

INTERNATIONAL STANDARD



**Short-circuit currents in three-phase AC systems –
Part 3: Currents during two separate simultaneous line-to-earth short circuits
and partial short-circuit currents flowing through earth**

**Courants de court-circuit dans les réseaux triphasés à courant alternatif –
Partie 3: Courants durant deux courts-circuits monophasés simultanés séparés
à la terre et courants de court-circuit partiels s'écoulant à travers la terre**



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CONTENTS

FOREWORD.....	5
1 Scope and object.....	7
2 Normative references	8
3 Terms and definitions	8
4 Symbols	10
5 Calculation of currents during two separate simultaneous line-to-earth short circuits	12
5.1 Initial symmetrical short-circuit current	12
5.1.1 Determination of $\underline{M}_{(1)}$ and $\underline{M}_{(2)}$	12
5.1.2 Simple cases of two separate simultaneous line-to-earth short circuits.....	13
5.2 Peak short-circuit current, symmetrical short circuit breaking current and steady-state short-circuit current	13
5.3 Distribution of the currents during two separate simultaneous line-to-earth short circuits.....	14
6 Calculation of partial short-circuit currents flowing through earth in case of an unbalanced short circuit.....	14
6.1 General.....	14
6.2 Line-to-earth short circuit inside a station	15
6.3 Line-to-earth short circuit outside a station	16
6.4 Line-to-earth short circuit in the vicinity of a station	18
6.4.1 Earth potential $\underline{U}_{ETn}$ at the tower n outside station B	19
6.4.2 Earth potential of station B during a line-to earth short circuit at the tower n	19
7 Reduction factor for overhead lines with earth wires	20
8 Calculation of current distribution and reduction factor in case of cables with metallic sheath or shield earthed at both ends	21
8.1 Overview	21
8.2 Three-core cable	22
8.2.1 Line-to-earth short circuit in station B	22
8.2.2 Line-to-earth short circuit on the cable between station A and station B	23
8.3 Three single-core cables	26
8.3.1 Line-to-earth short circuit in station B	26
8.3.2 Line-to-earth short circuit on the cable between station A and station B	26
Annex A (informative) Example for the calculation of two separate simultaneous line-to-earth short-circuit currents	30
Annex B (informative) Examples for the calculation of partial short-circuit currents through earth	33
Annex C (informative) Example for the calculation of the reduction factor r_1 and the current distribution through earth in case of a three-core cable	43
Annex D (informative) Example for the calculation of the reduction factor r_3 and the current distribution through earth in case of three single-core cables	48

Figure 1 – Driving point impedance $\underline{Z}_P$ of an infinite chain, composed of the earth wire impedance $\underline{Z}_Q = \underline{Z}'_Q d_T$ and the footing resistance R_T of the towers, with equal distances d_T between the towers	9
Figure 2 – Driving point impedance $\underline{Z}_{Pn}$ of a finite chain with n towers, composed of the earth wire impedance $\underline{Z}_Q = \underline{Z}'_Q d_T$, the footing resistance R_T of the towers, with equal distances d_T between the towers and the earthing impedance $\underline{Z}_{EB}$ of station B from Equation (29)	10
Figure 3 – Characterisation of two separate simultaneous line-to earth short circuits and the currents I_{KEE}''	12
Figure 4 – Partial short-circuit currents in case of a line-to-earth short circuit inside station B	15
Figure 5 – Partial short-circuit currents in case of a line-to-earth short circuit at a tower T of an overhead line	16
Figure 6 – Distribution of the total current to earth I_{ETtot}	17
Figure 7 – Partial short-circuit currents in the case of a line-to-earth short circuit at a tower n of an overhead line in the vicinity of station B	18
Figure 8 – Reduction factor r for overhead lines with non-magnetic earth wires depending on soil resistivity ρ	21
Figure 9 – Reduction factor of three-core power cables	23
Figure 10 – Reduction factors for three single-core power cables	27
Figure A.1 – Two separate simultaneous line-to-earth short circuits on a single fed overhead line (see Table 1)	30
Figure B.1 – Line-to-earth short circuit inside station B – System diagram for stations A, B and C	34
Figure B.2 – Line-to-earth short circuit inside station B – Positive-, negative- and zero-sequence systems with connections at the short-circuit location F within station B	34
Figure B.3 – Line-to-earth short circuit outside stations B and C at the tower T of an overhead line – System diagram for stations A, B and C	36
Figure B.4 – Line-to-earth short circuit outside stations B and C at the tower T of an overhead line – Positive-, negative- and zero-sequence systems with connections at the short-circuit location F	37
Figure B.5 – Earth potentials $u_{ETn} = U_{ETn}/U_{ET}$ with $U_{ET} = 1,912$ kV and $u_{EBn} = U_{EBn}/U_{EB}$ with $U_{EB} = 0,972$ kV, if the line-to-earth short circuit occurs at the towers $n = 1, 2, 3, \dots$ in the vicinity of station B	42
Figure C.1 – Example for the calculation of the cable reduction factor and the current distribution through earth in a 10-kV-network, $U_n = 10$ kV; $c = 1,1$; $f = 50$ Hz	44
Figure C.2 – Short-circuit currents and partial short-circuit currents through earth for the example in Figure C.1	45
Figure C.3 – Example for the calculation of current distribution in a 10-kV-network with a short circuit on the cable between A and B (data given in C.2.1 and Figure C.1)	46
Figure C.4 – Line-to-earth short-circuit currents, partial currents in the shield and partial currents through earth	47
Figure D.1 – Example for the calculation of the reduction factor and the current distribution in case of three single-core cables and a line-to-earth short circuit in station B	49
Figure D.2 – Positive-, negative- and zero-sequence system of the network in Figure D.1 with connections at the short-circuit location (station B)	50
Figure D.3 – Current distribution for the network in Figure D.1, depending on the length, ℓ , of the single-core cables between the stations A and B	51

Figure D.4 – Example for the calculation of the reduction factors r_3 and the current distribution in case of three single-core cables and a line-to-earth short circuit between the stations A and B	52
Figure D.5 – Positive-, negative- and zero-sequence system of the network in Figure D.4 with connections at the short-circuit location (anywhere between the stations A and B)	52
Figure D.6 – Current distribution for the cable in Figure D.4 depending on ℓ_A , $R_{EF} \rightarrow \infty$	54
Figure D.7 – Current distribution for the cable in Figure D.4 depending on ℓ_A , $R_{EF} = 5 \Omega$	56
Table 1 – Calculation of initial line-to-earth short-circuit currents in simple cases	13
Table 2 – Resistivity of the soil and equivalent earth penetration depth	20
Table C.1 – Results for the example in Figure C.1	45
Table C.2 – Results for the example in Figure C.3, $\ell = 5$ km	47
Table C.3 – Results for the example in Figure C.3, $\ell = 10$ km	47

INTERNATIONAL ELECTROTECHNICAL COMMISSION

SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –**Part 3: Currents during two separate simultaneous
line-to-earth short circuits and partial short-circuit
currents flowing through earth**

FOREWORD

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International Standard IEC 60909-3 has been prepared by IEC technical committee 73: Short-circuit currents.

This International Standard is to be read in conjunction with IEC 60909-0.

This third edition cancels and replaces the second edition published in 2003. This edition constitutes a technical revision.

The main changes with respect to the previous edition are listed below:

- New procedures are introduced for the calculation of reduction factors of the sheaths or shields and in addition the current distribution through earth and the sheaths or shields of three-core cables or of three single-core cables with metallic non-magnetic sheaths or shields earthed at both ends;
- The information for the calculation of the reduction factor of overhead lines with earth wires are corrected and given in the new Clause 7;

- A new Clause 8 is introduced for the calculation of current distribution and reduction factor of three-core cables with metallic sheath or shield earthed at both ends;
- The new Annexes C and D provide examples for the calculation of reduction factors and current distribution in case of cables with metallic sheath and shield earthed at both ends.

The text of this standard is based on the following documents:

FDIS	Report on voting
73/148/FDIS	73/149/RVD

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

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

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

The contents of the corrigendum of September 2013 have been included in this copy.

SHORT-CIRCUIT CURRENTS IN THREE-PHASE AC SYSTEMS –

Part 3: Currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents flowing through earth

1 Scope and object

This part of IEC 60909 specifies procedures for calculation of the prospective short-circuit currents with an unbalanced short circuit in high-voltage three-phase a.c. systems operating at nominal frequency 50 Hz or 60 Hz, i. e.:

- a) currents during two separate simultaneous line-to-earth short circuits in isolated neutral or resonant earthed neutral systems;
- b) partial short-circuit currents flowing through earth in case of single line-to-earth short circuit in solidly earthed or low-impedance earthed neutral systems.

The currents calculated by these procedures are used when determining induced voltages or touch or step voltages and rise of earth potential at a station (power station or substation) and the towers of overhead lines.

Procedures are given for the calculation of reduction factors of overhead lines with one or two earth wires.

The standard does not cover:

- a) short-circuit currents deliberately created under controlled conditions as in short circuit testing stations, or
- b) short-circuit currents in the electrical installations on board ships or aeroplanes, or
- c) single line-to-earth fault currents in isolated or resonant earthed systems.

The object of this standard is to establish practical and concise procedures for the calculation of line-to-earth short-circuit currents during two separate simultaneous line-to-earth short circuits and partial short-circuit currents through earth, earth wires of overhead lines and sheaths or shields of cables leading to conservative results with sufficient accuracy. For this purpose, the short-circuit currents are determined by considering an equivalent voltage source at the short-circuit location with all other voltage sources set to zero. Resistances of earth grids in stations or footing resistances of overhead line towers are neglected, when calculating the short-circuit currents at the short-circuit location.

This standard is an addition to IEC 60909-0. General definitions, symbols and calculation assumptions refer to that publication. Special items only are defined or specified in this standard.

The calculation of the short-circuit currents based on the rated data of the electrical equipment and the topological arrangement of the system has the advantage of being possible both for existing systems and for systems at the planning stage. The procedure is suitable for determination by manual methods or digital computation. This does not exclude the use of special methods, for example the super-position method, adjusted to particular circumstances, if they give at least the same precision.

As stated in IEC 60909-0, short-circuit currents and their parameters may also be determined by system tests.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60909-0:2001, *Short-circuit currents in three-phase a.c. systems – Part 0: Calculation of currents*

IEC/TR 60909-2:2008, *Short-circuit currents in three-phase a.c. systems – Part 2: Data of electrical equipment for short-circuit current calculations*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

3.1

two separate simultaneous line-to earth short circuits

line-to-earth short circuits at different locations at the same time on different conductors of a three-phase a.c. network having a resonant earthed or an isolated neutral

3.2

initial short-circuit currents during two separate simultaneous line-to-earth

short circuits I_{kEE}''

r.m.s value of the initial short-circuit currents flowing at both short-circuit locations with the same magnitude

3.3

partial short-circuit current through earth $I_{E\delta}$

r.m.s. value of the current flowing through earth in a fictive line in the equivalent earth penetration depth δ

NOTE In case of overhead lines remote from the short-circuit location and the earthing system of a station, where the distribution of the current between earthed conductors and earth is nearly constant, the current through earth depends on the reduction factor of the overhead line (Figures 4 and 5). In case of cables with metallic sheaths or shields, earthed at both ends in the stations A and B, current through earth between the stations A and B (Figures 9a) and 10a)), respectively between the short-circuit location and the stations A or B (Figures 9b) and 10b)).

3.4

total current to earth I_{ETot} at the short-circuit location on the tower T of an overhead line

r. m. s. value of the current flowing to earth through the footing resistance of an overhead line tower far away from a station connected with the driving point impedances of the overhead line at both sides, see Figure 5

3.5

total current to earth I_{EBtot} at the short-circuit location in the station B

r.m.s. value of the current flowing to earth through the earthing system of a station B (power station or substation) with connected earthed conductors (earth wires of overhead lines or sheaths or shields or armouring of cables or other earthed conductors as for instance metallic water pipes), see Figure 4

3.6

current to earth I_{ETn}

r.m.s. value of the current flowing to earth causing the potential rise at an overhead line tower n in the vicinity of a station

3.7**current to earth I_{EBn}**

r.m.s. value of the current flowing to earth causing the potential rise U_{EBn} of a station B, in case of a line-to-earth short circuit at an overhead line tower n in the vicinity of the station B

3.8**reduction factor r**

for overhead lines, which determines the part of the line-to-earth short-circuit current flowing through the earth remote from the short-circuit location and the earthing systems of the stations

3.9**reduction factor r_1**

for three-core cables with metallic sheath or shield earthed at both ends

3.10**reduction factor r_3**

for three single-core cables with metallic sheaths or shields earthed at both ends

3.11**driving point impedance Z_P of an infinite chain**

composed of the earth-wire impedance Z_Q between two towers with earth return and the footing resistance R_T of the overhead line towers (Figure 1):

$$Z_P = 0,5Z_Q + \sqrt{(0,5Z_Q)^2 + R_T Z_Q} \quad (1)$$

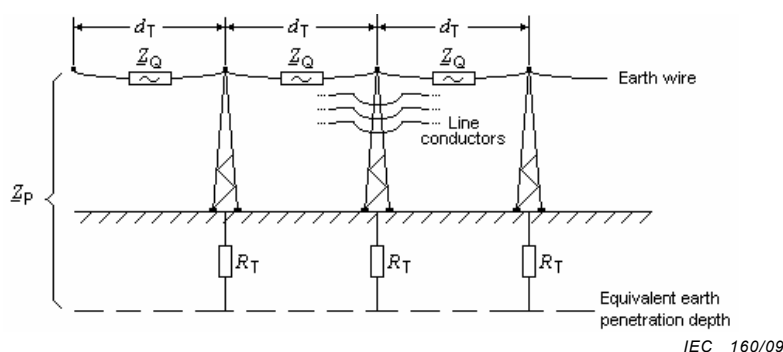


Figure 1 – Driving point impedance Z_P of an infinite chain, composed of the earth wire impedance $Z_Q = Z_Q d_T$ and the footing resistance R_T of the towers, with equal distances d_T between the towers

The driving point impedance Z_P can be assumed constant at a distance from the short-circuit location F longer than the far-from-station distance D_F defined by Equation (19).

3.12**driving point impedance Z_{Pn} of a finite chain**

with n towers of an overhead line as given in Figure 2 and with the impedance Z_{EB} at the end, calculated according to Equation (2).

$$Z_{Pn} = \frac{Z_P(Z_{EB} + Z_P)k^n + (Z_P - Z_Q)(Z_{EB} - Z_P + Z_Q)k^{-n}}{(Z_{EB} + Z_P)k^n - (Z_{EB} - Z_P + Z_Q)k^{-n}} \quad (2)$$

with

$$\underline{k} = 1 + \frac{\underline{Z}_P}{R_T} \quad (3)$$

NOTE For $n \rightarrow \infty$, Equation (2) is leading to Equation (1). In practical cases, this is true already for $n \approx 10 \dots 15$.

