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(Superseding IS 5728)
(Reaffirmed 2002)

भारतीय मानक

तीन-फेजी ए॰ सी॰ तंत्रों में शार्ट-सर्किट करेंट परिकलन की मार्ग दर्शिका

Indian Standard

GUIDE FOR SHORT-CIRCUIT CURRENT CALCULATION IN THREE-PHASE A. C. SYSTEMS

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Indian Standard

GUIDE FOR SHORT-CIRCUIT CURRENT CALCULATION IN THREE-PHASE A. C. SYSTEMS

NATIONAL FOREWORD

This Indian Standard which is identical with IEC Pub 909 (1988) 'Short-circuit current calculation in three-phase A. C. systems', issued by the International Electrotechnical Commission (IEC) was adopted by the Bureau of Indian Standards on the recommendations of the Electrical Installations Sectional Committee (ET 20) and approval of the Electrotechnical Division Council.

An important criterion for the proper selection of a circuit-breaker or any other fault protective devices for use at a point in an electrical circuit is the information on maximum fault current likely at that point. The electromagnetic, mechanical and thermal stresses which a switchgear and the associated apparatus have to withstand depends on the fault current. Proper selection of breaking and withstand capacities play a major role in the health of the electrical installations. Realizing this need and to provide uniform guide for calculation of short-circuit currents, IS 5728 was brought out in 1970.

Subsequent to the preparation of this standard, considerable more information have been collated the world over on calculation of fault lavels under different and specific circumstances. There was also a need to simplify calculation techniques in a practical way commensurate with the modern arithmatic tools available to engineers in the form of computers, digital transient network analysers, etc. With an objective to establish a general, practicable and concise procedure for short-circuit current calculations IS 5728 has been taken up for revision, aligning its contents with IEC 909 (1988).

On the publication of this standard, IS 5728 : 1970 would stand superseded.

CROSS REFERENCES

International Standard	*Corresponding Indian Standard (Technically Equivalent)*
IEC Pub 38 (1983) IEC standard voltages	IS 12360 : 1988 Voltage bands for electrical installations including preferred voltages and frequency
IEC Pub 50 : International electrotechnical vocabulary (IEV):	IS 1985 Electrotechnical vocabulary:
50 (131) (1978) Chapter 131 : Electric and magnetic circuits 50 (151) (1978) Chapter 151 : Electrical and magnetic devices	(Part 57) : 1982 Electric and magnetic circuits
50 (441) (1987) Chapter 441 : Switchgear, controlgear and fuses	(Part 17) : 1989 Switchgear and controlgear
IEC Pub 865 (1986) Calculation of the effects short-circuit currents	IS 13235 : 1991 Calculation of the effects of short-circuit currents

CONTENTS

1. Scope

This standard is applicable to the calculation of short-circuit currents:

- in low-voltage three-phase a.c. systems,
- in high-voltage three-phase a.c. systems with nominal voltages up to 230 kV operating at nominal frequency (50 Hz or 60 Hz).

This standardized procedure is given in such a form as to facilitate as far as possible its use by non-specialist engineers.

2. Object

The object of this standard is to establish a general, practicable and concise procedure leading to conservative results with sufficient accuracy. For this purpose, an equivalent voltage source at the short-circuit location is considered, as described under Clause 6. This does not exclude the use of special methods, for example the superposition method, adjusted to particular circumstances, if they give at least the same precision.

Short-circuit currents and short-circuit impedances may also be determined by system tests, by measurement on a network analyzer, or with a digital computer. In existing low-voltage systems it is possible to determine the short-circuit impedance on the basis of measurements at the location of the prospective short circuit considered.

The calculation of the short-circuit impedance 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.

There are two different short-circuit currents to be calculated which differ in their magnitude:

- the maximum short-circuit current which determines the capacity or rating of electrical equipment;
- the minimum short-circuit current which can be a basis, for example, for the selection of fuses and for the setting of protective devices and for checking the run-up of motors.

One has to distinguish between:

- systems with short-circuit currents having no a.c. component decay (far-from-generator short circuit), treated in Section One,
- systems with short-circuit currents having decaying a.c. components (near-to-generator short circuit), treated in Section Two. This section also includes the influence of motors.

This standard does not cover short-circuit currents deliberately created under controlled conditions (short-circuit testing stations).

This standard does not deal with installations on board ships and areoplanes.

For the calculation of the thermal equivalent short-circuit currents see Section Two of IEC Publication 865.

An application guide, dealing with non-meshed low-voltage three-phase a.c. systems and a technical report on the derivation of the parameters and various calculation factors of this standard are under consideration.

