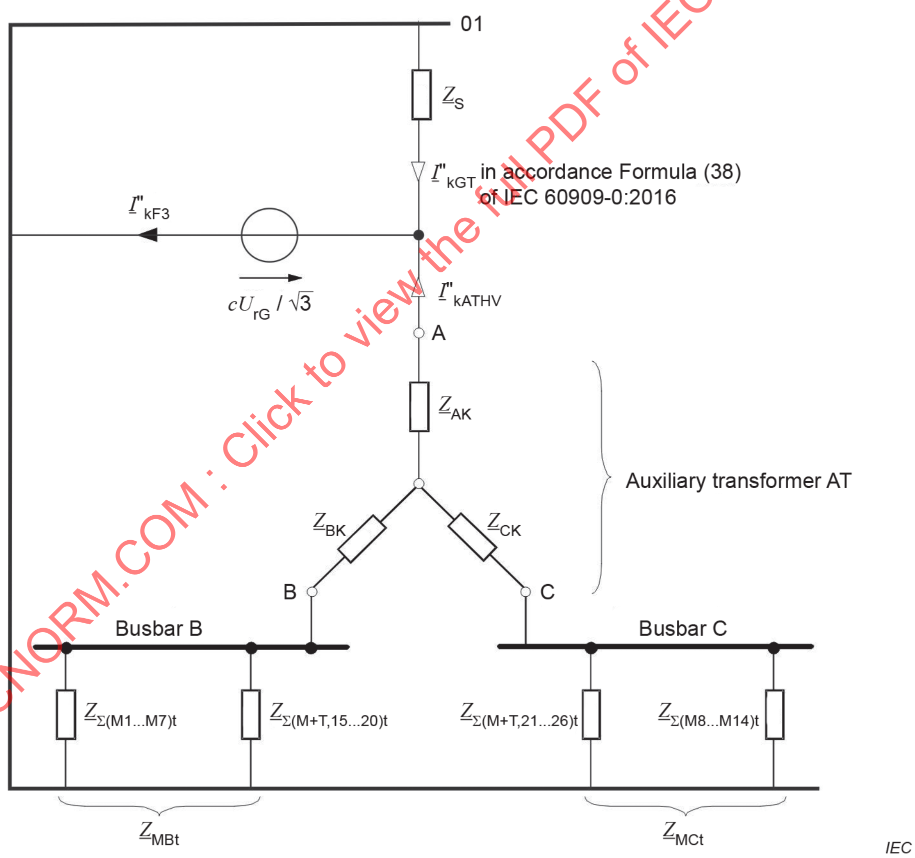


Figure 13 – Positive-sequence system for the calculation of the short-circuit currents at the location F3 (see Figure 12)

$$\underline{I}''_{kGT} = \frac{1{,}1 \cdot 21\,\text{kV}}{\sqrt{3} \cdot (0{,}002\,1 + j0{,}159\,2)\,\Omega} = (1{,}11 - j83{,}77)\,\text{kA} \qquad I''_{kGT} = 83{,}78\,\text{kA}$$

$$\underline{Z}_{S} = (0{,}002\,1 + j0{,}159\,2)\,\Omega$$

The addition of $\underline{I}''_{kG}$ and $\underline{I}''_{kT}$ from 7.3.2 would lead to $I''_{kG} + I''_{kT} = 44{,}73\,\text{kA} + 46{,}81\,\text{kA} = 91{,}54\,\text{kA}$, a result which is about 9,3 % higher than I''_{kGT} found with Formula (38) of IEC 60909-0:2016.

Impedances with index t are transferred to the high-voltage side A of the auxiliary transformer with t_{rAT} = 21 kV/10,5 kV = 2,0.

The partial short-circuit current $\underline{I}''_{kATHV}$ in Figure 13 can be found from the results of Table 8 and Table 9 for the low-voltage and medium-voltage motors. The impedances in Figure 13 are:

$$\underline{Z}_{\Sigma(M1...M7)t} = (0{,}089 + j0{,}776)\,\Omega \cdot \left(\frac{21\,\text{kV}}{10{,}5\,\text{kV}}\right)^2 = (0{,}354 + j3{,}105)\,\Omega$$

$$\underline{Z}_{\Sigma(M+T,15...20)t} = (0{,}980 + j2{,}601)\,\Omega \cdot \left(\frac{21\,\text{kV}}{10{,}5\,\text{kV}}\right)^2 = (3{,}929 + j10{,}402)\,\Omega$$

$$\underline{Z}_{MBt} = (0{,}409 + j2{,}418)\,\Omega \text{ (see Figure 13)}$$

$$\underline{Z}_{\Sigma(M8...M14)t} = (0{,}138 + j1{,}165)\,\Omega \cdot \left(\frac{21\,\text{kV}}{10{,}5\,\text{kV}}\right)^2 = (0{,}553 + j4{,}661)\,\Omega$$

$$\underline{Z}_{\Sigma(M+T,21...26)t} = \underline{Z}_{\Sigma(M+T,15...20)t} = (3{,}920 + j10{,}402)\,\Omega$$

$$\underline{Z}_{MCt} = (0{,}626 + j3{,}261)\,\Omega \text{ (see Figure 13)}$$

The impedances $\underline{Z}_{AK}$, $\underline{Z}_{BK}$ and $\underline{Z}_{CK}$ referred to side A are already calculated in 7.2.3. For the calculation of $\underline{I}''_{kATHV}$, the impedance $\underline{Z}_{M,AT}$ is needed:

$$\underline{Z}_{M,AT} = \underline{Z}_{AK} + \frac{(\underline{Z}_{BK} + \underline{Z}_{MBt}) \cdot (\underline{Z}_{CK} + \underline{Z}_{MCt})}{\underline{Z}_{BK} + \underline{Z}_{CK} + \underline{Z}_{MBt} + \underline{Z}_{MCt}} = (0{,}273 + j2{,}080)\,\Omega$$

$$\underline{I}''_{kATHV} = \frac{cU_{rG}}{\sqrt{3} \cdot \underline{Z}_{M,AT}} = \frac{1{,}1 \cdot 21\,\text{kV}}{\sqrt{3} \cdot (0{,}273 + j2{,}080)\,\Omega} = (0{,}826 - j6{,}304)\,\text{kA} \qquad I''_{kATHV} = 6{,}36\,\text{kA}$$

This partial short-circuit current $I''_{kATHV} = 6{,}36\,\text{kA}$ shall be considered, because its magnitude reaches 7,5 % of the current $I''_{kGT} = 83{,}78\,\text{kA}$.

The total short-circuit current in F3 (see Figure 13) therefore reaches:

$$\underline{I}''_{kF3} = \underline{I}''_{kGT} + \underline{I}''_{kATHV} = (1{,}94 - j90{,}08)\,\text{kA} \qquad I''_{kF3} = 90{,}10\,\text{kA}$$

NOTE In the case of a short circuit in F3 (Figure 13), the residual line-to-line voltages at the busbars B is approximately 4,1 kV, i.e. nearly 40 % of the line-to-line voltages before the short circuit.