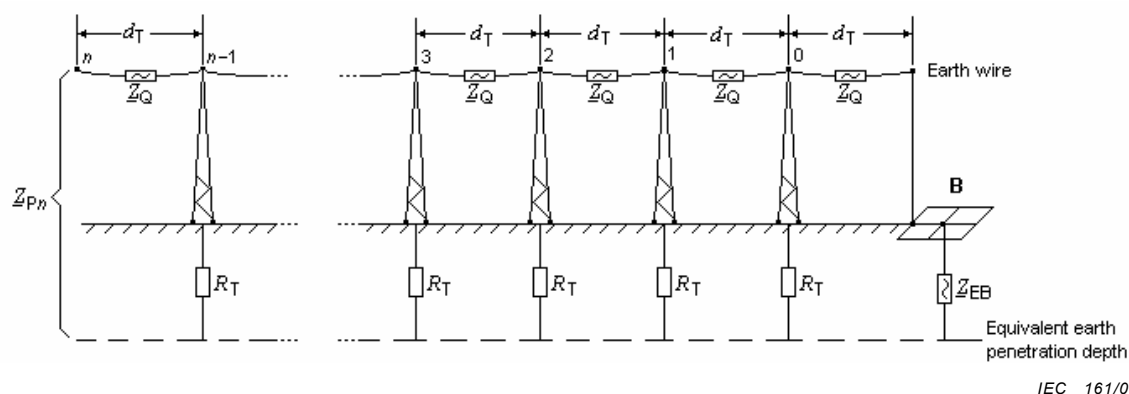


Figure 2 – Driving point impedance $\underline{Z}_{Pn}$ of a finite chain with n towers, composed of the earth wire impedance $\underline{Z}_Q = \underline{Z}'_Q d_T$, the footing resistance R_T of the towers, with equal distances d_T between the towers and the earthing impedance $\underline{Z}_{EB}$ of station B from Equation (29)

4 Symbols

All equations are written as quantity equations, in which the symbols represent physical quantities possessing both numerical values and dimensions. Symbols of complex quantities are underlined in the text and equations of this standard.

$cU_n / \sqrt{3}$	Equivalent voltage source (IEC 60909-0)
D_F	Far-from-station distance (Equation (19))
d_T	Distance between two towers
d_{L1L2}	Distance between the line conductors L1 and L2
d_{Q1Q2}	Distance between the earth wires Q1 and Q2
I_{bEE}	Short circuit breaking current in case of two separate simultaneous line-to-earth short circuits
I_E	Current flowing to earth (I_{EA} , I_{EB} , I_{EC} and I_{ET} in the Figures 4, 5, 7)
I_{EBn}	Current to earth in station B with a short-circuited tower n in the vicinity of station B (Figure 7)
I_{EBtot}	Total current to earth in the station B if a short circuit with earth connection occurs in station B (Figure 4)
I_{ETn}	Current to earth at the short-circuited tower n in the vicinity of a station (Figure 7)
I_{ETtot}	Total current to earth at a short-circuited tower T far away from stations (see Figure 5)
I_{KEE}''	Initial symmetrical short-circuit current in case of two separate simultaneous line-to-earth short circuits
I_{KE2E}''	Initial symmetrical short-circuit current flowing to earth in the case of a line-to-line short circuit with earth connection (IEC 60909-0)

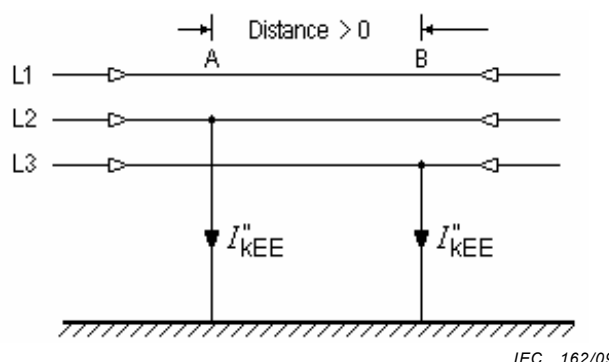
$I_{E\delta}$	Partial short-circuit current flowing through earth (for instance in Figure 4: $I_{E\delta A} = r_A \times 3I_{-(0)A}$ or in Figure 9b): Current $I_{E\delta A}$ flowing back to the station A according to Equation (45))
I_Q	Earth wire current
I_S	Current in the sheath or shield of a cable (in case of three single-core cables: I_{S1} , I_{S2} and I_{S3})
I_T	Partial short-circuit current through the footing resistance R_T of an overhead line tower
i_{pEE}	Peak short-circuit current in case of two separate simultaneous line-to-earth short circuits
$M_{(1)}, M_{(2)}$	Coupling impedances in the positive- and the negative-sequence system
R_{EA}, R_{EB}	Resistance of the earth grid in the station A or B
R_{EF}	Resistance to earth at the short-circuit location of a cable (Figure 9b) or 10b))
R_T	Footing resistance of an overhead line tower
r	Reduction factor for overhead line with earth wires
r_1	Reduction factor of the sheath or shield of a three-core cable (Figure 9a))
r_3	Reduction factor of the sheaths or shields of three single core cables (Figure 10a))
r_Q	Earth wire radius
r_S	Radius of the metallic sheath or shield of a cable (medium value)
$Z_{(1)A}, Z_{(1)B}$	Positive-sequence short-circuit impedance of a three-phase a.c. system at the connection point A, B (Annex B)
$Z_{(0)}$	Zero-sequence short-circuit impedance of the entire network between the short-circuit locations A and B (admittances between line conductors and earth are disregarded)
Z_{EB}	Earthing impedance of a station B according to Equation (29)
Z_{EBtot}	Total earthing impedance of a station B according to Equation (17)
Z_{ET}	Earthing impedance of the short-circuited tower according to Equation (28)
Z_{ETtot}	Total earthing impedance of the short-circuited tower according to Equation (23)
Z_P	Driving point impedance of an infinite chain (Equation (1) and Figure 1)
Z_{Pn}	Driving point impedance of a finite chain (Equation (2) and Figure 2)
$Z_Q = Z'_Q d_T$	Earth-wire impedance between two towers with earth return
Z'_Q	Earth-wire impedance per unit length with earth return
Z'_{QL}	Mutual impedance per unit length between earth wire and line conductors with earth return
Z'_S	Impedance per unit length of a metallic sheath or shield with earth return
Z'_{SL}	Mutual impedance per unit length between the sheath (or the shield) and a core inside the sheath (or the shield) of a cable with earth return
Z_U	Input impedance of sheaths, shields or armouring of cables or other metallic pipes or pipelines (Equation (17))

δ	Equivalent earth penetration depth (Equation (36))
μ_0	Magnetic constant, $\mu_0 = 4\pi \times 10^{-7}$ Vs/Am
ρ	Resistivity of the soil
α	Angular frequency, $\alpha = 2\pi f$ ($f = 50$ Hz or 60 Hz)

5 Calculation of currents during two separate simultaneous line-to-earth short circuits

5.1 Initial symmetrical short-circuit current

Figure 3 shows the short-circuit current I''_{kEE} during two separate simultaneous line-to-earth short circuits on different line conductors at the locations A and B with a finite distance between them. It is assumed that the locations A and B are far from stations.



NOTE The direction of current arrows is chosen arbitrarily.

Figure 3 – Characterisation of two separate simultaneous line-to earth short circuits and the currents I''_{kEE}

In networks with isolated or with resonant earthed neutral the initial symmetrical short-circuit current I''_{kEE} is calculated with

$$I''_{kEE} = \frac{3cU_n}{\left| \underline{Z}_{(1)A} + \underline{Z}_{(2)A} + \underline{Z}_{(1)B} + \underline{Z}_{(2)B} + \underline{M}_{(1)} + \underline{M}_{(2)} + \underline{Z}_{(0)} \right|} \quad (4)$$

NOTE For derivation of Equation (4) see ITU-T – *Directives concerning protection of telecommunication lines against harmful effects from electric power and electrified railway lines*, Volume V: *Inducing currents and voltages in power transmission and distribution systems*, 1999.

In case of a far-from-generator short circuit, where $\underline{Z}_{(1)} = \underline{Z}_{(2)}$ and $\underline{M}_{(1)} = \underline{M}_{(2)}$, the initial short-circuit current becomes

$$I''_{kEE} = \frac{3cU_n}{\left| 2\underline{Z}_{(1)A} + 2\underline{Z}_{(1)B} + 2\underline{M}_{(1)} + \underline{Z}_{(0)} \right|} \quad (5)$$

5.1.1 Determination of $\underline{M}_{(1)}$ and $\underline{M}_{(2)}$

The positive- and the negative-sequence coupling impedances $\underline{M}_{(1)}$ and $\underline{M}_{(2)}$ are determined as follows:

A voltage source is introduced at the short-circuit location A as the only active voltage of the network. If $\underline{I}_{(1)A}$ and $\underline{I}_{(2)A}$ are the currents due to this voltage source in the positive- and the negative-sequence system at the short-circuit location A, and if $\underline{U}_{(1)B}$ and $\underline{U}_{(2)B}$ are the resulting voltages in the positive- and negative-sequence system at the location B, then

$$\underline{M}_{(1)} = \frac{\underline{U}_{(1)B}}{\underline{I}_{(1)A}} \quad \underline{M}_{(2)} = \frac{\underline{U}_{(2)B}}{\underline{I}_{(2)A}} \quad (6)$$

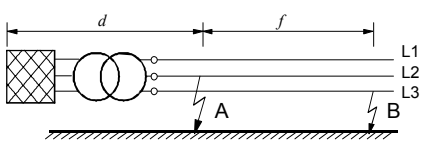
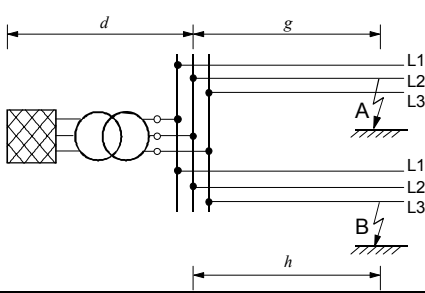
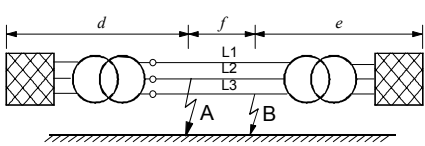
The coupling impedances may also be determined at the short-circuit location B instead of A

$$\underline{M}_{(1)} = \frac{\underline{U}_{(1)A}}{\underline{I}_{(1)B}} \quad \underline{M}_{(2)} = \frac{\underline{U}_{(2)A}}{\underline{I}_{(2)B}} \quad (7)$$

5.1.2 Simple cases of two separate simultaneous line-to-earth short circuits

In simple cases, the current I_{kEE}'' can be calculated as shown in Table 1, if $\underline{Z}_{(1)} = \underline{Z}_{(2)}$ and $\underline{M}_{(1)} = \underline{M}_{(2)}$ (far-from-generator short circuit). Equations (8) to (10) are derived from Equation (5). The indices in these equations refer to the relevant impedances in the respective network.

Table 1 – Calculation of initial line-to-earth short-circuit currents in simple cases

a)		Single-fed radial line $I_{kEE}'' = \frac{3cU_n}{\left 6\underline{Z}_{(1)d} + 2\underline{Z}_{(1)f} + \underline{Z}_{(0)f} \right } \quad (8)$
b)		Two single-fed radial lines $I_{kEE}'' = \frac{3cU_n}{\left 6\underline{Z}_{(1)d} + 2(\underline{Z}_{(1)g} + \underline{Z}_{(1)h}) + \underline{Z}_{(0)g} + \underline{Z}_{(0)h} \right } \quad (9)$
c)		Double-fed single line $I_{kEE}'' = \frac{3cU_n}{\left \frac{6\underline{Z}_{(1)d}\underline{Z}_{(1)e} + 2\underline{Z}_{(1)f}(\underline{Z}_{(1)d} + \underline{Z}_{(1)e})}{\underline{Z}_{(1)d} + \underline{Z}_{(1)f} + \underline{Z}_{(1)e}} + \underline{Z}_{(0)f} \right } \quad (10)$
The voltage factor, c , shall be taken from Table 1 of IEC 60909-0.		

5.2 Peak short-circuit current, symmetrical short circuit breaking current and steady-state short-circuit current

The peak short-circuit current is calculated according to IEC 60909-0:

$$i_{pEE} = \kappa \sqrt{2} I_{kEE}'' \quad (11)$$

For the factor, κ , the same value is used as in the case of a three-phase short circuit at the locations A or B, whichever is the largest.

If the short circuits can be assumed as far-from-generator short circuits, then

$$I_{kEE} = I_{bEE} = I_{kEE}'' \quad (12)$$

5.3 Distribution of the currents during two separate simultaneous line-to-earth short circuits

If two separate line-to-earth short circuits occur at the locations A and B, the current through earth can be calculated assuming $\underline{I}_{E0} = \underline{r} \underline{I}_{kEE}''$, with $\underline{I}_{kEE}''$ as the only active current source and $\underline{r}$ as the reduction factor of an overhead line with earth wire (Equation 33). For the short circuit at a tower (short-circuit location A or B) far from stations, the current I_T through the footing resistance R_T of the tower is

$$\underline{I}_T = \underline{r} \underline{I}_{kEE}'' \frac{\underline{Z}_P}{\underline{Z}_P + 2R_T} \quad (13)$$

$\underline{Z}_P$ is the driving point impedance of an infinite chain according to Equation (1).

NOTE Equation (13) can be derived from Figure 6 if $\underline{I}_{ETot}$ is replaced by $\underline{r} \cdot \underline{I}_{kEE}''$.

In case of two separate line-to-earth short circuits at overhead lines without earth wire (for instance in medium-voltage networks), the current through earth is equal to the short-circuit current I_{kEE}'' .

6 Calculation of partial short-circuit currents flowing through earth in case of an unbalanced short circuit

6.1 General

The following subclauses deal with partial short-circuit currents flowing through earth and earthed conductors (as earthing systems and earth wires of overhead lines) in the case of a line-to-earth short circuit. This type of short circuit in solidly earthed high-voltage networks is the most frequently occurring unbalanced short circuit. I_{k1}'' leads to the highest short-circuit current to earth compared with the line-to-line short circuit with earth connection if $Z_{(0)} > Z_{(1)}$ (see Figure 10 of IEC 60909-0 in case of $Z_{(2)} = Z_{(1)}$). For $Z_{(0)} < Z_{(1)}$, the current to earth I_{kE2E}'' in case of a line-to-line short circuit with earth connection, shall be considered according to IEC 60909-0.

For the calculation of short-circuit currents according to IEC 60909-0, the tower impedances with or without earth wire and the earth grid impedances and other connections to earth shall be disregarded.

The calculation procedure will be considered on a simplified network consisting of three stations A, B and C, and overhead lines with a single circuit and one earth wire. Moreover, it

6.2 Line-to-earth short circuit inside a station

Figure 1: Single-line diagram of a power system with three busbars (A, B, C) and their equivalent earth penetration depths. The diagram shows three busbars connected by a transmission line. Busbar A is on the left, Busbar B is in the middle, and Busbar C is on the right. Each busbar is connected to a transformer and a generator. The equivalent earth penetration depth for each busbar is represented by a vertical line with a downward arrow, labeled $Z_{EA\text{ tot}}$, $Z_{EB\text{ tot}}$, and $Z_{EC\text{ tot}}$ respectively. The diagram also shows the total fault current I_{QA} , I_{QB} , and I_{QC} , and the total fault current $I_{Q\text{ tot}}$. The diagram is labeled 'Figure 1' and 'IEC 163/01'.

Figure 4 – Partial short-circuit currents in case of a line-to-earth short circuit inside station B

$$\underline{I}_{k1}'' = 3\underline{I}_{(0)A} + 3\underline{I}_{(0)B} + 3\underline{I}_{(0)C} \quad (14)$$
$$3I_{(0)A} = I_{E\delta A} + I_{QA} = r_A 3I_{(0)A} + (1-r_A)3I_{(0)A} \quad (15a)$$

$$3I_{(0)C} = I_{E\delta C} + I_{QC} = r_C 3I_{(0)C} + (1-r_C)3I_{(0)C} \quad (15b)$$

The total current to earth in station B (short-circuit location) is:

$$\underline{I}_{EBtot} = \underline{r}_A \underline{3I}_{(0)A} + \underline{r}_C \underline{3I}_{(0)C} \quad (16)$$

The current I_{-EBtot} passes the total earthing impedance of station B:

$$\underline{Z}_{\text{EBtot}} = \frac{1}{\frac{1}{R_{\text{FB}}} + \sum_i \frac{1}{Z_{\text{Pi}}} + \sum_i \frac{1}{Z_{\text{Li}}}} \quad (17)$$

where

R_{EB} is the resistance of the earth grid in station B;

Z_P is the driving point impedance according to Equation (1);

Z_U is the input impedance of sheaths, shields or armouring of a cables or other metallic pipes or pipelines.