3. Definitions

For the purpose of this standard, the following definitions apply. Reference is made to the International Electrotechnical Vocabulary (IEV) [IEC Publication 50] when applicable.

3.1 *Short circuit*

The accidental or intentional connection, by a relatively low resistance or impedance, of two or more points in a circuit which are normally at different voltages (IEV 151-03-41).

3.2 *Short-circuit current*

An over-current resulting from a short circuit due to a fault or an incorrect connection in an electric circuit (IEV 441-11-07).

Note. – It is necessary to distinguish between the short-circuit current at the short-circuit location and in the network branches.

3.3 *Prospective (available) short-circuit current*

The current that would flow if the short circuit were replaced by an ideal connection of negligible impedance without any change of the supply.

Note. – The current in a three-phase short circuit is assumed to be made simultaneously in all poles. Investigations of non-simultaneous short circuits, which can lead to higher aperiodic components of short-circuit current, are beyond the scope of this standard.

3.4 *Symmetrical short-circuit current*

The r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current (see Sub-clause 3.3), the aperiodic component of current, if any, being neglected.

3.5 *Initial symmetrical short-circuit current* I''_k

The r.m.s. value of the a.c. symmetrical component of a prospective (available) short-circuit current (see Sub-clause 3.3) applicable at the instant of short circuit if the impedance remains at zero-time value (see Figures 1 and 12, pages 19 and 63).

3.6 *Initial symmetrical short-circuit (apparent) power* S''_k

The fictive value determined as a product of the initial symmetrical short-circuit current I''_k (see Sub-clause 3.5), the nominal system voltage U_n (see Sub-clause 3.14), and the factor $\sqrt{3}$:

$$S''_k = \sqrt{3}\, U_n\, I''_k$$

3.7 *D.C. (aperiodic) component* i_{DC} *of short-circuit current*

The mean value between the top and bottom envelope of a short-circuit current decaying from an initial value to zero according to Figures 1 and 12.

3.8 *Peak short-circuit current* i_p

The maximum possible instantaneous value of the prospective (available) short-circuit current (see Figures 1 and 12).

Note. – The magnitude of the peak short-circuit current varies in accordance with the moment at which the short circuit occurs. The calculation of the peak three-phase short-circuit current i_p applies for the phase conductor and moment at which the greatest possible short-circuit current exists. Sequential faults are not considered. For three-phase short circuits it is assumed that the short circuit occurs simultaneously in all phase conductors.

3.9 *Symmetrical short-circuit breaking current* I_b

The r.m.s. value of an integral cycle of the symmetrical a.c. component of the prospective short-circuit current at the instant of contact separation of the first pole of a switching device.

3.10 *Steady-state short-circuit current* I_k

The r.m.s. value of the short-circuit current which remains after the decay of the transient phenomena (see Figures 1 and 12, pages 19 and 63).

3.11 *Symmetrical locked-rotor current* I_{LR}

The highest symmetrical r.m.s. current of an asynchronous motor with locked rotor fed with rated voltage U_{rM} at rated frequency.

3.12 *Equivalent electric circuit*

A model to describe the behaviour of a circuit by means of a network of ideal elements (IEV 131-01-33).

3.13 *(Independent) voltage source*

An active element which can be represented by an ideal voltage source independent of all currents and voltages in the circuit, in series with a passive circuit element (IEV 131-01-37).

3.14 *Nominal system voltage* U_n

Voltage (line-to-line) by which a system is designated and to which certain operating characteristics are referred. Values are given in IEC Publication 38.

3.15 *Equivalent voltage source* $cU_n/\sqrt{3}$

The voltage of an ideal source applied at the short-circuit location in the positive-sequence system for calculating the short-circuit current according to Clause 6. This is the only active voltage of the network.

3.16 *Voltage factor c*

The ratio between the equivalent voltage source and the nominal system voltage U_n divided by $\sqrt{3}$. The values are given in Table I.

Note. – The introduction of a voltage factor *c* is necessary for various reasons. These are:

- voltage variations depending on time and place,
- changing of transformer taps,
- neglecting loads and capacitances by calculations according to Clause 6,
- the subtransient behaviour of generators and motors.

3.17 *Subtransient voltage E″ of a synchronous machine*

The r.m.s. value of the symmetrical internal voltage of a synchronous machine which is active behind the subtransient reactance X''_d at the moment of short circuit.

3.18 *Far-from-generator short circuit*

A short circuit during which the magnitude of the symmetrical a.c. component of prospective (available) short-circuit current remains essentially constant (see Clause 7).

3.19 *Near-to-generator short circuit*

A short circuit to which at least one synchronous machine contributes a prospective initial symmetrical short-circuit current which is more than twice the generator's rated current, or a short circuit to which synchronous and asynchronous motors contribute more than 5% of the initial symmetrical short-circuit current I''_k without motors (see Clause 10).