7.3.3.2 Peak short-circuit currents i_{pGT} and i_{pATHV}

The peak short-circuit current i_{pGT} can be found using the two parts of Formula (38) of IEC 60909-0:2016:

$$i_{pGT} = \kappa_{G,S} \cdot \sqrt{2} \cdot \frac{cU_{rG}}{\sqrt{3} \cdot K_{G,S} \cdot Z_G} + \kappa_{T,S} \cdot \sqrt{2} \cdot \frac{cU_{rG}}{\sqrt{3} \cdot \left| K_{T,S} \cdot \underline{Z}_{TLV} + \frac{\underline{Z}_{Qmin}}{t_r^2} \right|}$$

$$i_{pGT} = 1{,}86 \cdot \sqrt{2} \cdot 44{,}73\,\text{kA} + 1{,}95 \cdot \sqrt{2} \cdot 39{,}05\,\text{kA} = 225{,}34\,\text{kA}$$

with $\frac{R_{Gf}}{X_d''} = \frac{0{,}015\,0\,\Omega}{0{,}299\,9\,\Omega} = 0{,}05 \quad \rightarrow \quad \kappa_{G,S} = 1{,}86$ ($\underline{Z}_{Gf}$ from 7.2.2)

and $\frac{\text{Re}\left\{K_{T,S}\underline{Z}_{TLV} + \underline{Z}_{Qmin} / t_r^2\right\}}{\text{Im}\left\{K_{T,S}\underline{Z}_{TLV} + \underline{Z}_{Qmin} / t_r^2\right\}} = \frac{0{,}006\,5\,\Omega}{0{,}341\,\Omega} = 0{,}019 \quad \rightarrow \quad \kappa_{G,T} = 1{,}95$

NOTE 1 A calculation with the 20 Hz method in 8.1.2 c) of IEC 60909-0:2016, using $\underline{Z}_{Gf}$ from 7.2.2 and the impedance Z_{GTc} according to Formula (38) of IEC 60909-0:2016 leads to:

$$\frac{R}{X} = \frac{R_{GTc}}{X_{GTc}} \cdot \frac{f_c}{f} = \frac{0{,}005\,66\,\Omega}{0{,}063\,96\,\Omega} \cdot \frac{20\,\text{Hz}}{50\,\text{Hz}} = 0{,}035\,4 \quad \rightarrow \quad \kappa_{GT} = 1{,}90$$

$$i_{pGT} = \kappa_{GT} \cdot \sqrt{2} \cdot I_{kGT}'' = 1{,}90 \cdot \sqrt{2} \cdot 83{,}78\,\text{kA} = 225{,}27\,\text{kA}$$

The peak short-circuit current i_{pATHV} can be found with method b) (8.1.2 b) of IEC 60909-0:2016), but without the factor 1,15, because the relevant impedances of the medium-voltage motors have a ratio R/X < 0,3.

$$i_{pATHV} = \kappa_{(b)} \cdot \sqrt{2} \cdot I_{kATHV}'' = 1{,}68 \cdot \sqrt{2} \cdot 6{,}36\,\text{kA} = 15{,}12\,\text{kA}$$

With $\frac{R_{ATHV}}{X_{ATHV}} = \frac{0{,}273\,\Omega}{2{,}080\,\Omega} = 0{,}131 \quad \rightarrow \quad \kappa_{(b)} = 1{,}68$

NOTE 2 A calculation with the 20 Hz method leads nearly to the same result in this case (deviation smaller than 0,4 %).

7.3.3.3 Breaking current and steady-state short-circuit current

The breaking current I_b is of no interest at the short-circuit location F3.

The steady-state short-circuit I_k is dominated by $I_{kT} = I_{kT}''$:

$$I_{kF3} = I_{kG} + I_{kT} + I_{kATHV} \approx \lambda_{max} I_{rG} + I_{kT}'' = 12{,}02\,\text{kA} + 46{,}81\,\text{kA} = 58{,}84\,\text{kA}$$

with I_{kG} and I_{kT}'' from 7.3.2 and $I_{kATHV} \rightarrow 0$

7.3.4 Short-circuit location F4

The initial symmetrical three-phase short-circuit current at the location F4 (Figure 12) can be found from the partial short-circuit currents as shown in Figure 14 (Figure 9 of IEC 60909-0:2016):

$$I''_{kF4} = I''_{kAT} + I''_{k(1...7)} + I''_{k(15...20)}$$

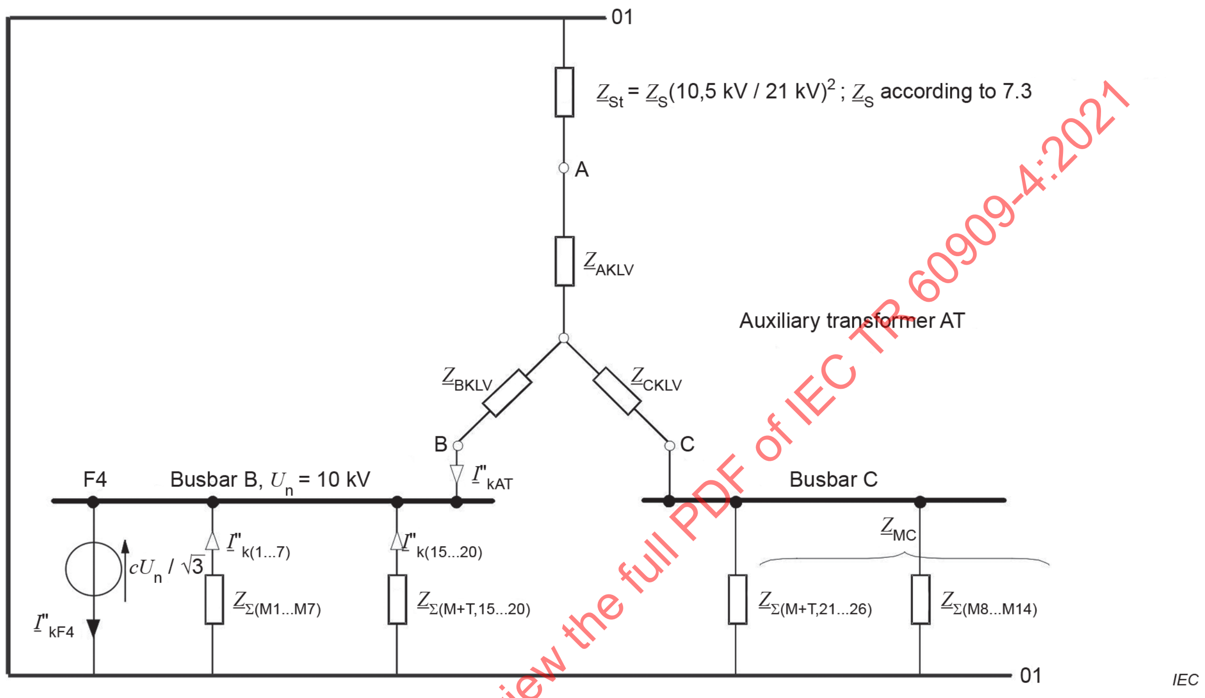


Figure 14 – Positive-sequence system for the calculation of the short-circuit currents at the location F4 (see Figure 12)

Impedances are referred to the secondary side B of the auxiliary transformer AT.