The current through Z_{EBtot} leads to the earth potential U_{EB} at the station B:

$$U_{EB} = Z_{EBtot} I_{EBtot} \quad (18)$$

The far-from-station distance (far from the short-circuit location) is calculated as follows:

$$D_F = 3\sqrt{R_T} \frac{d_T}{\text{Re}\{\sqrt{Z_Q}\}} \quad (19)$$

where

R_T is the tower footing resistance;

d_T is the distance between towers;

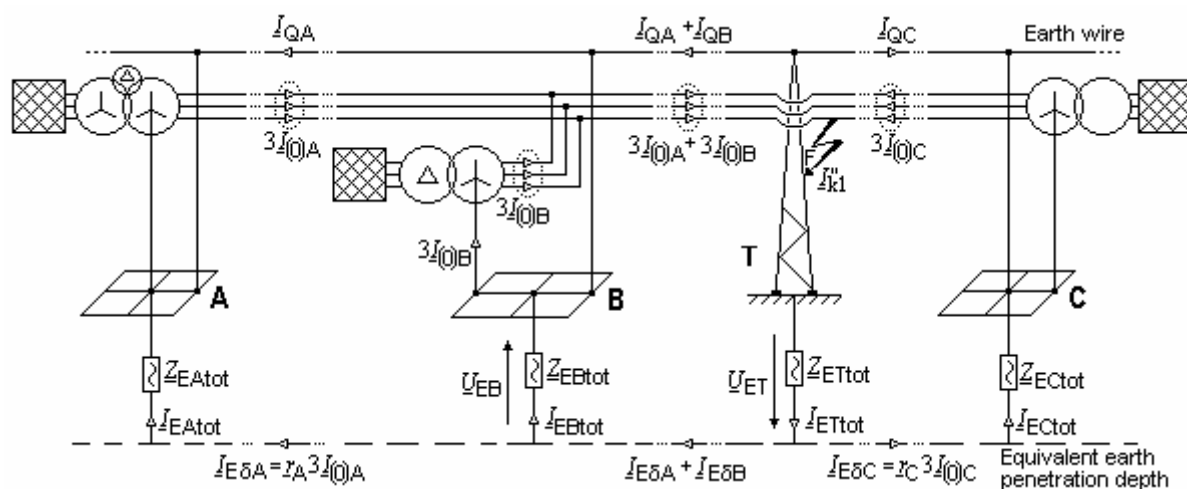
$\text{Re}\{\sqrt{Z_Q}\}$ is the real part of the square root of the earth wire impedance $Z_Q = Z'_Q d_T$ with Z'_Q from Equation (34).

NOTE 1 If the stations A or C are nearer than D_F to station B, the total current I_{EBtot} is reduced by an additional part of the currents $r_A 3I_{(0)A}$ or $r_C 3I_{(0)C}$ flowing back to the nearest station A or C via earth wires.

NOTE 2 Special considerations may be necessary in the case of double-circuit lines or parallel lines with coupled zero-sequence system.

6.3 Line-to-earth short circuit outside a station

A line-to-earth short circuit at a tower of an overhead line is shown in Figure 5. The short circuit is assumed to occur remote from the stations.



IEC 164/09

Figure 5 – Partial short-circuit currents in case of a line-to-earth short circuit at a tower T of an overhead line

The line-to-earth short-circuit current I_{k1}'' in Figure 5 is equal to three times the zero-sequence currents flowing to the short-circuit location F:

$$I_{k1}'' = 3I_{(0)A} + 3I_{(0)B} + 3I_{(0)C} \quad (20)$$

The three currents $3I_{(0)A}$, $3I_{(0)B}$ and $3I_{(0)C}$ in Figure 5 are flowing back to the stations A, B and C through the earth and the earth wires of the overhead lines between the stations:

$$3I_{(0)A} + 3I_{(0)B} = I_{E\delta A} + I_{E\delta B} + I_{QA} + I_{QB} = r_C(3I_{(0)A} + 3I_{(0)B}) + (1 - r_C)(3I_{(0)A} + 3I_{(0)B}) \quad (21)$$

and as already known from Figure 4 and the Equations (15):

$$3I_{(0)A} = I_{E\delta A} + I_{QA} = r_A 3I_{(0)A} + (1 - r_A) 3I_{(0)A}$$

$$3I_{(0)C} = I_{E\delta C} + I_{QC} = r_C 3I_{(0)C} + (1 - r_C) 3I_{(0)C}$$

r_A and r_B are the reduction factors of the earth wires between B and A and between B and C respectively.

The total current to earth at the tower T (short-circuit location), far away from stations B and C (distance higher than D_F) is:

$$I_{ETtot} = I_{E\delta A} + I_{E\delta B} + I_{E\delta C} = r_C(3I_{(0)A} + 3I_{(0)B} + 3I_{(0)C}) = r_C I_{k1}'' \quad (22)$$

This current passes the total earthing impedance of the short-circuited tower T connected to the earth wire of the overhead line $\overline{BC}$ according to Figure 6:

$$Z_{ETtot} = \frac{1}{\frac{1}{R_T} + \frac{2}{Z_P}} \quad (23)$$

R_T is the footing resistance of the tower and Z_P the driving point impedance according to Figure 1.

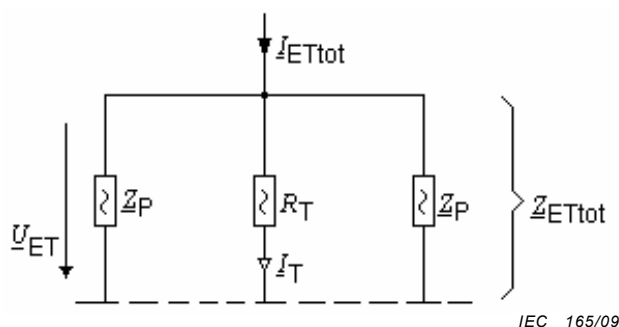


Figure 6 – Distribution of the total current to earth I_{ETtot}

I_T is found from Equation (13), if r_{KEE}'' is replaced by $r_C I_{k1}''$.

The current through $\underline{Z}_{ETtot}$ leads to the earth potential $\underline{U}_{ET}$ at the short-circuited tower (see Figure 6).

$$\underline{U}_{ET} = \underline{Z}_{ETtot} \underline{I}_{ETtot} = R_T \underline{I}_T \quad (24)$$

If the line-to-earth short circuit occurs on a tower in the vicinity of station B, then the earth potential may be higher than the result found with Equation (24). A determination needs special consideration as given in 6.4.

The current to earth in station B in the case of a line-to-earth short circuit at the tower T (distance higher than D_F from station B) is according to Figure 5 found from:

$$\underline{I}_{EBtot} = r_C (3\underline{I}_{(0)A} + 3\underline{I}_{(0)B}) - r_A 3\underline{I}_{(0)A} \quad (25)$$

The earth potential of station B with the current $\underline{I}_{EBtot}$ from Equation (25) becomes in this case:

$$\underline{U}_{EB} = \underline{Z}_{EBtot} \underline{I}_{EBtot} \quad (26)$$

If the line-to-earth short circuit occurs on a tower in the vicinity of station B, then the current to earth in station B may be higher than $\underline{I}_{EBtot}$ found from Equation (16) in case of a line-to-earth short circuit in station B (Figure 4). A determination needs special conditions as given in 6.4.

6.4 Line-to-earth short circuit in the vicinity of a station

If the line-to earth short circuit occurs at a tower in the vicinity (distance smaller than D_F) of a station (Figure 7), then the earth potential $\underline{U}_{EBn}$ (additional index n to point out that the line to-earth short circuit occurs at a tower $n = 0, 1, 2, 3 \dots$ outside the station) may be higher than $\underline{U}_{EB}$ calculated with Equation (18). In this case, the earth potential $\underline{U}_{ETn}$ of the short-circuited tower n in the vicinity of station B is also higher than the earth potential $\underline{U}_{ET}$ for a tower far outside station B calculated with Equation (24).

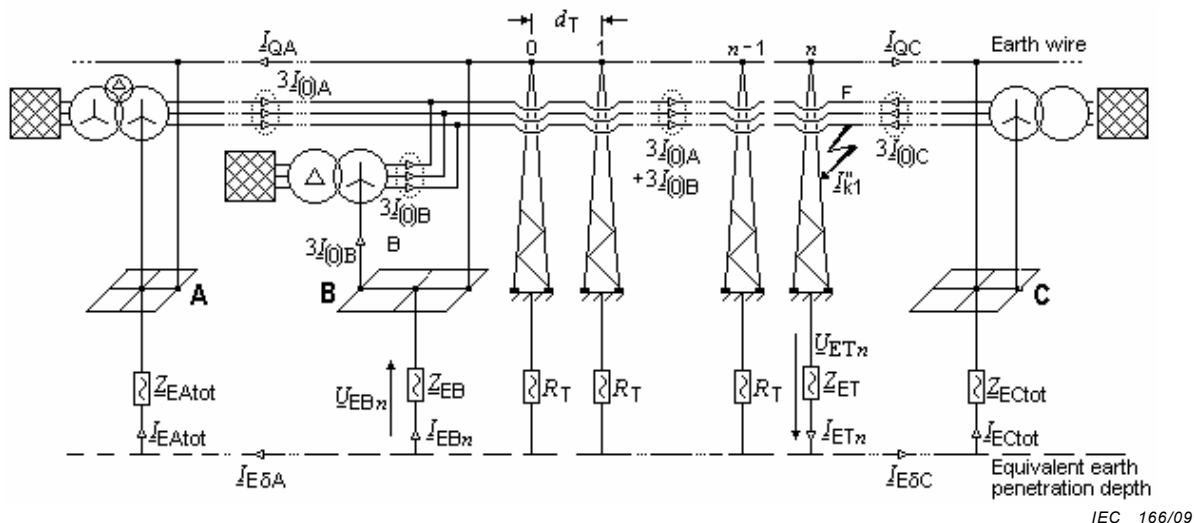


Figure 7 – Partial short-circuit currents in the case of a line-to-earth short circuit at a tower n of an overhead line in the vicinity of station B

Following Figure 2, the numbering of the towers has to be taken into account, when calculating I_{k1}'' and $3I_{(0)B}$.

6.4.1 Earth potential U_{ETn} at the tower n outside station B

The current I_{ETn} (Figure 7) at the short-circuited tower in the vicinity of station B flowing through Z_{ET} according to Equation (28) is found from the superposition of two terms, the first one depending on the current to earth $r_C I_{k1}''$ at the short-circuit location and the second one depending on the current $r_C 3I_{(0)B}$ flowing back through earth to the star point of the transformer in station B.

$$I_{ETn} = r_C I_{k1}'' \frac{Z_{Pn}}{Z_{Pn} + Z_{ET}} - r_C 3I_{(0)B} \frac{Z_{EB}}{Z_{EB} + Z_P} \cdot \frac{1}{k^n} \quad (27)$$

with

$$Z_{ET} = \frac{1}{\frac{1}{R_T} + \frac{1}{Z_P}} \quad (28)$$

and

$$Z_{EB} = \frac{1}{\frac{1}{R_{EB}} + \frac{1}{Z_P}} \quad (29)$$

The driving point Impedance Z_P is found from Equation (1), Z_{Pn} from Equation (2) and k from Equation (3).

The earth potential U_{ETn} at the short-circuited tower n is found with:

$$U_{ETn} = Z_{ET} I_{ETn} \quad (30)$$

6.4.2 Earth potential of station B during a line-to earth short circuit at the tower n

The current I_{EBn} passing Z_{EB} in Figure 7 in case of a line-to earth short circuit at a tower n in the vicinity of station B is found with the following equation:

$$I_{EBn} = r_C I_{k1}'' \frac{Z_{ET}}{Z_{ET} + Z_{Pn}} \cdot \frac{2Z_P - Z_Q}{(Z_{EB} + Z_P)k^n - (Z_{EB} - Z_P + Z_Q)k^{-n}} - r_C 3I_{(0)B} \frac{Z_P}{Z_{EB} + Z_P} \quad (31)$$

The earth potential of station B during the line-to-earth short circuit at the tower n in the vicinity of station B is:

$$U_{EBn} = Z_{EB} I_{EBn} \quad (32)$$

7 Reduction factor for overhead lines with earth wires

The reduction factor of overhead lines with earth wires can be calculated as follows:

$$\underline{r} = \frac{\underline{I_E \delta}}{3 \underline{I_{(0)}}} = 1 - \frac{\underline{Z'_{QL}}}{\underline{Z'_Q}} \quad (33)$$

$\underline{Z'_Q}$ and $\underline{Z'_{QL}}$ shall be calculated with the Equations (34) and (35). The result depends on the soil resistivity ρ , the distance d_{QL} between the earth wire and the line conductors and the equivalent earth wire radius, r_{QQ} , for one or more earth wires.

Table 2 – Resistivity of the soil and equivalent earth penetration depth

Soil types	Soil resistivity ρ Ωm	Equivalent earth penetration depth δ m	
		for 50 Hz	for 60 Hz
Granite	>10 000	>9 300	>8 500
Rocks	3 000 ... 10 000	5 100 ... 9 330	4 670 ... 8 520
Stony soil	1 000 ... 3 000	2 950 ... 5 110	2 690 ... 4 670
Pebbles, dry sand	200 ... 1 200	1 320 ... 3 230	1 200 ... 2 950
Calcareous soil, wet sand	70 ... 200	780 ... 1 320	710 ... 1 200
Farmland	50 ... 100	660 ... 931	600 ... 850
Clay, loam	10 ... 50	295 ... 660	270 ... 600
Marshy soil	<20	<420	<380

The earth wire impedance per unit length with earth return is

$$\underline{Z'_Q} = \frac{R'_Q}{\nu} + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \left(\frac{\mu_r}{4\nu} + \ln \frac{\delta}{r_{QQ}} \right) \quad (34)$$

and the mutual impedance per unit length between the earth wire and the line conductors with earth return

$$\underline{Z'_{QL}} = \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{d_{QL}} \quad (35)$$

The equivalent earth penetration depth δ depends on the soil type as given in Table 2 and can be found as follows:

$$\delta = \frac{1,851}{\sqrt{\omega \frac{\mu_0}{\rho}}} \quad (36)$$

The following definitions apply:

- R'_Q Earth wire resistance per unit length
- d_{Q1Q2} Distance between the two earth wires Q1 and Q2

r_Q Earth wire radius

r_{QQ} Equivalent earth wire radius

for one earth wire: $r_{QQ} = r_Q$

for two earth wires: $r_{QQ} = \sqrt{r_Q d_{Q1Q2}}$

ν Number of earth wires ($\nu = 1, 2$)

d_{QL} Mean geometric distance between the earth wire and the line conductors

for one earth wire: $d_{QL} = \sqrt[3]{d_{QL1} d_{QL2} d_{QL3}}$

for two earth wires $d_{QL} = \sqrt[6]{d_{Q1L1} d_{Q1L2} d_{Q1L3} d_{Q2L1} d_{Q2L2} d_{Q2L3}}$

μ_r Relative permeability of the earth wire material

Aluminium core steel reinforced (ACSR) wires with one layer of aluminium:

$\mu_r = 5 \dots 10$;

Other ACSR wires: $\mu_r \approx 1$;

Steel wires: $\mu_r \approx 75$.