3.20 *Short-circuit impedances at the short-circuit location F*

3.20.1 *Positive-sequence short-circuit impedance* $\underline{Z}_{(1)}$ *of a three-phase a.c. system*

The impedance of the positive-sequence system as viewed from the short-circuit location (see Sub-clause 8.3.1 and Figure 4a, page 27).

3.20.2 *Negative-sequence short-circuit impedance* $\underline{Z}_{(2)}$ *of a three-phase a.c. system*

The impedance of the negative-sequence system as viewed from the short-circuit location (see Sub-clause 8.3.1 and Figure 4b, page 27).

3.20.3 *Zero-sequence short-circuit impedance* $\underline{Z}_{(0)}$ *of a three-phase a.c. system*

The impedance of the zero-sequence system as viewed from the short-circuit location (see Sub-clause 8.3.1 and Figure 4c, page 27). It includes three times the neutral-to-earth impedance 3 $\underline{Z}_{NE}$.

3.20.4 *Short-circuit impedance* $\underline{Z}_k$ *of a three-phase a.c. system*

Abbreviated expression for the positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ according to Sub-clause 3.20.1 for the calculation of three-phase short-circuit currents.

3.21 *Short-circuit impedances of electrical equipment*

3.21.1 *Positive-sequence short-circuit impedance* $\underline{Z}_{(1)}$ *of electrical equipment*

The ratio of the line-to-neutral voltage to the short-circuit current of the corresponding phase of electrical equipment when fed by a symmetrical positive-sequence system of voltages (see Sub-clause 8.3.2).

Note. – Index of symbol $\underline{Z}_{(1)}$ may be omitted if there is no possibility of confusion with the negative-sequence and the zero-sequence short-circuit impedances.

3.21.2 *Negative-sequence short-circuit impedance* $\underline{Z}_{(2)}$ *of electrical equipment*

The ratio of the line-to-neutral voltage to the short-circuit current of the corresponding phase of electrical equipment when fed by a symmetrical negative-sequence system of voltages (see Sub-clause 8.3.2).

3.21.3 *Zero-sequence short-circuit impedance* $\underline{Z}_{(0)}$ *of electrical equipment*

The ratio of the line-to-earth voltage to the short-circuit current of one phase of electrical equipment when fed by an a.c. voltage source, if the three parallel phase conductors are used for the outgoing current and a fourth line and/or earth is joint return (see Sub-clause 8.3.2).

3.22 *Subtransient reactance* X''_d *of a synchronous machine*

The effective reactance at the moment of short circuit. For the calculation of short-circuit currents the saturated value of X''_d is taken.

Note. – When the reactance X''_d in ohms is divided by the rated impedance $Z_{rG} = U^2_{rG} / S_{rG}$ of the synchronous machine, the result in per unit is represented by a small letter $x''_d = X''_d / Z_{rG}$.

3.23 *Minimum time delay t_{min} of a circuit breaker*

The shortest time between the beginning of the short-circuit current and the first contact separation of one pole of the switching device.

Note. – The time t_{min} is the sum of the shortest possible operating time of an instantaneous relay and the shortest opening time of a circuit breaker. It does not take into account adjustable time delays of tripping devices.

4. Symbols, subscripts and superscripts

Symbols of complex quantities are underlined, for example: $\underline{Z} = R + jX$.

All equations are written without specifying units. The symbols represent quantities possessing both numerical values and dimensions that are independent of units, provided a coherent unit system is chosen, for example, the International System of Units (SI).