$$\underline{Z}_{kAT} = \underline{Z}_{BKLV} + \frac{(\underline{Z}_{AKLV} + \underline{Z}_{St}) \cdot (\underline{Z}_{CKLV} + \underline{Z}_{MC})}{\underline{Z}_{AKLV} + \underline{Z}_{St} + \underline{Z}_{CKLV} + \underline{Z}_{MC}}$$

$$\underline{Z}_{kAT} = (0{,}009\ 7 + j0{,}277\ 7)\Omega + (0{,}001\ 7 + j0{,}067\ 2)\Omega = (0{,}011\ 4 + j0{,}344\ 9)\Omega$$

$$Z_{kAT} = 0{,}345\ 1\ \Omega$$

with $\underline{Z}_{AKLV} = \underline{Z}_{AK} / t_r^2$; $\underline{Z}_{BKLV} = \underline{Z}_{CKLV} = \underline{Z}_{BK} / t_r^2$; $\underline{Z}_{AK}$ and $\underline{Z}_{BK}$ from 7.2.3, $\underline{Z}_{MC} = \underline{Z}_{MCt} / t_r^2$; $\underline{Z}_{MCt}$ from 7.3.3, $\underline{Z}_S$ from 7.3.3 (see Figure 13)

$$\underline{I}''_{kAT} = \frac{cU_n}{\sqrt{3} \cdot \underline{Z}_{kAT}} = \frac{1{,}1 \cdot 10\,kV}{\sqrt{3} \cdot (0{,}011\,4 + j0{,}344\,9)\Omega} = (0{,}610 - j18{,}394)kA \qquad I''_{kAT} = 18{,}40\,kA$$

From Table 8 and Table 9:

$$\underline{I}''_{k(1...7)} = \frac{cU_n}{\sqrt{3}\cdot\underline{Z}_{\Sigma(M1...M7)}} = \frac{1{,}1\cdot 10\,kV}{\sqrt{3}\cdot(0{,}089+j0{,}776)\Omega} = (0{,}921-j8{,}075)kA \qquad I''_{k(1...7)} = 8{,}13\,kA$$

$$\underline{I}''_{k(15...20)} = \frac{cU_n}{\sqrt{3}\cdot\underline{Z}_{\Sigma(M+T,15...20)}} = \frac{1{,}1\cdot 10\,kV}{\sqrt{3}\cdot(0{,}980+j2{,}601)\Omega} = (0{,}806-j2{,}138)kA \qquad I''_{k(15...20)} = 2{,}29\,kA$$

$$\underline{I}''_{kF4} = (2{,}336-j28{,}607)kA \qquad I''_{kF4} = 28{,}70\,kA$$

NOTE 1 Neglecting the influence of the motors fed from busbar C to the short-circuit current in F4 leads to:

$$\underline{Z}_{kAT} \approx \underline{Z}_{BKLV} + \underline{Z}_{AKLV} + \underline{Z}_{St} = (0{,}011+j0{,}349)\Omega$$

$$\underline{I}''_{kAT} \approx (0{,}571-j18{,}168)kA \qquad I''_{kAT} = 18{,}18\,kA$$

$$\underline{I}''_{kF4} = (2{,}297-j28{,}382)kA \qquad I''_{kF4} = 28{,}47\,kA$$

NOTE 2 The influence of the motors fed from busbar C is smaller than 1 % to the current I''_{kF4}. They can be neglected in this case.

The peak short-circuit currents are found according 8.1.1 of IEC 60909-0:2016), whereby the motors of busbar C are neglected. The currents of the individual branches are determined according to method b) (8.1.2 b) of IEC 60909-0:2016), taking into account the relevant R/X ratios.

$$i_{pF4} = \kappa_{AT}\cdot\sqrt{2}\cdot I''_{kAT} + \kappa_{(1...7)}\cdot\sqrt{2}\cdot I''_{k(1...7)} + 1{,}15\cdot\kappa_{(15...20)}\cdot\sqrt{2}\cdot I''_{k(15...20)}$$

$$i_{pF4} = 1{,}91\cdot\sqrt{2}\cdot 18{,}18\,kA + 1{,}72\cdot\sqrt{2}\cdot 8{,}13\,kA + 1{,}15 * 1{,}34\cdot\sqrt{2}\cdot 2{,}29\,kA = 73{,}84\,kA$$

If the partial short-circuit current I''_{kAT} is transferred to the high-voltage side of the auxiliary transformer, it can be seen that $I''_{kATt} = 9{,}09\,kA$ (without the contribution of busbar C) resp. $I''_{kGt} = 4{,}85\,kA$ is smaller than $2I_{rG} = 2\cdot 6{,}87\,kA$, so that the short circuit in F4 is a far-from-generator short circuit related to the generator G.

$$I_{bF4} = I_{bAT} + I_{b(1...7)} + I_{b(15...20)} = 22{,}8\,kA$$

with $I_{bAT} = I''_{kAT} = 18{,}18\,kA$

$$I_{b(1...7)} = \sum_{i=1}^{7}\mu_i q_i I''_{kMi} = 4{,}04\,kA \text{ (see Table 9)}$$

$$I_{b(15...20)} = \mu\cdot q\cdot I''_{k(15...20)} = 0{,}76\cdot 0{,}21\cdot 2{,}29\,kA = 0{,}36\,kA$$

(μ = 0,76 from t_{min} = 0,1 s and $I''_{kM}/I_{rM} = 5{,}19$ and q = 0,21 from t_{min} = 0,1 s and P_{rM}/p = 0,05 MW; according to 7.1.3 of IEC 60909-0:2016, and the rated power of the motors from Table 8, $I''_{k(15...20)} = 2{,}29\,kA$)

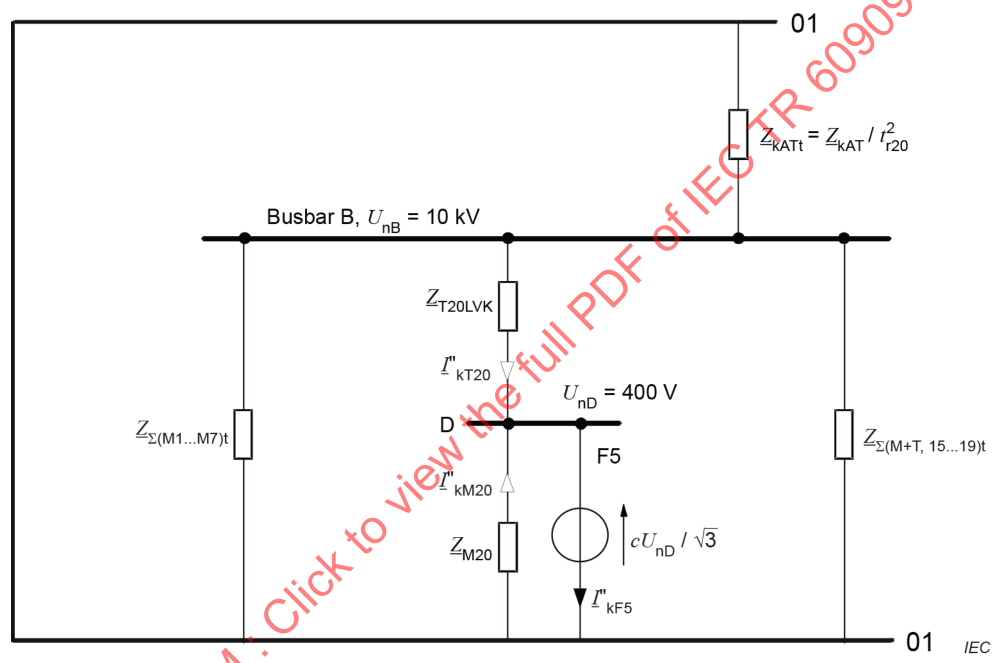
7.3.5 Short-circuit location F5

The initial symmetrical short-circuit current at the short-circuit location F5 can be calculated with the positive-sequence system given in Figure 15.

$$\underline{I}''_{\text{kF5}} = \underline{I}''_{\text{kT20}} + \underline{I}''_{\text{kM20}}$$

For the calculation of the partial short-circuit current $\underline{I}''_{\text{kT20}}$, the following impedances are used (see Figure 15):

$$\underline{Z}_{\text{kATt}} = \frac{\underline{Z}_{\text{kAT}}}{t_{\text{r20}}^2} = (0{,}0114 + \text{j}0{,}345)\,\Omega \cdot \left(\frac{0{,}42\,\text{kV}}{10\,\text{kV}}\right)^2 = (0{,}020 + \text{j}0{,}608)\,\text{m}\Omega$$



NOTE Impedances are referred to the low-voltage side of transformer T20 (t_{r20} = 10 kV/0,42 kV).