According to Equation (34) and (35), the reduction factor of usual ACSR earth wires depends on the soil resistivity ρ . Figure 8 shows reduction factors for non-magnetic earth wires of different overhead lines with nominal voltages 60 kV to 220 kV.

In case of overhead lines with one or two earth wires of steel, the magnitude of the reduction factor becomes about 0,95 and 0,90 respectively.

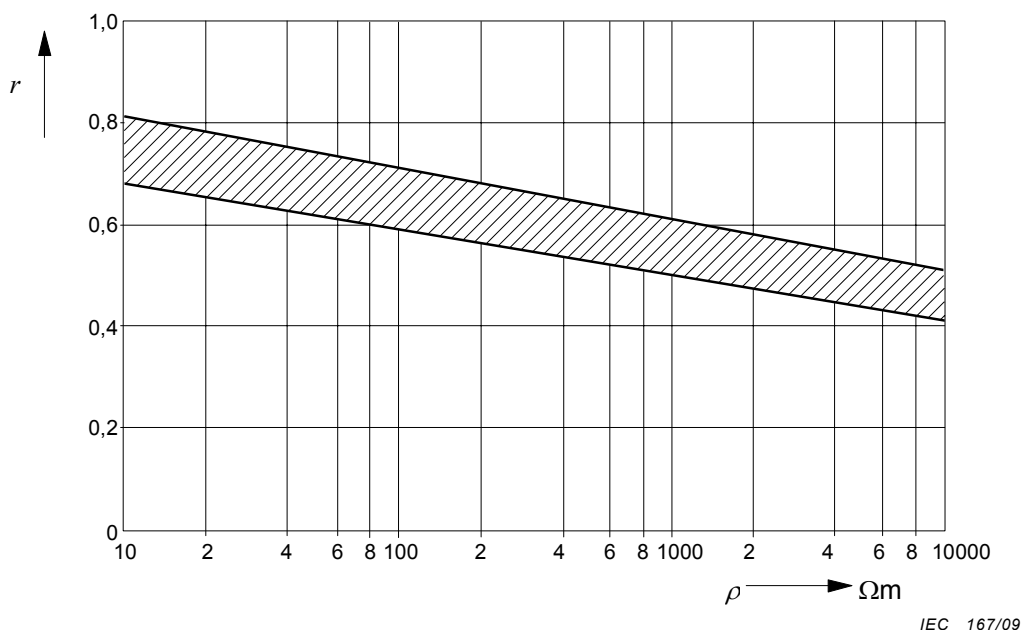


Figure 8 – Reduction factor r for overhead lines with non-magnetic earth wires depending on soil resistivity ρ

8 Calculation of current distribution and reduction factor in case of cables with metallic sheath or shield earthed at both ends

8.1 Overview

The reduction factor of power cables with metallic sheath, shield and armouring earthed at both ends depends on the type of cable: Three-core cable with a common sheath, three single-core cables with three sheaths or shields and, in some cases, with additional

armouring, the cross-section of the metallic sheath(s) or shield(s) in compliance with national techniques and standards.

Reduction factor of cables with steel armouring shall be given from the manufacturer (see IEC/TR 60909-2).

It is anticipated in this standard that the cables have an outer thermoplastic sheath (see IEC/TR 60909-2).

8.2 Three-core cable

Figure 9 gives the configurations dealt with in case of a three-core cable with metallic sheath or shield earthed at both ends and an outer thermoplastic sheath isolating the cable against the surrounding soil.

8.2.1 Line-to-earth short circuit in station B

In the case of Figure 9a), if the cable is fed from side A only with a line-to-earth short-circuit current $I_{k1}'' = 3I_{(0)A}$ in station B, the reduction factor r_1 gives that part $I_{E\delta A} = r_1 3I_{(0)A}$ of the line-to-earth short-circuit current, that is flowing back through earth by the induction effect.

$$r_1 = \frac{I_{E\delta A}}{3I_{(0)A}} = 1 - \frac{Z'_{SL}}{Z'_S} = \frac{R'_S}{R'_S + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S}} \quad (37)$$

Z'_S is the impedance of the metallic (non magnetic) sheath (or shield) per unit length with earth return:

$$Z'_S = R'_S + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S} \quad (38)$$

Z'_{SL} is the mutual impedance between the sheath and one of the cores (inside the sheath, independently of the position) per unit length with earth return:

$$Z'_{SL} = \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S} \quad (39)$$

where

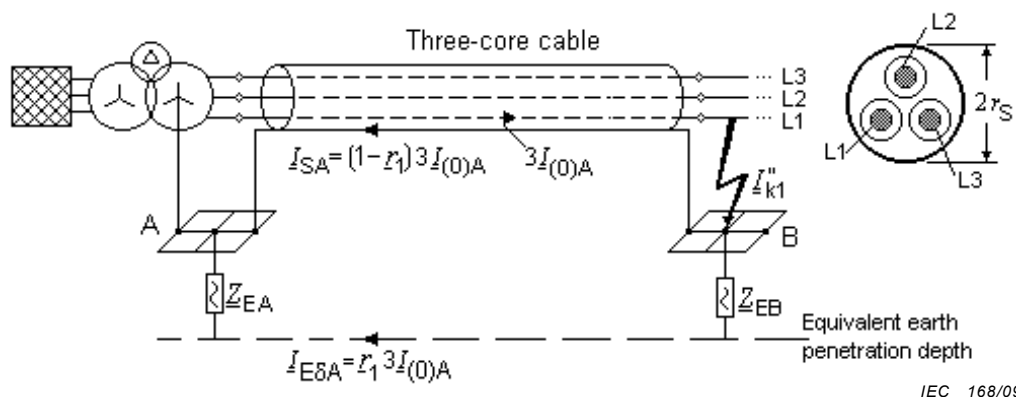
- R'_S Resistance per unit length of the sheath or shield (copper, aluminium, lead);
 $R'_S = 1/(\kappa \cdot q_S)$ with $q_S \approx 2\pi r_S d_S$ where d_S is the thickness of the sheath or shield
- r_S Medium radius of the sheath or shield;
- δ Equivalent earth penetration depth (Table 2 or Equation (36)).

The current in the sheath or shield in Figure 9a) is calculated as follows:

$$I_{SA} = (1 - r_1) 3I_{(0)A} \quad (40)$$

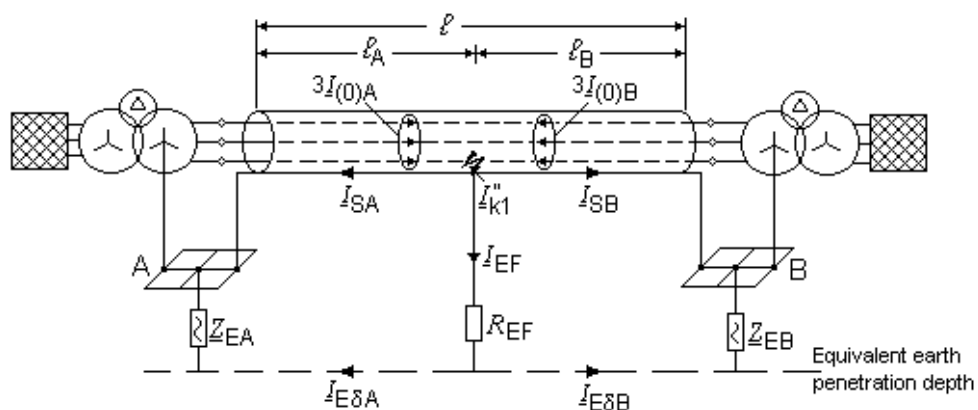
The current through earth in Figure 9a) is found with:

$$\underline{I}_{E\delta A} = r_1 3\underline{I}_{(0)A} \quad (41)$$



IEC 168/09

a) Feeding from station A only and line-to-earth short circuit in station B



IEC 169/09

$$(\underline{I}_{k1}'' = 3\underline{I}_{(0)A} + 3\underline{I}_{(0)B}; \quad 3\underline{I}_{(0)A} = \underline{I}_{SA} + \underline{I}_{E\delta A}; \quad 3\underline{I}_{(0)B} = \underline{I}_{SB} + \underline{I}_{E\delta B})$$

b) Feeding from stations A and B and line-to-earth short circuit on the cable between the stations A and B

Figure 9 – Reduction factor of three-core power cables

8.2.2 Line-to-earth short circuit on the cable between station A and station B

In case of a line-to-earth short circuit on the cable between the stations A and B the currents in the sheath or shield in Figure 9b) are calculated as follows:

$$\underline{I}_{SA} = (1-r_1)3\underline{I}_{(0)A} + r_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_A} + r_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_A} \quad (42)$$

$$\underline{I}_{SB} = (1-r_1)3\underline{I}_{(0)B} + r_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_B} + r_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_B} \quad (43)$$

The current to earth at the short-circuit location is given as:

$$\underline{I}_{EF} = r_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{R_{EF}} + r_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{R_{EF}} \quad (44)$$

The currents through earth in Figure 9b) are found with:

$$\underline{I}_{E\delta A} = \underline{r}_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_B} + \underline{r}_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{R_{EF}} - \underline{r}_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_A} \quad (45)$$

$$\underline{I}_{E\delta B} = \underline{r}_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_A} + \underline{r}_1 3\underline{I}_{(0)B} \frac{\underline{Z}_{EStot}}{R_{EF}} - \underline{r}_1 3\underline{I}_{(0)A} \frac{\underline{Z}_{EStot}}{\underline{Z}_S \ell_B} \quad (46)$$

with

$$\underline{Z}_{EStot} = \frac{1}{\frac{1}{\underline{Z}_S \ell_A} + \frac{1}{\underline{Z}_S \ell_B} + \frac{1}{R_{EF}}} = \frac{\underline{Z}_S \ell_A \ell_B}{\ell + \frac{\underline{Z}_S \ell_A \ell_B}{R_{EF}}} \quad (47)$$

The reduction factor $\underline{r}_1$ is given in Equation (37).

The given equations are valid for a cable length of at least $\ell \approx \delta/2$ ($\ell \approx 0,5$ km in case of $\rho = 100 \Omega\text{m}$) between the stations A and B in Figure 9a), and distances ℓ_A and ℓ_B between the short-circuit location and the adjacent stations A and B in Figure 9b), for at least $\ell \approx \delta/2$ in Case 2 according to 8.2.2.2.

Because in normal cases the resistance R_{EF} at the short-circuit location against reference earth is not known, the two cases $R_{EF} \rightarrow \infty$ (there is no connection at the short-circuit location between the metallic sheath (shield) of the cable and the surrounding soil) and $R_{EF} \rightarrow \text{Min.}$ have to be taken into account.

8.2.2.1 Case 1: $R_{EF} = \infty$

In case of $R_{EF} \rightarrow \infty$, it is anticipated that the outer thermoplastic sheath is not destroyed by the short-circuit current or by the arc at the short-circuit location. The following expressions are found from the Equations (42) and (43):

$$\underline{I}_{SA} = (1 - \underline{r}_1) 3\underline{I}_{(0)A} + \underline{r}_1 3\underline{I}_{(0)A} \frac{\ell_B}{\ell} + \underline{r}_1 3\underline{I}_{(0)B} \frac{\ell_B}{\ell} \quad (42a)$$

$$\underline{I}_{SB} = (1 - \underline{r}_1) 3\underline{I}_{(0)B} + \underline{r}_1 3\underline{I}_{(0)B} \frac{\ell_A}{\ell} + \underline{r}_1 3\underline{I}_{(0)A} \frac{\ell_A}{\ell} \quad (43a)$$

In this case the Equations (45) and (46) lead to:

$$\underline{I}_{E\delta A} = \underline{r}_1 3\underline{I}_{(0)A} \frac{\ell_A}{\ell} - \underline{r}_1 3\underline{I}_{(0)B} \frac{\ell_B}{\ell} \quad (45a)$$

$$\underline{I}_{E\delta B} = \underline{r}_1 3\underline{I}_{(0)B} \frac{\ell_B}{\ell} - \underline{r}_1 3\underline{I}_{(0)A} \frac{\ell_A}{\ell} \quad (46a)$$

The line-to-earth short-circuit current at the short-circuit location between A and B shall be calculated with the zero-sequence impedance per unit length $\underline{Z}'_{(0)S}$ of the cable for a current

return only through the sheath or shield (see IEC/TR 60909-2 and the information about the calculation of this value given in IEC/TR 60909-2, Equations (30) and (31)).

The highest current through the sheath or shield will occur, if the short-circuit location is near the station A or the station B and if the short circuit in Figure 9b) is fed from both sides.

$$I_{SA\max} = 3I_{(0)A} (\ell_A = 0) + r_1 3I_{(0)B} (\ell_A = 0) \quad (42b)$$

$$I_{SB\max} = 3I_{(0)B} (\ell_A = \ell) + r_1 3I_{(0)A} (\ell_A = \ell) \quad (43b)$$

The highest current through earth is also found if the short circuit occurs near the station A or B:

$$I_{E\delta A\max} = r_1 3I_{(0)A} (\ell_A = \ell) \quad (45b)$$

$$I_{E\delta B\max} = r_1 3I_{(0)B} (\ell_A = 0) \quad (46b)$$

8.2.2.2 Case 2: $R_{EF} = 5 \Omega$

The value $R_{EF} = 5 \Omega$ is to be seen as a conservative hypothesis, because the area of the connection to the surrounding soil is small even if the thermoplastic outer sheath is destroyed. When fixing this value, it is anticipated, that the short-circuit location is outside the stations A and B and that no metallic rods or pipes are in the neighbourhood of the short-circuit location.

In this case, the line-to-earth short-circuit current I_{k1}'' at the short-circuit location between A and B shall be calculated with the zero-sequence impedance $Z_{(0)SE}'$ for a current return through the sheath or shield of the cable and the earth (see IEC/TR 60909-2).

The currents in the sheath or shield and through the earth shall be calculated with Equations (42), (43) and (45), (46).

The highest current through the sheath or the shield can be calculated with Equations (42b) and (43b).

If the highest values for the currents through earth are searched for, use the highest line-to-earth short-circuit current fed from one side of the cable only and neglect the current fed from the other side. In this case Equations (45) and (46) lead to:

$$I_{E\delta A\max} = r_1 3I_{(0)A} \left(\frac{Z_{ES\text{tot}}}{Z_S \ell_B} + \frac{Z_{ES\text{tot}}}{R_{EF}} \right) \quad (45c)$$

$$I_{E\delta B\max} = r_1 3I_{(0)B} \left(\frac{Z_{ES\text{tot}}}{Z_S \ell_A} + \frac{Z_{ES\text{tot}}}{R_{EF}} \right) \quad (46c)$$

Calculations with the above equations may lead to higher currents through earth than those found with Equations (45b) or (46b).

NOTE Clause C.2 gives an example for the calculations, if the highest currents through earth are searched for.

If the cable has an additional iron armouring (for instance in the case of a lead sheath), the manufacturer shall give the reduction factor (depending on the current through the sheath) found for instance from measurements. See for information IEC/TR 60909-2.

8.3 Three single-core cables

As given under 8.2, in this case also a distinction shall be made between a line-to-earth short circuit in station B, if the short-current is fed from station A (Figure 10a)) or if the short circuit is on the cable at a location between the station A and B (Figure 10b)).