4.1 *Symbols*

A	Initial value of aperiodic component
c	Voltage factor
$cU_n/\sqrt{3}$	Equivalent voltage source (r.m.s.)
E''	Subtransient voltage of a synchronous machine
f	Frequency (50 Hz or 60 Hz)
I_b	Symmetrical short-circuit breaking current (r.m.s.)
I_k	Steady-state short-circuit current (r.m.s.)
I_{kP}	Steady-state short-circuit current at the terminals (poles) of a generator with compound excitation
$\underline{I}''_k$ or $\underline{I}''_{k3}$	Initial symmetrical short-circuit current (r.m.s.)
I_{LR}	Locked-rotor current of an asynchronous motor
i_{DC}	Decaying aperiodic component of short-circuit current
i_p	Peak short-circuit current
K	Correction factor for impedances
P_{krT}	Total loss in transformer windings at rated current
q	Factor for the calculation of breaking currents of asynchronous motors
q_n	Nominal cross section
R resp. r	Resistance, absolute respectively relative value
R_G	Fictitious resistance of a synchronous machine when calculating I''_k and i_p
S''_k	Initial symmetrical short-circuit power (apparent power)
S_r	Rated apparent power of electrical equipment
t_f	Fictitious transformation ratio
t_{min}	Minimum time delay
t_r	Rated transformation ratio (tap changer in main position); $t_r \geq 1$
U_n	Nominal system voltage, line-to-line (r.m.s.)
U_r	Rated voltage, line-to-line (r.m.s.)
u_{kr}	Rated short-circuit voltage in percent
u_{Rr}	Rated ohmic voltage in percent
$\underline{U}_{(1)}$, $\underline{U}_{(2)}$, $\underline{U}_{(0)}$	Positive-, negative-, zero-sequence voltage
X resp. x	Reactance, absolute respectively relative value
X_d resp. X_q	Synchronous reactance, direct axis respectively quadrature axis
X_{dP}	Fictitious reactance of a generator with compound excitation in the case of steady-state short circuit at the terminals (poles) if the excitation is taken into account
X''_d resp. X''_q	Subtransient reactance of a synchronous machine (saturated value), direct axis respectively quadrature axis
$X_{d\ sat}$	Reciprocal of the short-circuit ratio
Z resp. z	Impedance, absolute respectively relative value
$\underline{Z}_k$	Short-circuit impedance of a three-phase a.c. system
$\underline{Z}_{(1)}$	Positive-sequence short-circuit impedance
$\underline{Z}_{(2)}$	Negative-sequence short-circuit impedance
$\underline{Z}_{(0)}$	Zero-sequence short-circuit impedance
η	Efficiency of asynchronous motors

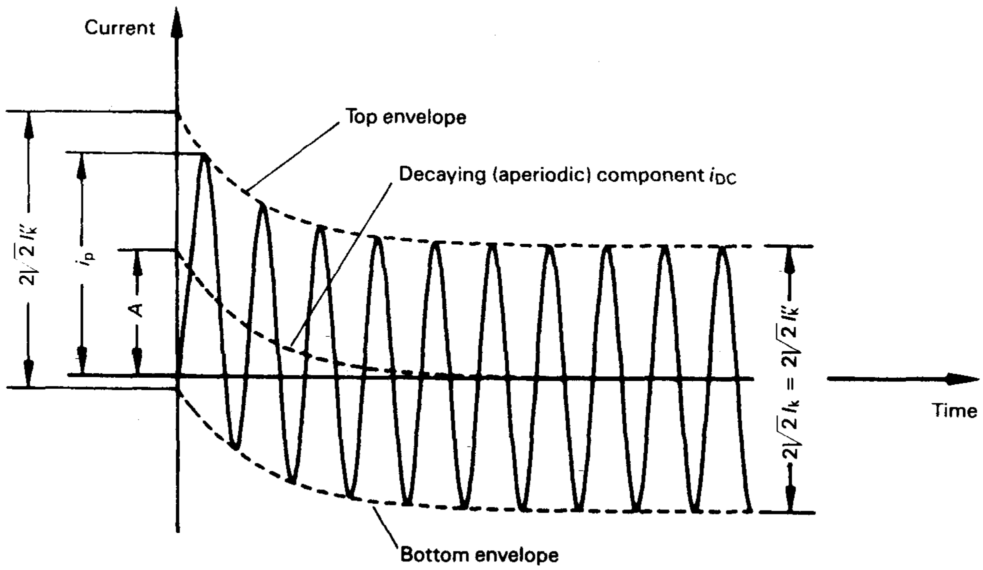
$\varkappa$	Factor for the calculation of the peak short-circuit current
λ	Factor for the calculation of the steady-state short-circuit current
μ	Factor for the calculation of the symmetrical short-circuit breaking current
μ_0	Absolute permeability of vacuum, $\mu_0 = 4\pi / 10^{-7}$ H/m
ϱ	Resistivity
φ	Phase angle

4.2 *Subscripts*

(1)	Positive-sequence component
(2)	Negative-sequence component
(0)	Zero-sequence component
f	Fictitious
k or k3	Three-phase short circuit
k1	Line-to-earth short circuit, line-to-neutral short circuit
k2	Line-to-line short circuit without earth connection
k2E resp. kE2E	Line-to-line short circuit with earth connection, line current respectively earth current
max	Maximum
min	Minimum
n	Nominal value (IEV 151-04-01)
r	Rated value (IEV 151-04-03)
rsl	Resulting
t	Transformed value
AT	Auxiliary transformer
B	Busbar
E	Earth
F	Fault, short-circuit location
G	Generator
HV	High-voltage, high-voltage winding of a transformer
LV	Low-voltage, low-voltage winding of a transformer
L	Line
LR	Locked rotor
L1, L2, L3	Line 1, 2, 3 of a three-phase system
M	Asynchronous motor or group of asynchronous motors
$\not{M}$	Without motor
MV	Medium-voltage, medium-voltage winding of a transformer
N	Neutral of a three-phase a.c. system
P	Terminal, pole
PSU	Power-station unit (generator and transformer)
Q	Feeder connection point
T	Transformer