Figure 15 – Positive-sequence system for the calculation of the short-circuit currents at the location F5 (see Figure 12)

$$\underline{Z}_{\Sigma(\text{M1...M7})\text{t}} = \underline{Z}_{\Sigma(\text{M1...M7})} \cdot \frac{1}{t_{\text{r20}}^2} = (0{,}089 + \text{j}0{,}776)\,\Omega \cdot \left(\frac{0{,}42\,\text{kV}}{10\,\text{kV}}\right)^2 = (0{,}157 + \text{j}1{,}370)\,\text{m}\Omega$$

$$\underline{Z}_{\Sigma(\text{M+T,15...19})\text{t}} = \underline{Z}_{\Sigma(\text{M+T,15...19})} \cdot \frac{1}{t_{\text{r20}}^2} = (1{,}183 + \text{j}3{,}114)\,\Omega \cdot \left(\frac{0{,}42\,\text{kV}}{10\,\text{kV}}\right)^2 = (2{,}087 + \text{j}5{,}494)\,\text{m}\Omega$$

The impedance $\underline{Z}_{\text{kAT}}$ is already calculated in 7.3.4. The impedances $\underline{Z}_{\Sigma(\text{M,1...M7})}$, respectively $\underline{Z}_{\Sigma(\text{M+T,15...19})}$, are given in Table 9 and Table 8 respectively.

The impedance of the low-voltage transformer T20 is given in 7.2.4 related to the low-voltage side:

$$\underline{Z}_{\text{T20LVK}} = (1{,}095 + \text{j}6{,}278)\,\text{m}\Omega \qquad \underline{Z}_{\text{kT20}} = (1{,}126 + \text{j}6{,}672)\,\text{m}\Omega$$

$$\underline{I}''_{\text{kT20}} = \frac{cU_{\text{n}}}{\sqrt{3}\,\underline{Z}_{\text{kT20}}} = \frac{1{,}05 \cdot 400\,\text{V}}{\sqrt{3}\,(1{,}126 + \text{j}6{,}672)\,\text{m}\Omega} = (5{,}96 - \text{j}35{,}34)\,\text{kA} \qquad I''_{\text{kT20}} = 35{,}84\,\text{kA}$$

The impedance Z_{kT20} is found from $\underline{Z}_{\text{T20LVK}}$ in series with the three parallel impedances $\underline{Z}_{\text{kATt}}$, $\underline{Z}_{\Sigma(\text{M1...M7})\text{t}}$ and $\underline{Z}_{\Sigma(\text{M+T,15...19})\text{t}}$.

The impedance $\underline{Z}_{\text{M20}}$ is given in Table 8.

$$\underline{I}''_{\text{kM20}} = \frac{cU_{\text{n}}}{\sqrt{3}\,\underline{Z}_{\text{M20}}} = \frac{1{,}05 \cdot 400\,\text{V}}{\sqrt{3}\,(8{,}9 + \text{j}21{,}2)\,\text{m}\Omega} = (4{,}08 - \text{j}9{,}71)\,\text{kA} \qquad I''_{\text{kM20}} = 10{,}53\,\text{kA}$$

$$\underline{I}''_{\text{kF5}} = \underline{I}''_{\text{kT20}} + \underline{I}''_{\text{kM20}} = (10{,}04 - \text{j}45{,}05)\,\text{kA} \qquad I''_{\text{kF5}} = 46{,}16\,\text{kA}$$

The peak short-circuit current is found with

$$i_{\text{pF5}} = i_{\text{pT20}} + i_{\text{pM20}} = 1{,}15 \cdot \kappa_{\text{T20}}\,\sqrt{2}\,I''_{\text{kT20}} + \kappa_{\text{M20}}\,\sqrt{2}\,I''_{\text{kM20}}$$

where κ_{T20} = 1,61 found from $R_{\text{kT20}}/X_{\text{kT20}}$ = 0,169 and κ_{M20} = 1,30 for the equivalent motor of the motor group (7.1.3 of IEC 60909-0:2016). The current i_{pT} is determined according to method b) (8.1.2 b) of IEC 60909-0:2016), taking into account the factor 1,15 due to the impedance $\underline{Z}_{\square(\text{M+T,15...19})\text{t}}$.

$$i_{\text{pF5}} = 1{,}15 \cdot 1{,}61 \cdot \sqrt{2} \cdot 35{,}84\,\text{kA} + 1{,}30 \cdot \sqrt{2} \cdot 10{,}53\,\text{kA} = 113{,}24\,\text{kA}$$

Due to the small contribution of the motors M15...19 to the short-circuit current ($I''_{\text{kT20}} = 35{,}70\,\text{kA}$ without motors instead of 35,84 kA), this can be neglected. In this case, the factor 1,15 does not have to be taken into account, resulting in a peak short-circuit current of i_{pF5} = 100,83 kA.

Short-circuit breaking current:

Based on the topology, the calculation of the breaking current can be divided into two parts: contribution via the impedance $\underline{Z}_{\text{T20LVK}}$ according to Formula (77) of IEC 60909-0:2016 and the direct contribution of the motor M2 according to Formula (74) of IEC 60909-0:2016. The total breaking current becomes:

$$\underline{I}_{\text{bF5}} = \underline{I}''_{\text{kT20}} - \sum_{j} \frac{\underline{Z}_{\text{M}j} \cdot \underline{I}''_{\text{kM}j}}{cU_{\text{n}}/\sqrt{3}} \cdot (1 - \mu_j q_j) \cdot \underline{I}''_{\text{kM}j} + \mu_{\text{M20}} \cdot q_{\text{M20}} \cdot \underline{I}''_{\text{kM20}} =$$

$$(5{,}96 - \text{j}35{,}34)\,\text{kA} - (-\text{j}0{,}01)_{\text{M1–M7}}\,\text{kA} - (0{,}02 - \text{j}0{,}03)_{\text{M15–M19}}\,\text{kA} + 0{,}906 \cdot 0{,}671 \cdot (4{,}08 - \text{j}9{,}71)\,\text{kA}$$

$$\underline{I}_{\text{bF5}} = (8{,}42 - \text{j}41{,}19)\,\text{kA} \qquad I_{\text{bF5}} = 42{,}04\,\text{kA}$$

at t_{min} = 0,02 s with $\mu_{\text{M20}} = 0{,}84 + 0{,}26 \cdot \text{e}^{-0{,}26 \cdot 5{,}5}$ and q_{M20} = 0,671 taking P_{rM}/p = 0,05 MW for the equivalent motor M20 (see 7.1.3, 9.1.1, and 9.1.2 of IEC 60909-0:2016). The factors μ_j and q_j, the impedances, and the currents of the other motors are determined according to Table 8 and Table 9, for a time of t_{min} = 0,02 s, where the factor μ always has the value 1 in all cases.