8.3.1 Line-to-earth short circuit in station B

In case of three single-core cables in Figure 10a), with three sheaths (shields) earthed and connected at both ends, the reduction factor r_3 shall be calculated as follows:

$$r_3 = 1 - \frac{I_{S1} + I_{S2} + I_{S3}}{3I_{(0)}} = \frac{R'_S}{R'_S + 3 \cdot \omega \frac{\mu_0}{8} + j3 \cdot \omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{\sqrt[3]{r_S d_{L1L2} d_{L1L3}}}} \quad (48)$$

The distances d_{L1L2} and d_{L1L3} according to Figure 10a) shall be used for a triangular and a flat configuration. The result found from Equation (48) is the exact result for a triangular configuration. For a flat configuration the result of Equation (48) can be used as a sufficient approximation for this standard, independently if the line-to-earth short-circuit current will occur in an outer cable or the central cable of the flat configuration.

The sum of the currents through the three sheaths or shields according to Figure 10a) is calculated as follows:

$$I_{SA} = I_{S1A} + I_{S2A} + I_{S3A} = (1 - r_3) 3I_{(0)A} \quad (49)$$

The current through earth, flowing back to station A of Figure 10a), is found with the reduction factor r_3 from Equation (48):

$$I_{E\delta A} = r_3 3I_{(0)A} \quad (50)$$

8.3.2 Line-to-earth short circuit on the cable between station A and station B

In case of a line-to-earth short circuit on the cable between the stations A and B, fed from both sides in Figure 10b), currents generally are flowing in the three line conductors and in the three sheaths or shields of the single core cables.

The sum of the currents in the three sheaths or shields are calculated as follows:

$$I_{SA} = (1 - r_3) 3I_{(0)A} + r_3 3I_{(0)A} \frac{Z_{ES\text{tot}}}{Z_{S\ell A}} + r_3 3I_{(0)B} \frac{Z_{ES\text{tot}}}{Z_{S\ell A}} \quad (51)$$

$$I_{SB} = (1 - r_3) 3I_{(0)B} + r_3 3I_{(0)B} \frac{Z_{ES\text{tot}}}{Z_{S\ell B}} + r_3 3I_{(0)A} \frac{Z_{ES\text{tot}}}{Z_{S\ell B}} \quad (52)$$

The current to earth at the short circuit location is given as:

$$I_{EF} = r_3 3I_{(0)A} \frac{Z_{EStot}}{R_{EF}} + r_3 3I_{(0)B} \frac{Z_{EStot}}{R_{EF}} \quad (53)$$

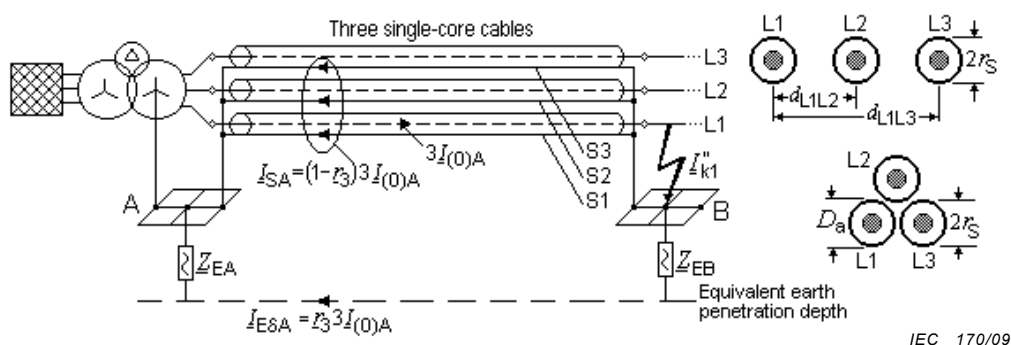
The currents through earth are found with:

$$I_{E\delta A} = r_3 3I_{(0)A} \frac{Z_{EStot}}{Z_S \ell_B} + r_3 3I_{(0)A} \frac{Z_{EStot}}{R_{EF}} - r_3 3I_{(0)B} \frac{Z_{EStot}}{Z_S \ell_A} \quad (54)$$

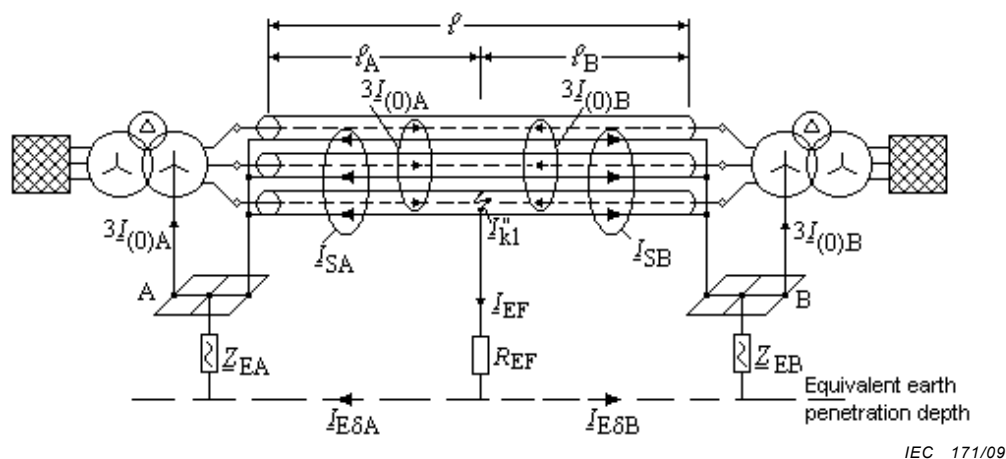
$$I_{E\delta B} = r_3 3I_{(0)B} \frac{Z_{EStot}}{Z_S \ell_A} + r_3 3I_{(0)B} \frac{Z_{EStot}}{R_{EF}} - r_3 3I_{(0)A} \frac{Z_{EStot}}{Z_S \ell_B} \quad (55)$$

with Z_{EStot} according to Equation (47).

In this case Z'_S is the self impedance per unit length of one of the three sheaths or shields, calculated with Equation (38).



a) Feeding from station A only and line-to-earth short circuit in station B



$$(I_{k1}'' = 3I_{(0)A} + 3I_{(0)B}; 3I_{(0)A} = I_{SA} + I_{E\delta A}; 3I_{(0)B} = I_{SB} + I_{E\delta B})$$

b) Feeding from stations A and B and line-to-earth short circuit on the cable between the stations A and B

Figure 10 – Reduction factors for three single-core power cables

Because in normal cases the resistance R_{EF} at the short-circuit location against reference earth is not known, the two cases $R_{EF} \rightarrow \infty$ (there is no connection at the short-circuit location between the metallic sheath or shield of the cable and the surrounding soil) and $R_{EF} \rightarrow \text{Min.}$ have to be taken into account.

8.3.2.1 Case 1: $R_{EF} \rightarrow \infty$

In case of $R_{EF} \rightarrow \infty$, it is anticipated that the outer thermoplastic sheath is not destroyed by the short-circuit current or by the arc at the short-circuit location. The following expressions are found from Equations (51) and (52):

$$\underline{I}_{SA} = (1 - r_3) 3 \underline{I}_{(0)A} + r_3 3 \underline{I}_{(0)A} \frac{\ell_B}{\ell} + r_3 3 \underline{I}_{(0)B} \frac{\ell_B}{\ell} \quad (51a)$$

$$\underline{I}_{SB} = (1 - r_3) 3 \underline{I}_{(0)B} + r_3 3 \underline{I}_{(0)B} \frac{\ell_A}{\ell} + r_3 3 \underline{I}_{(0)A} \frac{\ell_A}{\ell} \quad (52a)$$

In this case the Equations (54) and (55) lead to:

$$\underline{I}_{E\delta A} = r_3 3 \underline{I}_{(0)A} \frac{\ell_A}{\ell} - r_3 3 \underline{I}_{(0)B} \frac{\ell_B}{\ell} \quad (54a)$$

$$\underline{I}_{E\delta B} = r_3 3 \underline{I}_{(0)B} \frac{\ell_B}{\ell} - r_3 3 \underline{I}_{(0)A} \frac{\ell_A}{\ell} \quad (55a)$$

The line-to-earth short-circuit current at the short-circuit location between A and B shall be calculated with the zero-sequence impedance $\underline{Z}'_{(0)S}$ of the cable system for a current return only through the sheaths or shields (see IEC/TR 60909-2).

The highest current through the sheath or shield, S1, will occur, if the short-circuit location is near the station A or the station B and if the short circuit in Figure 10b) is fed from both sides.

$$\ell_A = 0 \quad \underline{I}_{S1Amax} \approx 3 \underline{I}_{(0)A} + (2 + r_3) \underline{I}_{(0)B} \quad (51b)$$

$$\ell_A = \ell \quad \underline{I}_{S1Bmax} \approx 3 \underline{I}_{(0)B} + (2 + r_3) \underline{I}_{(0)A} \quad (52b)$$

The highest currents through earth are also found if the short circuit occurs near the station A or B.

$$\ell_A = 0 \quad \underline{I}_{E\delta Amax} = -r_3 3 \underline{I}_{(0)B} \quad (54b)$$

$$\ell_B = 0 \quad \underline{I}_{E\delta Bmax} = -r_3 3 \underline{I}_{(0)A} \quad (55b)$$

8.3.2.2 Case 2: $R_{EF} = 5 \Omega$

The value $R_{EF} = 5 \Omega$ is to be seen as a conservative hypothesis, see 8.2.2.2.

The line-to-earth short-circuit current I_{k1}'' at the short-circuit location between A and B shall be calculated with the zero-sequence impedance per unit length $\underline{Z}_{(0)SE}'$ for a current return through the sheaths or shields of the cable and the earth (see IEC/TR 60909-2).

The sum of the currents in the sheaths or shields and the currents through earth shall be calculated with Equations (51), (52) and (54), (55).

The highest currents through the sheath or shield, S1, can be found with Equations (51b) and (52b).

If the highest values for the currents through earth are searched for, use the highest line-to-earth short-circuit current fed from one side of the cable only and neglect the current fed from the other side. In this case, Equations (54) and (55) lead to:

$$I_{E\delta Amax} = r_3 3I_{(0)A}(\ell_A = \ell) \left(\frac{\underline{Z}_{EStot}(\ell_A = \ell)}{\underline{Z}_S' \ell_B} + \frac{\underline{Z}_{EStot}(\ell_A = \ell)}{R_{EF}} \right) = r_3 3I_{(0)A}(\ell_A = \ell) \quad (54c)$$

$$I_{E\delta Bmax} = r_3 3I_{(0)B}(\ell_A = 0) \left(\frac{\underline{Z}_{EStot}(\ell_A = 0)}{\underline{Z}_S' \ell_A} + \frac{\underline{Z}_{EStot}(\ell_A = 0)}{R_{EF}} \right) = r_3 3I_{(0)B}(\ell_A = 0) \quad (55c)$$

NOTE Annex D gives an example for the calculation of the currents flowing through earth.

If the cables should have additional iron armouring, the manufacturer shall give the reduction factor and the current distribution.

Annex A (informative)

Example for the calculation of two separate simultaneous line-to-earth short-circuit currents

A.1 Overview

Two separate simultaneous line-to-earth short circuits on a single fed overhead line are shown in Figure A.1.

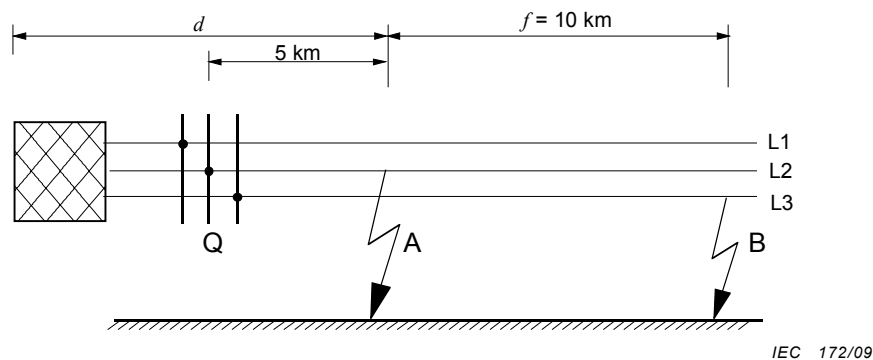


Figure A.1 – Two separate simultaneous line-to-earth short circuits on a single fed overhead line (see Table 1)

A.2 Data

Nominal voltage: $U_n = 66 \text{ kV}$

Nominal frequency: 50 Hz

Network with isolated or resonant earthed neutral

Network impedance at the feeder connection point Q: $\underline{Z}_{(1)Q} = (1,5 + j15) \Omega$

Initial symmetrical short-circuit current at Q (see IEC 60909-0):

$$I_{kQ}'' = \frac{1,1 \times 66 \text{ kV}}{\sqrt{3} |1,5 + j15| \Omega} = 2,8 \text{ kA}$$

Overhead line:

Conductors $3 \times 1 \times 166/88 \text{ mm}^2$ ACSR

Earth wire $1 \times 49 \text{ mm}^2$ steel, $r_Q = 4,5 \text{ mm}$, $R_Q' = 2,92 \Omega/\text{km}$, $\mu_r = 75$

Mean geometric distance between the earth wire and the line conductors: $d_{QL} = 6 \text{ m}$

Line impedance per unit length:

Positive-sequence impedance $\underline{Z}_{(1)}' = (0,17 + j0,40) \Omega/\text{km}$

Zero-sequence impedance $\underline{Z}_{(0)}' = (0,32 + j1,40) \Omega/\text{km}$

Stony soil resistivity $\rho = 1\,000 \Omega\text{m}$

Equivalent earth penetration depth $\delta = 2\,950\text{ m}$ from Table 2 or Equation (36)

Tower footing resistance $R_T = 10\ \Omega$

Tower distance $d_T = 300\text{ m}$

A.3 Calculations

Earth-wire impedance per unit length with earth return according to Equation (34) with $\nu = 1$:

$$\underline{Z}'_Q = 2,92 \frac{\Omega}{\text{km}} + 0,0493 \frac{\Omega}{\text{km}} + j314\text{s}^{-1} \frac{4\pi \cdot 10^{-4} \text{ Vs}}{2\pi \text{ Akm}} \left(\frac{75}{4} + \ln \frac{2950\text{m}}{4,5\text{mm}} \right) = (2,969 + j2,020) \frac{\Omega}{\text{km}}$$

Mutual impedance per unit length between the earth wire and the line conductors with earth return according to Equation (35):

$$\underline{Z}'_{QL} = 0,0493 \frac{\Omega}{\text{km}} + j314\text{s}^{-1} \frac{4\pi \cdot 10^{-4} \text{ Vs}}{2\pi \text{ Akm}} \ln \frac{2950\text{m}}{6\text{m}} = (0,049 + j0,389) \frac{\Omega}{\text{km}}$$

Reduction factor of the earth wire according to Equation (33):

$$\underline{r} = 1 - \frac{\underline{Z}'_{QL}}{\underline{Z}'_Q} = 1 - \frac{(0,049 + j0,389)\Omega/\text{km}}{(2,969 + j2,020)\Omega/\text{km}} = 0,928 - j0,082; \quad r = 0,931$$

Driving point impedance according to Equation (1) with:

$$\underline{Z}_Q = \underline{Z}'_Q d_T = (2,97 + j2,02)(\Omega/\text{km}) \cdot 0,3\text{km}:$$

$$\underline{Z}_P = 0,5 \cdot (0,891 + j0,606)\Omega + \sqrt{[0,5 \cdot (0,891 + j0,606)]^2 + 10 \cdot (0,891 + j0,606)\Omega} = (3,610 + j1,303)\Omega$$

Equation (8) from Table 1 leads to:

$$\underline{I}''_{kEE} = \frac{3 \cdot 11,66\text{kV}}{(14,1 + 3,4 + 3,2)\Omega + j(102 + 8 + 14)\Omega} = (0,285 - j1,709)\text{ kA}; \quad I''_{kEE} = 1,732\text{ kA}$$

where

$$6\underline{Z}_{(1)d} = 6 \cdot \left((1,5 + j15)\Omega + 5\text{km} \cdot (0,17 + j0,40) \frac{\Omega}{\text{km}} \right) = (14,1 + j102)\Omega$$

$$2\underline{Z}_{(1)f} = 2 \cdot 10\text{km}(0,17 + j0,40) \frac{\Omega}{\text{km}} = (3,4 + j8)\Omega$$

$$\underline{Z}_{(0)f} = 10\text{km}(0,32 + j1,4) \frac{\Omega}{\text{km}} = (3,2 + j14)\Omega$$

The current to earth through the footing resistance, R_T , of the tower at the short-circuit locations A or B is determined with Equation (13):

$$\underline{I}_T = (0,928 - j0,082)(0,285 - j1,709)\text{kA} \frac{(3,610 + j1,303)\Omega}{(3,610 + j1,303)\Omega + 2 \cdot 10\Omega} = (0,094 - j0,244)\text{kA};$$
$$I_T = 0,262\text{kA}$$

Annex B (informative)

Examples for the calculation of partial short-circuit currents through earth

B.1 Overview

A 132-kV-network, 50 Hz, is given as shown in Figures B.1 and B.3. The distances are 40 km between the stations A and B and 100 km between the stations B and C.