4.3 *Superscripts*

$''$	Initial (subtransient) value
$'$	Resistance or reactance per unit length



I''_k = initial symmetrical short-circuit current
i_p = peak short-circuit current
I_k = steady-state short-circuit current
i_{DC} = decaying (aperiodic) component of short-circuit current
A = initial value of the aperiodic component i_{DC}

FIG. 1. – Short-circuit current of a far-from-generator short circuit (schematic diagram).

5. Calculation assumptions

A complete calculation of short-circuit currents should give the currents as a function of time at the short-circuit location from the initiation of the short circuit up to its end, corresponding to the instantaneous value of the voltage at the beginning of short circuit (see Figures 1 and 12, pages 19 and 63).

In most practical cases a determination like this is not necessary. Depending on the application of the results, it is of interest to know the r.m.s. value of the symmetrical a.c. component and the peak value i_p of the short-circuit current following the occurrence of a short circuit. The value i_p depends on the time constant of the decaying aperiodic component and the frequency f, that is on the ratio R/X or X/R of the short-circuit impedance $\underline{Z}_k$, and is nearly reached if the short circuit starts at zero voltage.

In meshed networks there are several time constants. That is why it is not possible to give an easy exact method of calculating i_p and i_{DC}. Special methods to calculate i_p with sufficient accuracy are given in Sub-clause 9.1.3.2.

For the determination of the asymmetrical short-circuit breaking current the decaying aperiodic component i_{DC} of the short-circuit current as shown in Figures 1 or 12 may be calculated with sufficient accuracy by:

$$i_{DC} = \sqrt{2}\, I''_k\, e^{-2\pi f t\, R/X} \tag{1}$$

where:

I''_k = initial symmetrical short-circuit current
f = nominal frequency 50 Hz or 60 Hz
t = time
R/X = ratio according to Sub-clause 9.1.1.2, 9.1.2.2 or 9.1.3.2

In meshed networks according to Sub-clause 9.1.3.2 – Method A – the right hand side of equation (1) should be multiplied by 1.15. According to Sub-clause 9.1.3.2 – Method B – the equivalent frequency should be selected as follows:

$2\pi ft$	$<2\pi$	$<5\pi$	$<10\pi$	$<25\pi$
f_c/f	0.27	0.15	0.092	0.055

where f = 50 Hz or 60 Hz.

Furthermore, the calculation of maximum and minimum short-circuit currents is based on the following simplifications:

1) For the duration of the short circuit there is no change in the number of circuits involved, that is, a three-phase short circuit remains three phase and a line-to-earth short circuit remains line-to-earth during the time of short circuit.

2) Tap changers of the transformers are assumed to be in main position.

3) Arc resistances are not taken into account.

While these assumptions are not strictly true for the power systems considered, the recommended short-circuit calculations have acceptable accuracy.