Steady-state short-circuit current:

$I_{kF5} = I_{kT20} + I_{kM20} \approx I''_{kT20M} = 34{,}72\,\text{kA}$

because $I_{kM20} = 0$ (see Table 4 of IEC 60909-0:2016).

8 Calculation of three-phase short-circuit currents in a wind power plant

8.1 General

Wind power stations and photovoltaic power stations shall be considered only in case of the calculation of the maximum short-circuit current I''_{kmax} (see IEC 60909-0). Therefore, the subscript "max" is omitted in the following.

8.2 Problem

A wind power plant with ten wind power station units W is given in Figure 16. The wind power plant is connected by two parallel cables L1 and the transformer TWP to the 110 kV network feeder Q.

The initial symmetrical short-circuit currents and the peak short-circuit currents shall be calculated at the short-circuit locations F1 to F14 which are identical to the node numbers 1 to 14.

Three variants are to be regarded:

1) the wind power plant consists of ten wind power station units with doubly fed asynchronous generators (WD);
2) the wind power plant consists of ten wind power station units with full size converters (WF);
3) the wind power plant consists of five wind power station units with doubly fed asynchronous generators (W1 to W5 in Figure 16) and of five wind power station units with full size converter (W6 to W10).

The lengths of the cables are given in Figure 16. The other equipment data shall be seen from Table 10.

The short-circuit currents at the short-circuit locations F1 to F3 shall be calculated without consideration of these cables, to show the influence of the internal wind power plant cables to the short-circuit currents.

In addition, the symmetrical breaking currents at the short-circuit locations F1 to F3 shall be calculated neglecting the internal wind power plant cables.

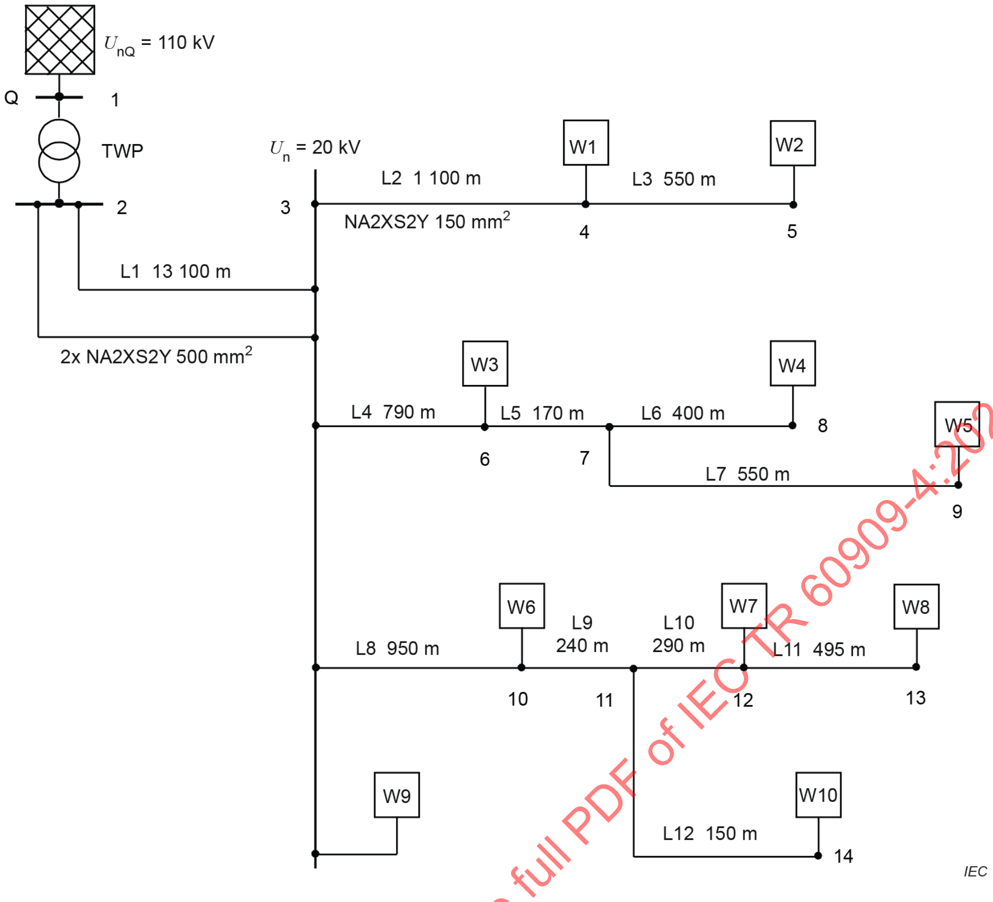


Figure 16 – Windfarm with ten wind power station units

8.3 Data and short-circuit impedances of electrical equipment

The short-circuit impedances of electrical equipment are arranged in Table 10, calculated according to the formulae of IEC 60909-0.

Table 10 – Data and impedances of the electrical equipment (see Figure 16) referred to the 20 kV side