B.2 Data

Station A:

Short-circuit impedance	$\underline{Z}_A = (0 + j6,4)\Omega$
Zero-sequence impedance of the transformer	$\underline{Z}_{(0)A} = (0 + j12)\Omega$

Station B:

Short-circuit impedance	$\underline{Z}_B = (0 + j7,6)\Omega$
Zero-sequence impedance of the transformer	$\underline{Z}_{(0)B} = (0 + j7)\Omega$
Resistance of earth grid	$R_{EB} = 5\Omega$

Station C:

Short-circuit impedance	$\underline{Z}_C = (0 + j21)\Omega$
Zero-sequence impedance of the transformer	$\underline{Z}_{(0)C} = (0 + j20,3)\Omega$

Overhead line:

Conductors	$3 \times 2 \times 240/40\text{mm}^2$ ACSR
Earth wire	$1 \times 240/40\text{mm}^2$ ACSR
Positive-sequence line impedance per unit length	$\underline{Z}'_{(1)L} = \underline{Z}'_L = (0,06 + j0,298)\Omega/\text{km}$
Zero-sequence line impedance per unit length	$\underline{Z}'_{(0)L} = (0,272 + j1,48)\Omega/\text{km}$
Soil resistivity	$\rho = 1000\Omega\text{m}$
Equivalent earth penetration depth	$\delta = 2950\text{ m}$ from Table 2
Earth-wire impedance per unit length	$\underline{Z}'_Q = (0,17 + j0,801)\Omega/\text{km}$
Earth-wire reduction factor	$r_A = r_C = r = 0,6 - j0,03 \approx 0,6$
Tower footing resistance	$R_T = 10\Omega$
Tower distance	$d_T = 400\text{ m}$
Length of overhead line between A and B	$\ell_1 = 40\text{ km}$
Length of overhead line between B and C	$\ell_2 = 100\text{ km}$

B.3 Line-to-earth short circuit in a station

A line-to-earth short circuit occurs inside station B as shown in Figure B.1

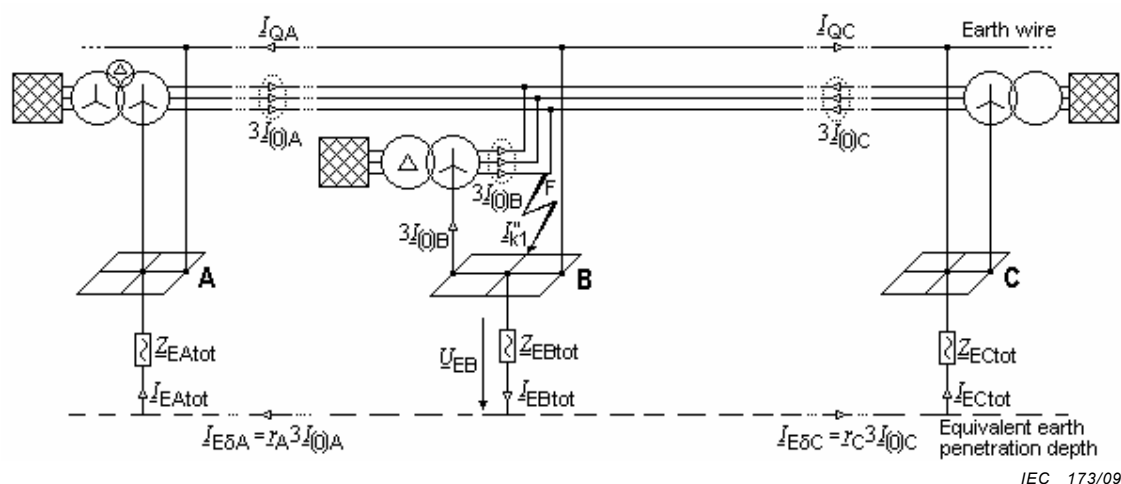


Figure B.1 – Line-to-earth short circuit inside station B –
System diagram for stations A, B and C

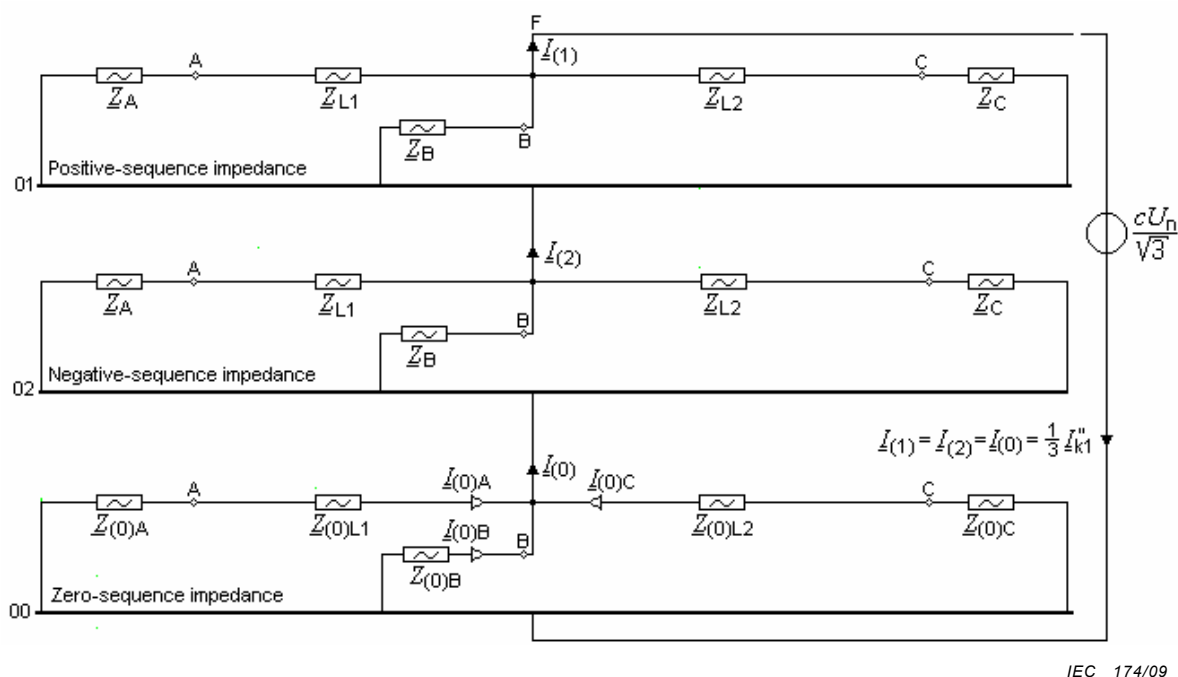


Figure B.2 – Line-to-earth short circuit inside station B –
Positive-, negative- and zero-sequence systems with connections
at the short-circuit location F within station B

The line-to-earth short-circuit current can be calculated according to IEC 60909-0, Equation (52), using Figure B.2.

$$I_{k1}'' = \frac{\sqrt{3} \cdot 1,1 \cdot 132 \text{ kV}}{2(0,222 + j4,876) \Omega + (0,115 + j6,157) \Omega} = (0,555 - j15,789) \text{ kA} ;$$

$$I_{k1}'' = 15,799 \text{ kA}$$

where

$$\underline{Z}_{(1)} = \frac{1}{\frac{1}{\underline{Z}_A + \underline{Z}_{L1}} + \frac{1}{\underline{Z}_B} + \frac{1}{\underline{Z}_C + \underline{Z}_{L2}}} = (0,222 + j4,876)\Omega$$

$$\underline{Z}_{(0)} = \frac{1}{\frac{1}{\underline{Z}_{(0)A} + \underline{Z}_{(0)L1}} + \frac{1}{\underline{Z}_{(0)B}} + \frac{1}{\underline{Z}_{(0)C} + \underline{Z}_{(0)L2}}} = (0,115 + j6,157)\Omega$$

The zero-sequence current at the short-circuit location is given by

$$\underline{I}_{(0)} = \frac{1}{3} \underline{I}_{k1}'' = (0,185 - j5,263)\text{kA}$$

The partial zero-sequence currents in Figure B.2 are:

$$\underline{I}_{(0)A} = (0,0753 - j0,4439)\text{kA}; \quad I_{(0)A} = 0,450\text{kA}$$

$$\underline{I}_{(0)B} = (0,0763 - j4,6319)\text{kA}; \quad I_{(0)B} = 4,633\text{kA}$$

$$\underline{I}_{(0)C} = (0,0334 - j0,1872)\text{kA}; \quad I_{(0)C} = 0,190\text{kA}$$

The total current $\underline{I}_{EBtot}$ flowing to earth through $\underline{Z}_{EBtot}$ at the short-circuit location in station B (Figure B.1) is calculated with Equation (16), if $\underline{r}_A = \underline{r}_C = \underline{r}$:

$$\underline{I}_{EBtot} = \underline{r} \cdot 3(\underline{I}_{(0)A} + \underline{I}_{(0)C}) = 0,6 \cdot 3(0,1088 - j0,6311)\text{kA} = (0,1958 - j1,1360)\text{kA};$$

$$I_{EBtot} = 1,1528\text{kA}$$

The driving point impedance for calculation of $\underline{Z}_{EBtot}$ is found with $\underline{Z}_Q = \underline{Z}'_Q d_T$ from Equation (1):

$$\underline{Z}_P = 0,5(0,068 + j0,3204)\Omega + \sqrt{[0,5(0,068 + j0,3204)]^2 + 10(0,068 + j0,3204)}\Omega = (1,4369 + j1,306)\Omega$$

The total earth impedance $\underline{Z}_{EBtot}$ of station B with two outgoing overhead lines is calculated with Equation (17):

$$\underline{Z}_{EBtot} = \frac{1}{\frac{1}{5\Omega} + \frac{2}{(1,4369 + j1,306)\Omega}} = (0,6845 + j0,4928)\Omega$$

The earth potential of station B is found with Equation (18):

$$\underline{U}_{EB} = (0,6845 + j0,4928)\Omega(0,1958 - j1,1360)\text{kA} = (0,6938 - j0,6811)\text{kV}; \quad U_{EB} = 0,9722\text{kV}$$

The far-from-station distance D_F (Equation (19)) is:

$$D_F = 3\sqrt{R_T} \frac{d_T}{\operatorname{Re}\{\sqrt{Z_Q}\}} = 3\sqrt{10\Omega} \frac{0,4\text{ km}}{\operatorname{Re}\{\sqrt{(0,068 + j0,3204)\Omega}\}} = 8,53\text{ km}$$

In a distance longer than D_F , i.e. in a distance remote from the stations, the earth–wire currents are found from the relations given in Equations (15).

$$\underline{I}_{QA} = (1 - r)3I_{(0)A} = 0,4 \cdot 3 \cdot (0,0753 - j0,4439)\text{ kA} = (0,0904 - j0,5327)\text{ kA} ;$$

$$I_{QA} = 0,540\text{ kA}$$

$$\underline{I}_{QC} = (1 - r)3I_{(0)C} = 0,4 \cdot 3 \cdot (0,0334 - j0,1873)\text{ kA} = (0,0401 - j0,2247)\text{ kA} ;$$

$$I_{QC} = 0,288\text{ kA}$$

The currents through earth remote from the stations A and B as well as B and C are:

$$I_{E\delta A} = r \cdot 3I_{(0)A} = 0,6 \cdot 3 \cdot 0,450\text{ kA} = 0,810\text{ kA}$$

$$I_{E\delta C} = r \cdot 3I_{(0)C} = 0,6 \cdot 3 \cdot 0,190\text{ kA} = 0,342\text{ kA}$$

B.4 Line-to-earth short circuit outside a station

The line-to-earth short circuit shall occur far outside the stations at an overhead line tower T between B and C in Figure B.3. Distances $\ell_{2a} = 60\text{ km}$ and $\ell_{2b} = 40\text{ km}$.

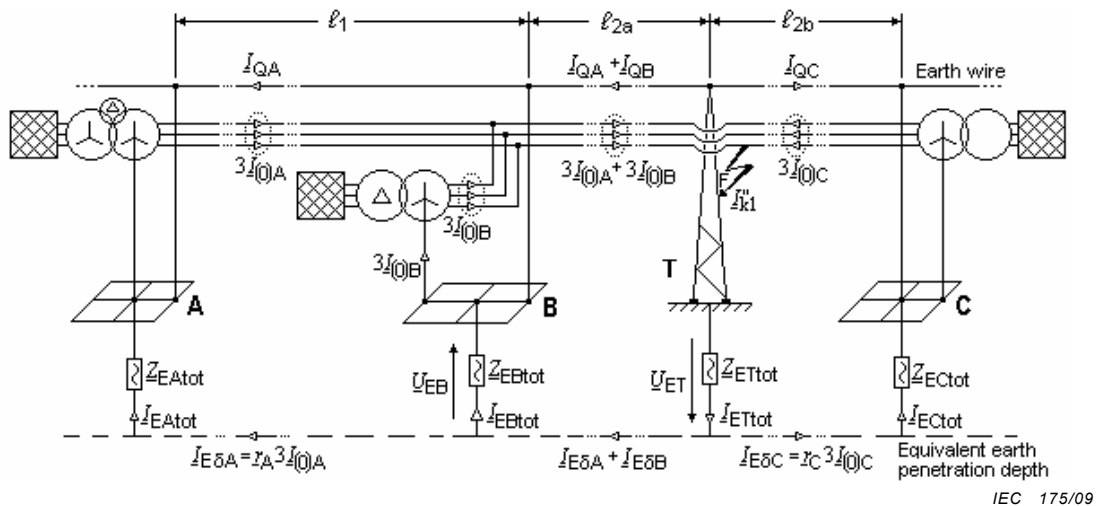


Figure B.3 – Line-to-earth short circuit outside stations B and C at the tower T of an overhead line – System diagram for stations A, B and C