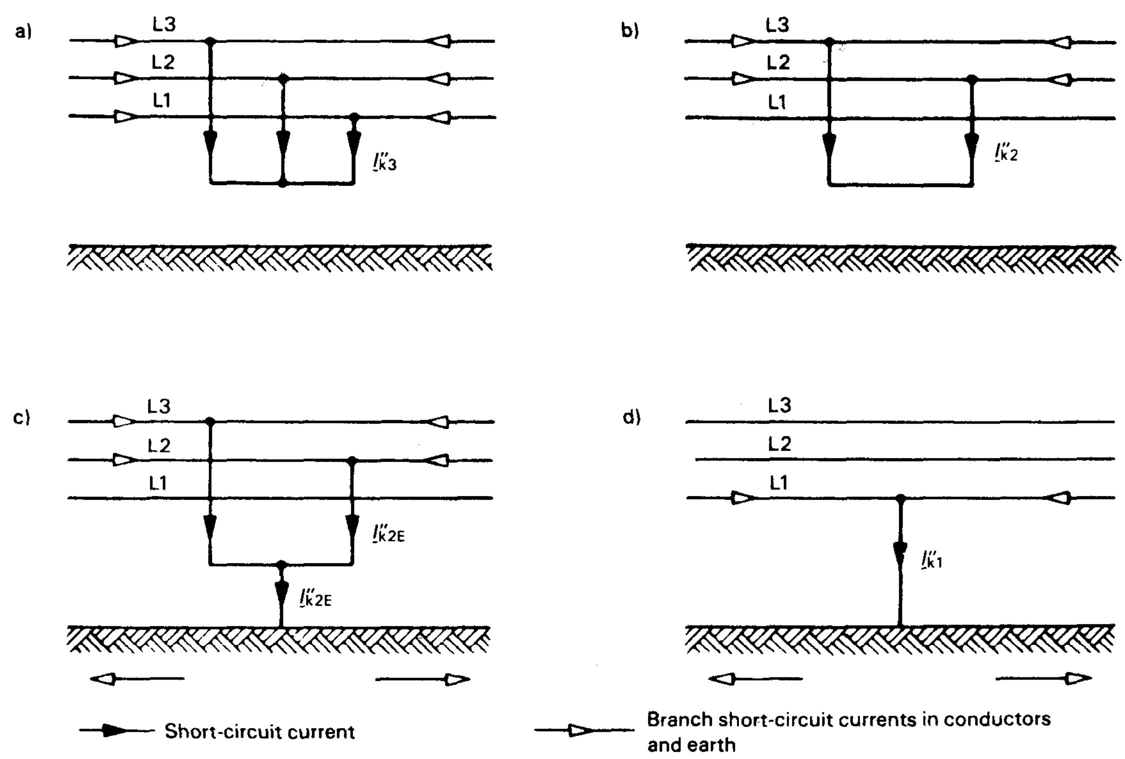
For balanced and unbalanced short circuits as shown in Figure 2, page 23, it is useful to calculate the short-circuit currents by the method of symmetrical components (see Sub-clause 8.2).

6. Equivalent voltage source at the short-circuit location

In all cases in Sections One and Two it is possible to determine the short-circuit current at the short-circuit location F with the help of an equivalent voltage source. Operational data on the static load of consumers, tap changer position of transformers, excitation of generators and so on are dispensable; additional calculations about all the different possible load flows at the moment of short circuit are superfluous.

The equivalent voltage source is the only active voltage of the system. All network feeders, synchronous and asynchronous machines are replaced by their internal impedances (see Sub-clause 8.3.1).

Furthermore, with this method all line capacitances and parallel admittances of non-rotating loads, except those of the zero-sequence system (see Sub-clauses 8.3.1 and 11.4), shall be neglected.



a) Balanced three-phase short circuit.

b) Line-to-line short circuit without earth connection.

c) Line-to-line short circuit with earth connection.

d) Line-to-earth short circuit.

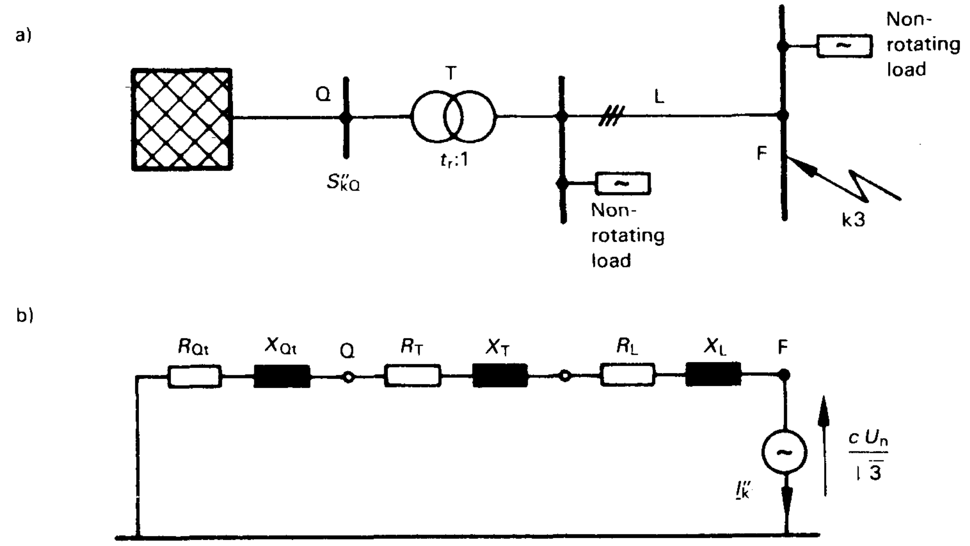
FIG. 2. – Characterization of short circuits and their currents. The direction of current arrows is chosen arbitrarily.

Finally high-voltage transformers in many cases are equipped with regulators and tap changers operating under load flow conditions, whereas transformers feeding low-voltage systems have normally only a few taps, for example +2.5% or +4%. The actual regulator or tap changer position of transformers in the case of far-from-generator short circuits may be disregarded without unacceptable loss of accuracy by use of this method.