Data	Formulae (IEC 60909-0:2016) and calculation	Impedance Ω
Network feeder Q $U_{nQ} = 110\,kV$ $I''_{kQ} = 10{,}5\,kA$ $c_Q = c_{max} = 1{,}1$ $R_Q = 0{,}1\ X_Q$	(6) $Z_{Qt} = \frac{c_Q U_{nQ}}{\sqrt{3}\cdot I''_{kQ}}\cdot\frac{1}{t_r^2} = \frac{1{,}1\cdot 110\ kV}{\sqrt{3}\cdot 10{,}5\ kA}\cdot\left(\frac{20\ kV}{110\ kV}\right)^2$ $X_{Qt} = \frac{Z_{Qt}}{\sqrt{1+(R_Q/X_Q)^2}}$; $R_{Qt} = 0{,}1\ X_{Qt}$ $\underline{Z}_{Qt} = R_{Qt} + jX_{Qt}$	$Z_{Qt} = 0{,}219\ 9$ $\underline{Z}_{Qt} = 0{,}021\ 9 + j0{,}218\ 8$
Transformer TWP $S_{rTWP} = 31{,}5\,MVA$ $U_{rTWPHV} = 110\,kV$ $U_{rTWPLV} = 20\,kV$ $u_{kr} = 12\,\%$ $u_{Rr} = 0{,}6\,\%$	(7) $Z_{TWP} = \frac{u_{kr}}{100\ \%}\cdot\frac{U_{rTWPLV}^2}{S_{rTWP}} = \frac{12\ \%}{100\ \%}\cdot\frac{(20\ kV)^2}{31{,}5\ MVA}$ (8) $R_{TWP} = \frac{u_{Rr}}{100\ \%}\cdot\frac{U_{rTWPLV}^2}{S_{rTWP}} = \frac{0{,}6\ \%}{100\ \%}\cdot\frac{(20\ kV)^2}{31{,}5\ MVA}$ (9) $X_{TWP} = \sqrt{Z_{TWP}^2 - R_{TWP}^2}$ $\underline{Z}_{TWP} = R_{TWP} + jX_{TWP}$ (12a) $K_T = \frac{0{,}95\cdot c_{max}}{1+0{,}6\cdot x_{TWP}} = \frac{0{,}95\cdot 1{,}1}{1+0{,}6\cdot 0{,}11985} = 0{,}9749$ $\underline{Z}_{TWPK} = K_T \underline{Z}_{TWP}$	$Z_{TWP} = 1{,}523\ 8$ $R_{TWP} = 0{,}076\ 2$ $X_{TWP} = 1{,}521\ 9$ $\underline{Z}_{TWP} = 0{,}076\ 2 + j1{,}521\ 9$ $\underline{Z}_{TWPK} = 0{,}074\ 3 + j1{,}483\ 7$
Wind Power Station Units WD $S_{rWD} = 2{,}5\,MVA$ $U_{rWD} = U_{rTWDHV} = 20\,kV$ $i_{WDmax} = 388\,A$ $I_{kWDmax} = 1{,}2\cdot I_{rWD}$ [a] $\kappa_{WD} = 1{,}7$; $R_{WD} = 0{,}1\ X_{WD}$	(28) $Z_{WD} = \frac{\sqrt{2}\cdot\kappa_{WD}\cdot U_{rTWDHV}}{\sqrt{3}\cdot i_{WDmax}} = \frac{\sqrt{2}\cdot 1{,}7\cdot 20\ kV}{\sqrt{3}\cdot 0{,}388\ kA}$ (29) $\underline{Z}_{WD} = (R_{WD}/X_{WD} + j)\cdot\frac{Z_{WD}}{\sqrt{1+(R_{WD}/X_{WD})^2}}$	$Z_{WD} = 71{,}548\ 7$ $\underline{Z}_{WD} = 7{,}119\ 4 + j71{,}193\ 6$
Wind Power Station Units WF $S_{rWF} = 2{,}5\,MVA$ $U_{rWF} = 20\,kV$ $I_{skWF} = I_{kWFmax} = 1{,}3\cdot I_{rWF}$ [b]	$I_{rWF} = \frac{S_{rWF}}{\sqrt{3}\cdot U_{rWF}} = \frac{2{,}5\ MVA}{\sqrt{3}\cdot 20\ kV} = 72{,}17\ A$ $I_{skWF} = I_{kWFmax} = 1{,}3\cdot I_{rWF} = 1{,}3\cdot 72{,}17\ A = 93{,}82\ A$	$Z_{WF} = \infty$
Cable L1 NA2XS2Y 500 mm^2 $R' = 0{,}0681\ \Omega/km$ $X' = 0{,}102\ \Omega/km$	Two parallel cables: $\underline{Z}_{L1} = \frac{1}{2}\cdot(0{,}0681 + j\ 0{,}102)\ \Omega/km\cdot 13{,}1\ km$	$\underline{Z}_{L1} = 0{,}446\ 1 + j0{,}668\ 1$
Cable L2 to L12 NA2XS2Y 150 mm^2 $R' = 0{,}211\ \Omega/km$ $X' = 0{,}122\ \Omega/km$	$\underline{Z}_{L2}$ = (0,211 + j0,122) Ω/km·1,1 km $\underline{Z}_{L3}$ = (0,211 + j0,122) Ω/km·0,55 km $\underline{Z}_{L4}$ = (0,211 + j0,122) Ω/km·0,79 km $\underline{Z}_{L5}$ = (0,211 + j0,122) Ω/km·0,17 km $\underline{Z}_{L6}$ = (0,211 + j0,122) Ω/km·0,4 km $\underline{Z}_{L7}$ = (0,211 + j0,122) Ω/km·0,55 km $\underline{Z}_{L8}$ = (0,211 + j0,122) Ω/km·0,95 km $\underline{Z}_{L9}$ = (0,211 + j0,122) Ω/km·0,24 km $\underline{Z}_{L10}$ = (0,211 + j0,122) Ω/km·0,29 km $\underline{Z}_{L11}$ = (0,211 + j0,122) Ω/km·0,495 km $\underline{Z}_{L12}$ = (0,211 + j0,122) Ω/km·0,15 km	$\underline{Z}_{L2}$ = 0,232 1 + j0,134 2 $\underline{Z}_{L3}$ = 0,116 1 + j0,067 1 $\underline{Z}_{L4}$ = 0,166 7 + j0,096 3 $\underline{Z}_{L5}$ = 0,035 9 + j0,020 7 $\underline{Z}_{L6}$ = 0,084 4 + j0,048 8 $\underline{Z}_{L7}$ = 0,116 1 + j0,067 1 $\underline{Z}_{L8}$ = 0,200 4 + j0,115 9 $\underline{Z}_{L9}$ = 0,050 6 + j0,029 3 $\underline{Z}_{L10}$ = 0,061 2 + j0,035 4 $\underline{Z}_{L11}$ = 0,104 4 + j0,060 4 $\underline{Z}_{L12}$ = 0,031 6 + j0,018 3

[a] Specified by the manufacturer.

[b] The short-circuit contribution of a full size converter depends on the requirements of the system operator, the typical range is between 1,0 to 1,3 related to the rated current I_{rWF}. In this case, a factor of 1,3 is used.

8.4 Nodal admittance and nodal impedance matrices

The nodal admittances and nodal impedance matrices are symmetrical and have the order 14 × 14. The rule for the formulation of the nodal admittance is given in Annex B of IEC 60909-0:2016. The non-diagonal elements are equal for the three variants of the wind power plant. The non-zero elements above the main diagonal are found as follows in 1/Ω:

$$\underline{Y}_{1,2} = \frac{1}{\underline{Z}_{\text{TWPK}}} = 0{,}033\,7 - \text{j}\,0{,}672\,3\,;\ \underline{Y}_{2,3} = \frac{1}{\underline{Z}_{\text{L1}}} = 0{,}691\,2 - \text{j}\,1{,}035\,3\,;\ \underline{Y}_{3,4} = \frac{1}{\underline{Z}_{\text{L2}}} = 3{,}2290 - \text{j}\,1{,}8670$$

$$\underline{Y}_{3,6} = \frac{1}{\underline{Z}_{\text{L4}}} = 4{,}496\,1 - \text{j}\,2{,}599\,6\,;\ \underline{Y}_{3,10} = \frac{1}{\underline{Z}_{\text{L8}}} = 3{,}738\,8 - \text{j}\,2{,}161\,8\,;\ \underline{Y}_{4,5} = \frac{1}{\underline{Z}_{\text{L3}}} = 6{,}458\,0 - \text{j}\,3{,}734\,0$$

$$\underline{Y}_{6,7} = \frac{1}{\underline{Z}_{\text{L5}}} = 20{,}893\,5 - \text{j}\,12{,}080\,6\,;\ \underline{Y}_{7,8} = \frac{1}{\underline{Z}_{\text{L6}}} = 8{,}879\,7 - \text{j}\,5{,}134\,2\,;\ \underline{Y}_{7,9} = \frac{1}{\underline{Z}_{\text{L7}}} = 6{,}4580 - \text{j}\,3{,}7340$$

$$\underline{Y}_{10,11} = \frac{1}{\underline{Z}_{\text{L9}}} = 14{,}799\,5 - \text{j}\,8{,}557\,1\,;\ \underline{Y}_{11,12} = \frac{1}{\underline{Z}_{\text{L10}}} = 12{,}247\,9 - \text{j}\,7{,}0817$$

$$\underline{Y}_{11,14} = \frac{1}{\underline{Z}_{\text{L12}}} = 23{,}679\,3 - \text{j}\,13{,}691\,3\,;\ \underline{Y}_{12,13} = \frac{1}{\underline{Z}_{\text{L11}}} = 7{,}175\,5 - \text{j}\,4{,}148\,9$$

The diagonal elements of the nodal admittance matrices are listed in Table 11.