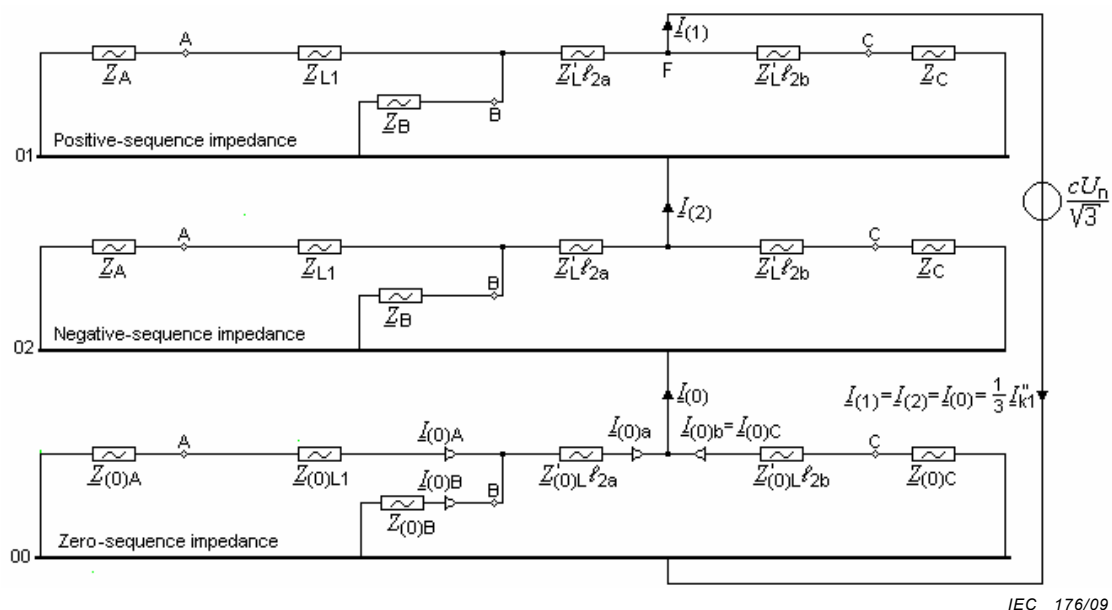


Figure B.4 – Line-to-earth short circuit outside stations B and C at the tower T of an overhead line – Positive-, negative- and zero-sequence systems with connections at the short-circuit location F

The line-to-earth short-circuit current can be calculated with IEC 60909-0, Equation (52), using Figure B.4.

$$I_{k1}'' = \frac{\sqrt{3} \cdot 1,1 \cdot 132 \text{ kV}}{2(1,7145 + j13,6602)\Omega + (6,6262 + j43,3324)\Omega} = (0,4965 - j3,4889) \text{ kA}$$

where

$$Z_{(1)} = Z_{(2)} = \frac{1}{\frac{1}{Z_{L'_{2b}} + Z_C} + \frac{1}{Z_{L'_{2a}} + \frac{1}{\frac{1}{Z_B} + \frac{1}{Z_{L1} + Z_A}}}} = (1,7145 + j13,6602)\Omega$$

$$Z_{(0)} = \frac{1}{\frac{1}{Z_{(0)L'_{2b}} + Z_{(0)C}} + \frac{1}{Z_{(0)L'_{2a}} + \frac{1}{\frac{1}{Z_{(0)B}} + \frac{1}{Z_{(0)L1} + Z_{(0)A}}}}} = (6,6262 + j43,3324)\Omega$$

The zero-sequence current at the short-circuit location is given by

$$I_{(0)} = \frac{1}{3} I_{k1}'' = (0,1655 - j1,1630) \text{ kA}$$

The partial zero-sequence currents $I_{(0)a}$ and $I_{(0)b}$ on the left and right side of the short-circuit location F in Figure B.4 are found as follows:

$$\underline{I}_{(0)a} = \underline{I}_{(0)} \frac{\underline{Z}'_{(0)L} \ell_{2b} + \underline{Z}_{(0)C}}{\underline{Z}'_{(0)L} \ell_{2b} + \underline{Z}_{(0)C} + \underline{Z}'_{(0)L} \ell_{2a} + \frac{1}{\frac{1}{\underline{Z}_{(0)B}} + \frac{1}{\underline{Z}_{(0)L1} + \underline{Z}_{(0)A}}}} = (0,0851 - j0,5263) \text{ kA}$$

$$\underline{I}_{(0)b} = \underline{I}_{(0)} - \underline{I}_{(0)a} = (0,0804 - j0,6367) \text{ kA} = \underline{I}_{(0)C}; \quad I_{(0)C} = 0,6417 \text{ kA}$$

The partial zero-sequence currents $\underline{I}_{(0)A}$ and $\underline{I}_{(0)B}$ are found from $\underline{I}_{(0)a}$:

$$\underline{I}_{(0)A} = \underline{I}_{(0)a} \frac{\underline{Z}_{(0)B}}{\underline{Z}_{(0)A} + \underline{Z}_{(0)B} + \underline{Z}_{(0)L1}} = (0,0139 - j0,0452) \text{ kA};$$

$$I_{(0)A} = 0,0473 \text{ kA}$$

$$\underline{I}_{(0)B} = \underline{I}_{(0)a} \frac{\underline{Z}_{(0)A} + \underline{Z}_{(0)L1}}{\underline{Z}_{(0)A} + \underline{Z}_{(0)B} + \underline{Z}_{(0)L1}} = (0,0712 - j0,4811) \text{ kA};$$

$$I_{(0)B} = 0,4864 \text{ kA}$$

The total current to earth at the short-circuited tower in Figure B.3 is calculated with Equation (22):

$$\underline{I}_{ETot} = \underline{r} \underline{I}_{k1}'' = 0,6 \cdot (0,4965 - j3,4889) \text{ kA} = (0,2979 - j2,0933) \text{ kA};$$

$$I_{ETot} = 2,114 \text{ kA}$$

With the tower footing resistance R_T and the driving point impedance as calculated in Clause B.3, the total earth impedance $\underline{Z}_{ETot}$ is found according to Equation (23):

$$\underline{Z}_{ETot} = \frac{1}{\frac{1}{10 \Omega} + \frac{2}{(1,437 + j1,306) \Omega}} = (0,7048 + j0,5663) \Omega;$$

$$\underline{Z}_{ETot} = 0,9041 \Omega$$

The earth potential at the tower is calculated with Equation (24):

$$\underline{U}_{ET} = \underline{Z}_{ETot} \underline{I}_{ETot} = (0,7048 + j0,5653) \Omega \cdot (0,2979 - j2,0933) \text{ kA} = (1,3954 - j1,3067) \text{ kV};$$

$$U_{ET} = 1,912 \text{ kV}$$

The currents in the stations A, B and C are:

$$\underline{I}_{EAot} = \underline{r} 3 \underline{I}_{(0)A} = 0,6 \cdot 3 \cdot 0,0473 \text{ kA} = 0,0851 \text{ kA}$$

$$\underline{I}_{EBtot} = r \cdot 3 \underline{I}_{(0)B} = 0,6 \cdot 3 \cdot 0,4864 \text{ kA} = 0,8754 \text{ kA}$$

$$\underline{I}_{ECtot} = r \cdot 3 \underline{I}_{(0)C} = 0,6 \cdot 3 \cdot 0,6417 \text{ kA} = 1,1551 \text{ kA}$$

The earth potential of station B for example is found as follows:

$$\underline{U}_{EB} = \underline{Z}_{EBtot} \cdot r \cdot 3 \underline{I}_{(0)B} = (0,6845 + j0,4928) \Omega \cdot 0,6 \cdot 3 \cdot (0,0712 - j0,4811) \text{ kA} = (0,5145 - j0,5296) \text{ kV}$$

$$U_{EB} = 0,7383 \text{ kV}$$

The currents in the earth wires and through the earth at a longer distance from the stations and the short-circuited tower (Figure B.3) are:

$$\underline{I}_{QA} = (1 - r) \cdot 3 \underline{I}_{(0)A} = 0,4 \cdot 3 \cdot (0,0139 - j0,0452) \text{ kA} = (0,0167 - j0,0542) \text{ kA} ;$$

$$I_{QA} = 0,0567 \text{ kA}$$

$$\underline{I}_{QA} + \underline{I}_{QB} = (1 - r) \cdot 3 (\underline{I}_{(0)A} + \underline{I}_{(0)B}) = 0,4 \cdot 3 \cdot (0,0851 - j0,5263) \text{ kA} = (0,1021 - j0,6316) \text{ kA} ;$$

$$|\underline{I}_{QA} + \underline{I}_{QB}| = 0,6397 \text{ kA} ;$$

$$\underline{I}_{QC} = (1 - r) \cdot 3 \underline{I}_{(0)C} = 0,4 \cdot 3 \cdot (0,0804 - j0,6367) \text{ kA} = (0,0965 - j0,7640) \text{ kA} ;$$

$$I_{QC} = 0,7701 \text{ kA}$$

$$I_{E\delta A} = r \cdot 3 \underline{I}_{(0)A} = 0,6 \cdot 3 \cdot 0,0473 \text{ kA} = 0,0851 \text{ kA}$$

$$I_{E\delta A} + I_{E\delta B} = r \cdot 3 |\underline{I}_{(0)A} + \underline{I}_{(0)B}| = 0,6 \cdot 3 \cdot 0,5331 \text{ kA} = 0,9596 \text{ kA}$$

$$I_{E\delta C} = r \cdot 3 \underline{I}_{(0)C} = 0,6 \cdot 3 \cdot 0,6417 \text{ kA} = 1,1551 \text{ kA}$$

B.5 Line-to-earth short circuit in the vicinity of a station

As an example, the line-to-earth short-circuit current and the earth potentials shall be calculated, if the short circuit occurs at a tower T with the number $n = 10$ at the overhead line between the stations B and C at a distance of 4,4 km from station B (see Figure 7).

The line-to-earth short-circuit current is calculated according to IEC 60909-0, Equation (52) using Figure B.4 with changed line lengths.

$$\underline{I}_{k1}'' = \frac{\sqrt{3} \cdot 11,132 \text{ kV}}{2(0,4449 + j5,9037) \Omega + (1,2412 + j11,9481) \Omega} = (0,9421 - j10,5022) \text{ kA} ;$$

$$I_{k1}'' = 10,5444 \text{ kA}$$

where

$$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \frac{1}{\frac{1}{\underline{Z}'_L(\ell_2 - 11 \cdot d_T) + \underline{Z}_C} + \frac{1}{\underline{Z}'_L \cdot 11 \cdot d_T + \frac{1}{\frac{1}{\underline{Z}_B} + \frac{1}{\underline{Z}_{L1} + \underline{Z}_A}}}} = (0,4449 + j5,9037)\Omega$$

$$\underline{Z}_{(0)} = \frac{1}{\frac{1}{\underline{Z}'_{(0)L}(\ell_2 - 11 \cdot d_T) + \underline{Z}_{(0)C}} + \frac{1}{\underline{Z}'_{(0)L} \cdot 11 \cdot d_T + \frac{1}{\frac{1}{\underline{Z}_{(0)B}} + \frac{1}{\underline{Z}_{(0)L1} + \underline{Z}_{(0)A}}}}} = (1,2412 + j11,9481)\Omega$$

The zero-sequence current at the short-circuit location is given by

$$\underline{I}_{(0)} = \frac{1}{3} \underline{I}_{k1}'' = (0,3141 - j3,5007)\text{kA}$$

The partial zero-sequence currents $\underline{I}_{(0)a}$ and $\underline{I}_{(0)b}$ on the left and right side of the tower T ($n=10$) are found as follows:

$$\underline{I}_{(0)a} = \underline{I}_{(0)} \frac{\underline{Z}'_{(0)L}(\ell_2 - 11 \cdot d_T) + \underline{Z}_{(0)C}}{\underline{Z}'_{(0)L}(\ell_2 - 11 \cdot d_T) + \underline{Z}_{(0)C} + \underline{Z}'_{(0)L} \cdot 11 \cdot d_T + \frac{1}{\frac{1}{\underline{Z}_{(0)B}} + \frac{1}{\underline{Z}_{(0)L1} + \underline{Z}_{(0)A}}}} = (0,2767 - j3,2458)\text{kA}$$

$$\underline{I}_{(0)b} = \underline{I}_{(0)} - \underline{I}_{(0)a} = (0,03731 - j0,2549)\text{kA} = \underline{I}_{(0)C};$$

$$I_{(0)C} = 0,2577\text{kA}$$

The partial zero-sequence currents $\underline{I}_{(0)A}$ and $\underline{I}_{(0)B}$ are found from $\underline{I}_{(0)a}$:

$$\underline{I}_{(0)A} = \underline{I}_{(0)a} \frac{\underline{Z}_{(0)B}}{\underline{Z}_{(0)A} + \underline{Z}_{(0)B} + \underline{Z}_{(0)L1}} = (0,0640 - j0,2817)\text{kA};$$

$$I_{(0)A} = 0,2888\text{kA}$$

$$\underline{I}_{(0)B} = \underline{I}_{(0)a} \frac{\underline{Z}_{(0)A} + \underline{Z}_{(0)L1}}{\underline{Z}_{(0)A} + \underline{Z}_{(0)B} + \underline{Z}_{(0)L1}} = (0,2128 - j2,9642)\text{kA};$$

$$I_{(0)B} = 2,9718\text{kA}$$

The factor $\underline{k}$ can be calculated from Equation (3):

$$\underline{k} = 1 + \frac{\underline{Z}_P}{R_T} = 1 + \frac{(1,4369 + j1,3060)\Omega}{10\Omega} = (1,1437 + j0,1306)$$

The earthing impedance of station B in this case is calculated with Equation (29):

$$\underline{Z}_{EB} = \frac{1}{\frac{1}{R_B} + \frac{1}{\underline{Z}_P}} = \frac{1}{\frac{1}{5\Omega} + \frac{1}{(1,4370 + j1,3060)\Omega}} = (1,2698 + j0,7568)\Omega$$

The driving point impedance of the finite chain for $n=10$ is found from Equation (2):

$$\underline{Z}_{P10} = (1,4294 + j1,3200)\Omega; \quad \underline{Z}_{P10} = 1,9457\Omega$$

The earthing impedance for the short-circuited tower is to be calculated with Equation (28):

$$\underline{Z}_{ET} = \frac{1}{\frac{1}{R_T} + \frac{1}{\underline{Z}_P}} = \frac{1}{\frac{1}{10\Omega} + \frac{1}{(1,4370 + j1,3060)\Omega}} = (1,3690 + j0,9856)\Omega$$

The current $\underline{I}_{ET10}$ flowing through $\underline{Z}_{ET}$ at the tower $n = 10$ is found with Equation (27):

$$\begin{aligned} \underline{I}_{ET10} &= r\underline{I}_{k1}'' \frac{\underline{Z}_{P10}}{\underline{Z}_{P10} + \underline{Z}_{ET}} - r3\underline{I}_{(0)B} \frac{\underline{Z}_{EB}}{\underline{Z}_{EB} + \underline{Z}_P} \cdot \frac{1}{\underline{k}^{10}} = 0,6(0,9421 - j10,5022)\text{kA} \frac{(1,4294 + j1,3200)\Omega}{(2,798 + j2,306)\Omega} \\ &- 0,6 \cdot 3 \cdot (0,2128 - j2,9642)\text{kA} \frac{(1,2697 + j0,7568)\Omega}{(2,7067 + j2,0628)\Omega} \cdot \frac{1}{(1,1437 + j0,1306)^{10}} = (1,0194 - j3,1417)\text{kA} \\ \underline{I}_{ET10} &= 3,3029\text{kA} \end{aligned}$$

The earth potential at the short-circuited tower is given according to Equation (30):

$$\underline{U}_{ET10} = \underline{Z}_{ET} \underline{I}_{ET10} = (4,4918 - j3,2961)\text{kV};$$

$$U_{ET10} = 5,5714\text{kV}$$

The current passing $\underline{Z}_{EB}$ in this case of a line-to-earth short circuit at the tower ($n=10$) in the vicinity of station B is found with Equation (31):

$$\begin{aligned} \underline{I}_{EB10} &= r\underline{I}_{k1}'' \frac{\underline{Z}_{ET}}{\underline{Z}_{ET} + \underline{Z}_{P10}} \cdot \frac{2\underline{Z}_P - \underline{Z}_Q}{(\underline{Z}_{EB} + \underline{Z}_P)\underline{k}^{10} - (\underline{Z}_{EB} - \underline{Z}_P + \underline{Z}_Q)\underline{k}^{-10}} - r3\underline{I}_{(0)B} \frac{\underline{Z}_P}{\underline{Z}_{EB} + \underline{Z}_P} \\ &= 0,6(0,9421 - j10,5022)\text{kA} \frac{(1,3690 + j0,9856)\Omega}{(2,7984 + j2,3056)\Omega} (0,1185 - j0,2323) \\ &- 0,6 \cdot 3 \cdot (0,2128 - j2,9642)\text{kA} \frac{(1,4370 + j1,3060)\Omega}{(2,7067 + j2,0628)\Omega} = (1,1557 - j2,6487)\text{kA}; \\ \underline{I}_{EB10} &= 2,8899\text{kA} \end{aligned}$$

The earth potential of the station B is calculated with Equation (32):

$$\underline{U}_{EB10} = \underline{Z}_{EB} I_{EB10} = (-3,4720 + j2,4884) \text{ kV};$$

$$U_{EB10} = 4,272 \text{ kV}$$

Figure B.5 shows the earth potentials U_{ETn} related to $U_{ET} = 1,912 \text{ kV}$ from Clause B.4 and U_{EBn} related to the earth potential $U_{EB} = 0,972 \text{ kV}$ from Clause B.3.