The modelling of the system equipment by means of impedances according to Sub-clauses 8.3.2 and 11.5.3 applies in conjunction with the equivalent voltage source at the short-circuit location irrespective of whether a far-from-generator short-circuit according to Section One or a near-to-generator short-circuit according to Section Two is involved.

Figure 3, page 25, shows an example of the equivalent voltage source at the short-circuit location F as the sole active voltage of the system in the case of a low-voltage system fed by a single transformer. All other active voltages in the system are assumed to be zero. Thus the network feeder in Figure 3a, page 25, is represented only by its internal impedance $\underline{Z}_Q$ (see Sub-clause 8.3.2.1). Parallel admittances (e. g. line capacitances and passive loads) are not to be considered when calculating short-circuit currents in accordance with Figure 3b, page 25.

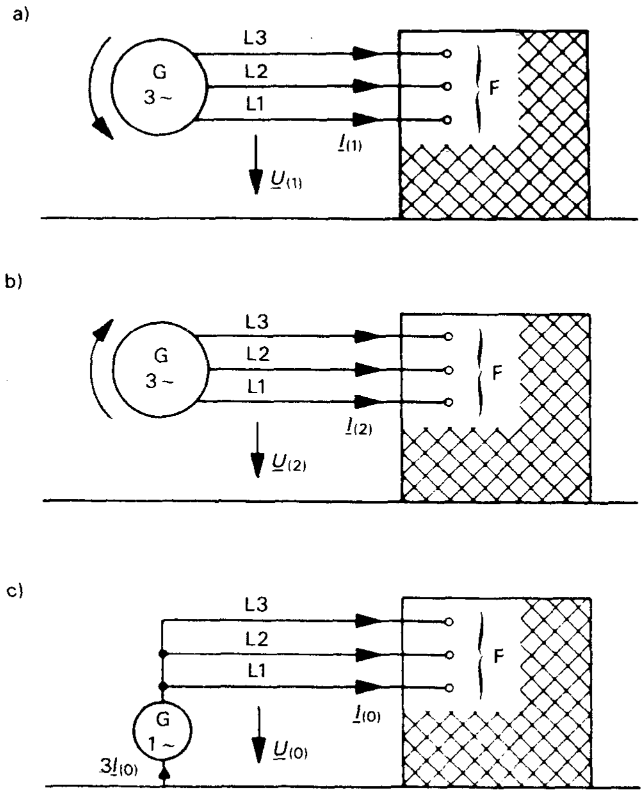
The equivalent voltage source $cU_n/\sqrt{3}$ (see Sub-clause 3.15) at the short-circuit location F is composed of the voltage factor c, the nominal system voltage U_n and $\sqrt{3}$. The voltage factor c is different for the calculation of maximum or minimum short-circuit currents. If there are no national standards, it seems adequate to choose a voltage factor c according to Table I, considering that the highest voltage in a normal system does not differ, on average, by more than +5% (LV) or +10% (HV) approximately from the nominal voltage.



a) System diagram.

b) Equivalent circuit diagram (positive-sequence system).

FIG. 3. – Illustration for calculating the initial symmetrical short-circuit current $\underline{I}''_k$ in compliance with the procedure for the equivalent voltage source.



a) Positive-sequence short-circuit impedance: $\underline{Z}_{(1)} = \underline{U}_{(1)} / \underline{I}_{(1)}$.
b) Negative-sequence short-circuit impedance: $\underline{Z}_{(2)} = \underline{U}_{(2)} / \underline{I}_{(2)}$.
c) Zero-sequence short-circuit impedance: $\underline{Z}_{(0)} = \underline{U}_{(0)} / \underline{I}_{(0)}$.

FIG. 4. – Short-circuit impedance of a three-phase a. c. system at the short-circuit location F.

TABLE I

Voltage factor c

Nominal voltage U_n	Voltage factor *c* for the calculation of maximum short-circuit current c_{max}	Voltage factor *c* for the calculation of minimum short-circuit current c_{min}
Low voltage 100 V to 1000 V (IEC Publication 38, Table I) *a)* 230 V / 400 V *b)* Other voltages	1.00 1.05	0.95 1.00
Medium voltage > 1 kV to 35 kV (IEC Publication 38, Table III)	1.10	1.00
High voltage > 35 kV to 230 kV (IEC Publication 38, Table IV)	1.10	1.00

Note. – cU_n should not exceed the highest voltage U_m for equipment of power systems.