Table 11 – The diagonal elements of the nodal admittance matrices for the three variants in 1/Ω

	Variant 1 **Wind power plant with ten wind power station units WD**	**Variant 2** **Wind power plant with ten wind power station units WF**	**Variant 3** **Wind power plant with five wind power station units WD and five WF**
$\underline{Y}_{1,1}$	–0,486 1 + j5,196 4	–0,486 1 + j5,196 4	–0,486 1 + j5,196 4
$\underline{Y}_{2,2}$	–0,724 9 + j1,707 6	–0,724 9 + j1,707 6	–0,724 9 + j1,707 6
$\underline{Y}_{3,3}$	–12,156 5 + j7,677 6	–12,155 1 + j7,663 7	–12,155 1 + j7,663 7
$\underline{Y}_{4,4}$	–9,688 4 + j5,614 9	–9,687 0 + j5,601 0	–9,688 4 + j5,614 9
$\underline{Y}_{5,5}$	–6,459 4 + j3,747 9	–6,458 0 + j3,734 0	–6,459 4 + j3,747 9
$\underline{Y}_{6,6}$	–25,390 9 + j14,694 1	–25,389 5 + j14,680 2	–25,390 9 + j14,694 1
$\underline{Y}_{7,7}$	–36,231 2 + j20,948 8	–36,231 2 + j20,948 8	–36,231 2 + j20,948 8
$\underline{Y}_{8,8}$	–8,881 1+ j5,148 2	–8,879 7+ j5,134 2	–8,881 1+ j5,148 2
$\underline{Y}_{9,9}$	–6,459 4 + j3,747 9	–6,458 0 + j3,734 0	–6,459 4 + j3,747 9
$\underline{Y}_{10,10}$	–18,539 8 + j10,732 8	–18,538 4 + j10,718 9	–18,538 4 + j10,718 9
$\underline{Y}_{11,11}$	–50,726 7 + j29,330 1	–50,726 7 + j29,330 1	–50,726 7 + j29,330 1
$\underline{Y}_{12,12}$	–19,424 8 + j11,244 5	–19,423 4 + j11,230 6	–19,423 4 + j11,230 6
$\underline{Y}_{13,13}$	–7,176 9 + j4,162 8	–7,175 5 + j4,148 9	–7,175 5 + j4,148 9
$\underline{Y}_{14,14}$	–23,680 7 + j13,705 2	–23,679 3 + j13,691 3	–23,679 3 + j13,691 3

The nodal impedance matrices are the inverse of the nodal admittance matrices.

8.5 Short-circuit currents for the wind power plant with ten wind power station units WD

The initial symmetrical short-circuit currents at the short circuit locations F1 to F14 are calculated by Formula (33) of IEC 60909-0:2016 with U_n = 20 kV and $c = c_{max}$ = 1,1 (Table 1 of IEC 60909-0:2016):

$$I''_{kFi} = \frac{cU_n}{\sqrt{3} \cdot Z_{kFi}} \qquad i = 1\ldots14$$

The absolute short-circuit impedances are identical to the absolute diagonal elements Z_{ii} of the nodal impedance matrix (see Table 12), see Annex B of IEC 60909-0:2016.

The initial symmetrical short-circuit current at the short-circuit location F1 is obtained from:

$$I''_{kF1} = I''_{kF120kV} \cdot \frac{U_{nQ}}{U_n} \cdot \frac{1}{t^2_{rTWP}} = 59{,}100\,\text{kA} \cdot \frac{110\,\text{kV}}{20\,\text{kV}} \cdot \left(\frac{20\,\text{kV}}{110\,\text{kV}}\right)^2 = 10{,}745\,\text{kA}$$

The peak short-circuit currents i_{p50} and i_{p20} are found from Formula (56) and Formula (57) of IEC 60909-0:2016 with the ratio R_k/X_k from 8.1.2 b) of IEC 60909-0:2016 without the factor 1,15 and with the ratio R/X for 20 Hz accordingly 8.1.2 c) of IEC 60909-0:2016.

$$i_p = \kappa\sqrt{2} \cdot I''_k \qquad \kappa = 1{,}02 + 0{,}98 \cdot e^{-3R/X}$$

The results are given in Table 12.

Table 12 – Short-circuit impedances and short-circuit currents at F1 to F14 for wind power stations units with doubly fed asynchronous generators WD

F	U_n	$\underline{Z}_k$	Z_k	I''_{kN} [a]	I''_{kWD} [b]	I''_k	R_k/X_k	i_{p50}	i_{p20}
	kV	Ω	Ω	kA	kA	kA	---	kA	kA
1	110	0,652 7 +j6,468 5	6,501 3	10,500	0,246	10,745	0,100 9	26,503	26,504
2	20	0,103 8 +j1,400 4	1,404 3	7,449	1,603	9,045	0,074 1	23,085	23,129
3	20	0,353 7 +j1,785 6	1,820 3	5,223	1,764	6,978	0,198 1	15,403	15,469
4	20	0,559 4 +j1,909 1	1,989 4	4,758	1,638	6,385	0,293	12,883	12,974
5	20	0,668 2 +j1,973 8	2,083 9	4,537	1,570	6,095	0,338 5	11,852	11,945
6	20	0,492 6 +j1,870 2	1,934 0	4,893	1,687	6,568	0,263 4	13,604	13,698
7	20	0,524 2 +j1,889 4	1,960 7	4,823	1,668	6,478	0,277 5	13,25	13,348
8	20	0,603 5 +j1,936 4	2,028 2	4,659	1,617	6,262	0,311 7	12,441	12,540
9	20	0,633 2 +j1,954 0	2,054 0	4,599	1,598	6,184	0,324	12,162	12,262
10	20	0,509 5 +j1,882 6	1,950 3	4,838	1,689	6,513	0,270 6	13,402	13,517
11	20	0,551 1 +j1,908 6	1,986 5	4,743	1,667	6,394	0,288 7	12,95	13,075
12	20	0,604 8 +j1,941 3	2,033 4	4,628	1,635	6,247	0,311 5	12,411	12,542
13	20	0,702 5 +j1,999 6	2,119 5	4,436	1,574	5,993	0,351 3	11,540	11,670
14	20	0,580 8 +j1,926 2	2,011 8	4,682	1,648	6,313	0,301 5	12,648	12,773

[a] Partial short-circuit currents of the network feeder.

[b] Partial short-circuit currents of the wind power station units.

Figure 17 shows the equivalent circuit diagram of the positive-sequence system if the internal wind power plant cables L2 to L12 (see Figure 16) are not taken into consideration.