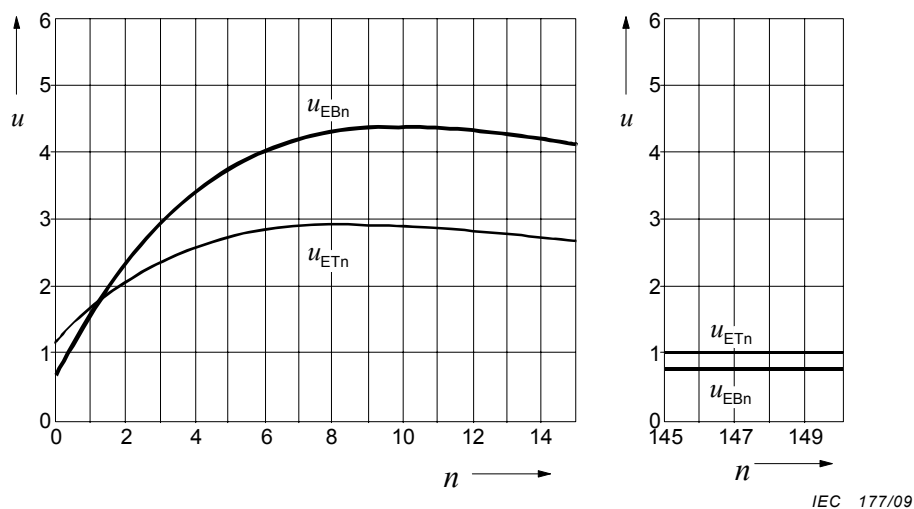


Figure B.5 – Earth potentials $u_{ETn} = U_{ETn}/U_{ET}$ with $U_{ET} = 1,912 \text{ kV}$ and $u_{EBn} = U_{EBn}/U_{EB}$ with $U_{EB} = 0,972 \text{ kV}$, if the line-to-earth short circuit occurs at the towers $n = 1, 2, 3, \dots$ in the vicinity of station B

Annex C (informative)

Example for the calculation of the reduction factor r_1 and the current distribution through earth in case of a three-core cable

C.1 Overview

A 10-kV-cable-connection between the stations A and B is given through a three-core cable with a copper shield earthed at both ends in a 10-kV-network with direct earthing (the star point of a feeding transformer is earthed at the medium-voltage side).

C.2 Line-to-earth short circuit at the end of the cable

C.2.1 Data

Cable: 6/10 kV NA2XS2Y 3 × 150/25

Aluminium cores: $q_L = 150 \text{ mm}^2$; $r_L = 6,91 \text{ mm}$; $R'_L = 0,206 \text{ } \Omega / \text{km}$;

Copper shield: $q_S = 25 \text{ mm}^2$; $r_S = 23,6 \text{ mm}$; $R'_S = 0,714 \text{ } \Omega / \text{km}$;

Distance between the cores of the cable $d = 22,38 \text{ mm}$;

Outer diameter of the cable $D_a = 53 \text{ mm}$

Earthing impedances: $Z_{EA} = 0,5 \text{ } \Omega$; $Z_{EB} = 0,5 \text{ } \Omega$;

Soil resistivity: $\rho = 100 \text{ } \Omega \text{m}$

C.2.2 Cable impedances per unit length

With Equations (30) and (32), given in IEC/TR 60909-2, the following results are found.

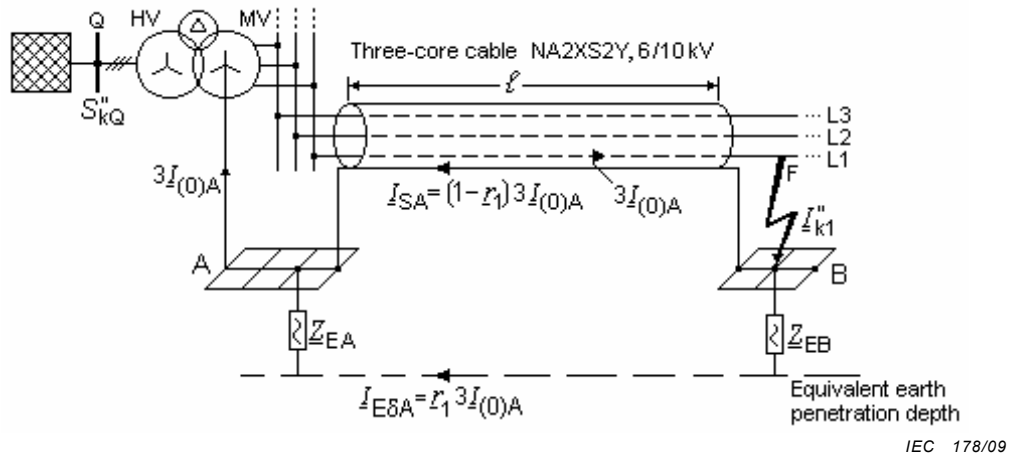
Positive-sequence impedance per unit length:

$$\underline{Z}'_{(1)L} = R'_L + j\omega \frac{\mu_0}{2\pi} \left(\frac{1}{4} + \ln \frac{d}{r_L} \right) = (0,206 + j0,0896) \text{ } \Omega / \text{km}$$

Zero-sequence impedance per unit length in case of current flowing back through the shield (S) and the earth (E):

$$\underline{Z}'_{(0)LSE} = R'_L + 3\omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \left(\frac{1}{4} + 3 \ln \frac{\delta}{\sqrt[3]{r_L d^2}} \right) - \frac{3 \left(\omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S} \right)^2}{R'_S + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S}} = (1,209 + j1,092) \frac{\Omega}{\text{km}}$$

C.2.3 Short-circuit currents



Network feeder: $S_{kQ}'' = 3000 \text{ MVA}$; $U_{nQ} = 110 \text{ kV}$; $R_Q/X_Q = 0,1$;

Transformer: $S_{TT} = 31,5 \text{ MVA}$; $U_{TTHV} = 115 \text{ kV}$; $U_{TTLV} = 10,5 \text{ kV}$; $u_{kr} = 12\%$; $u_{Rr} = 1\%$; $Z_{(0)T} = 1,6 \cdot Z_{(1)T}$.

Figure C.1 – Example for the calculation of the cable reduction factor and the current distribution through earth in a 10-kV-network, $U_n = 10 \text{ kV}$; $c = 1,1$; $f = 50 \text{ Hz}$

According to 6.1, the impedances Z_{EA} and Z_{EB} are neglected when calculating the short-circuit currents with earth connection.

Short-circuit currents:

$$\underline{I}_k'' = \underline{I}_{k3}'' = \frac{cU_n}{\sqrt{3}(Z_{Qt} + Z_{TLV} + Z_{(1)L}' \ell)};$$

$$\underline{I}_k''(\ell = 0) = (1,186 + j13,844) \text{ kA}$$

Line-to-earth short-circuit current flowing back through the shield and the earth

$$\underline{I}_{k1SE}'' = \frac{\sqrt{3}cU_n}{2 \cdot Z_{Qt} + 2 \cdot Z_{TLV} + Z_{(0)TLV} + (2 \cdot Z_{(1)L}' + Z_{(0)LSE}') \cdot \ell}$$

$$\underline{I}_{k1SE}''(\ell = 0) = (1,015 - j11,968) \text{ kA}$$

C.2.4 Reduction factor, current in the shield and current through earth

The current in the shield is calculated with Equation (40):

$$\underline{I}_{SA} = (1-r_1) 3\underline{I}_{(0)A} = (1-r_1) \underline{I}_{k1SE}''$$

The partial short-circuit current flowing through earth is found with Equation (41):

$$\underline{I}_{E\delta A} = r_1 3\underline{I}_{(0)A} = r_1 \underline{I}_{k1SE}''$$

Reduction factor r_1 from Equation (37):

$$\underline{r}_1 = \frac{R'_S}{R'_S + \omega \frac{\mu_0}{8} + j\omega \frac{\mu_0}{2\pi} \ln \frac{\delta}{r_S}} = \frac{0,714 \frac{\Omega}{\text{km}}}{\left(0,714 + 0,04935 + j \cdot 0,06283 \cdot \ln \frac{931\text{m}}{23,6 \cdot 10^{-3}\text{m}} \right) \frac{\Omega}{\text{km}}}$$

$$\underline{r}_1 = 0,5318 - j0,4633 ;$$

$$r_1 = 0,7053$$

Figure C.2 gives the calculated short-circuit currents, the current in the shield and the current through earth depending on the length $\ell \geq 1$ km of the cable between stations A and B.

Earthing voltage in station A, in case of $\ell = 5$ km and $I_{E\delta A} = 1,175$ kA (see Table C.1) is:

$$U_{EA} = Z_{EA} I_{E\delta A} = 0,5 \Omega \cdot 1,175 \text{ kA} = 588 \text{ V}$$

Table C.1 – Results for the example in Figure C.1

ℓ	$\underline{I}_{k1SE}''$	I_{k1SE}''	$\underline{I}_{SA}$	I_{SA}	$\underline{I}_{E\delta A}$	$I_{E\delta A}$
km	kA	kA	kA	kA	kA	kA
1	2,983 -j4,846	5,690	3,641 -j0,887	3,748	-0,659 -j3,959	4,014
5	1,200 -j1,156	1,666	1,097 +j0,015	1,097	0,103 -j1,170	1,175
10	0,661 -j0,578	0,878	0,577 +j0,036	0,578	0,084 -j0,613	0,619

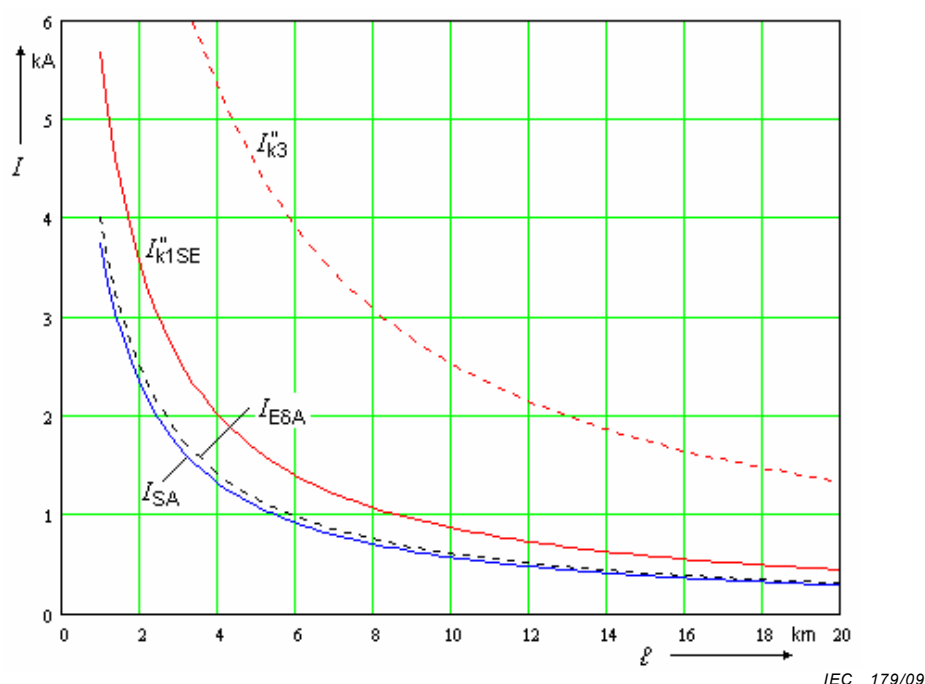


Figure C.2 – Short-circuit currents and partial short-circuit currents through earth for the example in Figure C.1

C.3 Line-to-earth short circuit on the cable between the stations A and B

C.3.1 Configuration and data

The configuration is given in Figure C.3.

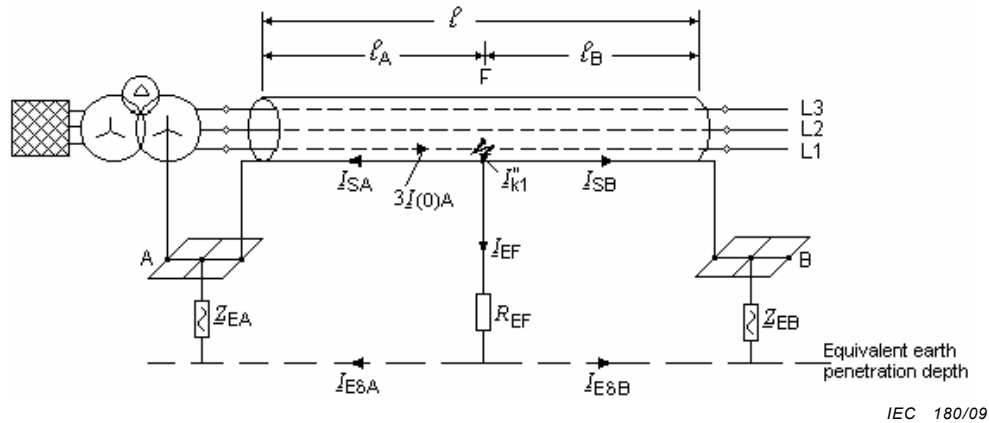


Figure C.3 – Example for the calculation of current distribution in a 10-kV-network with a short circuit on the cable between A and B (data given in C.2.1 and Figure C.1)

The line-to-earth short circuit in Figure C.3 is fed only from station A. The line-to-earth short-circuit is anticipated with earth connection at the short-circuit location F having $R_{EF} = 5\Omega$ (see 8.2.2.2).

C.3.2 Results of calculation

The reduction factor $\underline{r}_1 = 0,5318 - j0,4633$ is already calculated with Equation (37).

The currents $\underline{I}_{SA}$ and $\underline{I}_{E\delta A}$ on the left side of the short-circuit location are calculated with Equations (42) and (45) and the currents on the right side of the short-circuit location with Equations (43) and (46). In case of $3\underline{I}_{(0)B} = 0$ according to Figure C.3, the following relation is valid: $\underline{I}_{E\delta B} = -\underline{I}_{SB}$.