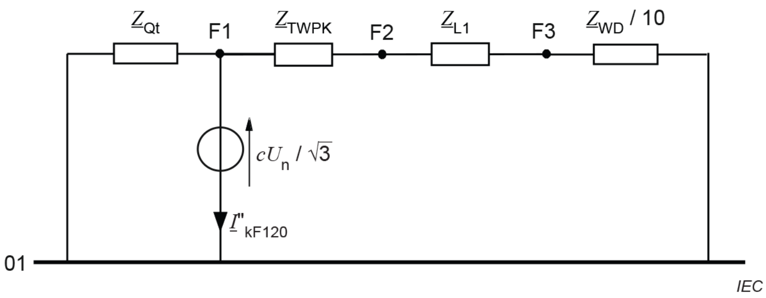


Figure 17 – Equivalent circuit diagram for the calculation of the short-circuit current at the location F1 without the consideration of the internal wind power plant cables (values are related to the 20 kV voltage level), variant 1

The following short-circuit impedances in the 20 kV level can be found from Figure 17.

$$\underline{Z}_{kF1} = \frac{\underline{Z}_{Qt} \cdot \left(\underline{Z}_{TWPK} + \underline{Z}_{L1} + \underline{Z}_{WD}/10\right)}{\underline{Z}_{Qt} + \underline{Z}_{TWPK} + \underline{Z}_{L1} + \underline{Z}_{WD}/10} = (0{,}021\,5 + j0{,}213\,8)\,\Omega$$

$$\underline{Z}_{kF2} = \frac{\left(\underline{Z}_{Qt} + \underline{Z}_{TWPK}\right) \cdot \left(\underline{Z}_{L1} + \underline{Z}_{WD}/10\right)}{\underline{Z}_{Qt} + \underline{Z}_{TWPK} + \underline{Z}_{L1} + \underline{Z}_{WD}/10} = (0{,}101\,8 + j1{,}398\,8)\,\Omega$$

$$\underline{Z}_{kF3} = \frac{\left(\underline{Z}_{Qt} + \underline{Z}_{TWPK} + \underline{Z}_{L1}\right) \cdot \underline{Z}_{WD}/10}{\underline{Z}_{Qt} + \underline{Z}_{TWPK} + \underline{Z}_{L1} + \underline{Z}_{WD}/10} = (0{,}348\,9 + j1{,}783\,9)\,\Omega$$

The short-circuit currents at the locations F1 to F3 calculated by Formula (33) of IEC 60909-0:2016 are shown in Table 13.

Table 13 – Short-circuit impedances and short-circuit currents at F1 to F3 for wind power stations units with doubly fed asynchronous generators WD neglecting the internal wind power plant cables

F	U_n kV	$\underline{Z}_k$ Ω	Z_k Ω	I''_{kN} kA	I''_{kWD} kA	I''_k kA	i_b kA
1	110	0,651 6 +j6,467 7	6,500 5	10,500	0,247	10,747	10,657
2	20	0,101 8 +j1,398 8	1,402 5	7,449	1,613	9,056	8,315
3	20	0,348 9 +j1,783 9	1,817 7	5,223	1,775	6,988	6,089

Without the consideration of the internal wind power plant cables, the symmetrical breaking currents at F1 to F3 can be calculated by summation of the contributions of the network feeder and the wind power plant (see 9.1.6 of IEC 60909-0:2016):

$$I_{bFi} = I_{bFiN} + I_{bFiWP} = I''_{kFiN} + \mu_{WDFi} I''_{kWDFi} = I''_{kFiN} + 10 I_{kWDmax} \qquad i = 1, 2, 3$$

The results are listed in Table 13, last column.

Alternatively, Formula (77) of IEC 60909-0:2016 can be used with U_n = 110 kV for F1 and U_n = 20 kV for F2 and F3 and the factor μ_{WD} according Formula (71) of IEC 60909-0:2016:

$$\mu_{WDFi} = \frac{I_{kWDmax}}{I''_{kWDFi}} = \frac{I_{kWPmax}}{I''_{kWPFi}}; \qquad I_{kWPmax} = 10 I_{kWDmax} = 0{,}866\,0\,\text{kA}$$

$$\underline{I}_{bF1} = \underline{I}''_{kF1} - 10 \cdot \frac{\underline{Z}_{WDt} \cdot \underline{I}''_{kWDF1}}{cU_n/\sqrt{3}} \cdot (1 - \mu_{WDF1}) \cdot \underline{I}''_{kWDF1} = (1{,}077\,3 - j10{,}692\,7)\text{kA} - (0{,}011\,2 - j0{,}067\,5)\text{kA} = (1{,}066\,1 - j10{,}625\,1)\text{kA}$$

$$I_{bF1} = 10{,}678\,\text{kA}$$

$$\underline{I}_{bF2} = \underline{I}''_{kF2} - 10 \cdot \frac{\underline{Z}_{WD} \cdot \underline{I}''_{kWDF2}}{cU_n/\sqrt{3}} \cdot (1 - \mu_{WDF2}) \cdot \underline{I}''_{kWDF2} = (0{,}6573 - j9{,}0324)\text{kA} - (0{,}1459 - j0{,}7366)\text{kA} = (0{,}5254 - j8{,}3663)\text{kA}$$

$$I_{bF2} = 8{,}383\,\text{kA}$$

$$\underline{I}_{bF3} = \underline{I}''_{kF3} - 10 \cdot \frac{\underline{Z}_{WD} \cdot \underline{I}''_{kWDF3}}{cU_n/\sqrt{3}} \cdot (1 - \mu_{WDF3}) \cdot \underline{I}''_{kWDF3} = (1{,}3412 - j6{,}8580)\text{kA} - (0{,}0905 - j0{,}9047)\text{kA} = (1{,}2507 - j5{,}9533)\text{kA}$$

$$I_{bF3} = 6{,}083\,\text{kA}$$

The small differences of I_{bF1} and I_{bF2} in comparison to the corresponding values in Table 13 justify the use of Formula (77) of IEC 60909-0:2016, which represents a (very good) approximation.

8.6 Short-circuit currents for the wind power plant with ten wind power station units WF

The initial symmetrical short-circuit currents at the short circuit locations F1 to F14 are calculated by Formula (34) of IEC 60909-0:2016 with U_n = 20 kV and $c = c_{max}$ = 1,1 (Table 1 of IEC 60909-0:2016):

$$I''_{kFi} = \frac{1}{Z_{kFi}} \cdot \frac{cU_n}{\sqrt{3}} + \frac{1}{Z_{kFi}} \sum_j Z_{ij} I_{skWFj} = I''_{kFiWFO} + I''_{kFiWF}; \; i = 1\ldots14;\; j = 3\ldots6,\ 8\ldots10,\ 12\ldots14$$

The values for the relevant quotients Z_{ij}/Z_{kFi} in the above formula for all short-circuit locations are arranged in Table 14. The partial short-circuit currents of the wind power stations at the short-circuit locations are obtained by multiplying the last column of Table 14 with I_{skWF} = 0,093 8 kA (see Table 15).

The peak short-circuit currents shall be determined using Formula (56) and Formula (57) of IEC 60601-0:2016 with the ratio R_k/X_k from 8.1.2 b) of IEC 60909-0:2016 without the factor 1,15 and with the ratio R/X for 20 Hz according to 8.1.2 c) of IEC 60909-0:2016.

$$i_p = \kappa\sqrt{2} \cdot I''_{kWFO} + \sqrt{2} \cdot I''_{kWF}$$

$$\kappa = 1{,}02 + 0{,}98 \cdot e^{-3R/X}$$

The results shall be seen from Table 15.