In this way the equivalent voltage source for the calculation of the maximum short-circuit current can be established, according to Table I, by:

$cU_n/\sqrt{3} = 1.00\ U_n/\sqrt{3}$ in low-voltage systems 230 V / 400 V, 50 Hz (2a)

$cU_n/\sqrt{3} = 1.05\ U_n/\sqrt{3}$ in other low-voltage systems (2b)

$cU_n/\sqrt{3} = 1.10\ U_n/\sqrt{3}$ in medium and high-voltage systems. (2c)

SECTION ONE – SYSTEMS WITH SHORT-CIRCUIT CURRENTS HAVING NO A.C. COMPONENT DECAY (FAR-FROM-GENERATOR SHORT CIRCUITS)

7. General

This section refers to short circuits where there is no change for the duration of the short circuit in the voltage or voltages that caused the short-circuit current to develop (i. e. a quasi-stationary voltage condition), nor any significant change in the impedance of the circuit (i. e. constant and linear impedances).

Therefore, the prospective (available) short-circuit current can be considered as the sum of the following two components:

- the a.c. component with constant amplitude during the whole short circuit,
- the aperiodic component beginning with an initial value A and decaying to zero.

Figure 1, page 19, gives schematically the general course of the short-circuit current in the case of a far-from-generator short circuit. The symmetrical a.c. components I''_k and I_k are r.m.s. values and are nearly equal in magnitude.

This assumption is generally satisfied in power systems fed from extended high-voltage systems through transformers, that is in the case of a far-from-generator short circuit.

Single-fed short-circuits supplied by a transformer according to Figure 3, page 25, may a priori be regarded as far-from-generator short circuits if $X_{TLV} \geqslant 2\ X_{Qt}$ with X_{Qt} to be calculated in accordance with Sub-clause 8.3.2.1 and X_{TLV} in accordance with Sub-clause 8.3.2.2.

8. Short-circuit parameters

8.1 *Balanced short circuit*

The balanced three-phase short circuit of a three-phase a.c. system in accordance with Figure 2a, page 23, is of special interest, because this kind of fault often leads to the highest values of prospective (available) short-circuit current and the calculation becomes particularly simple on account of the balanced nature of the short circuit.

In calculating the short-circuit current, it is sufficient to take into account only the positive-sequence short-circuit impedance $\underline{Z}_{(1)} = \underline{Z}_k$ as seen from the fault location (see Sub-clause 8.3.1).

Details of calculation are given in Clause 9.

8.2 *Unbalanced short circuit*

The following types of unbalanced (asymmetrical) short circuits are treated in this standard:

- line-to-line short circuit without earth connection (see Figure 2b, page 23),
- line-to-line short circuit with earth connection (see Figure 2c, page 23),
- line-to-earth short circuit (see Figure 2d, page 23).

As a rule, the three-phase short-circuit current is the largest. In the event of a short circuit near to a transformer with neutral earthing or a neutral-earthing transformer, the line-to-earth short-circuit current may be greater than the three-phase short-circuit current. This applies in particular to transformers of vector group Yz, Dy and Dz when earthing the y- or z-winding on the low voltage side of the transformer.

In three-phase systems the calculation of the current values resulting from unbalanced short circuits is simplified by the use of the method of symmetrical components which requires the calculation of three independent system components, avoiding any coupling of mutual impedances.

Using this method, the currents in each line are found by superposing the currents of three symmetrical component systems:

- positive-sequence current $\underline{I}_{(1)}$,
- negative-sequence current $\underline{I}_{(2)}$,
- zero-sequence current $\underline{I}_{(0)}$.

Taking the line L1 as reference, the currents $\underline{I}_{L1}$, $\underline{I}_{L2}$ and $\underline{I}_{L3}$ are given by:

$$\underline{I}_{L1} = \underline{I}_{(1)} + \underline{I}_{(2)} + \underline{I}_{(0)} \tag{3a}$$

$$\underline{I}_{L2} = \underline{a}^2\,\underline{I}_{(1)} + \underline{a}\,\underline{I}_{(2)} + \underline{I}_{(0)} \tag{3b}$$

$$\underline{I}_{L3} = \underline{a}\,\underline{I}_{(1)} + \underline{a}^2\,\underline{I}_{(2)} + \underline{I}_{(0)} \tag{3c}$$

$$\underline{a} = -\frac{1}{2} + j\frac{1}{2}\sqrt{3}; \quad \underline{a}^2 = -\frac{1}{2} - j\frac{1}{2}\sqrt{3} \tag{4}$$

Each of the three symmetrical component systems has its own impedance (see Sub-clause 8.3).

The method of the symmetrical components postulates that the system impedances are balanced, for example in the case of transposed lines. The results of the short-circuit calculation have an acceptable accuracy also in the case of untransposed lines.

8.3 *Short-circuit impedances*

For the purpose of this standard, one has to make a distinction between short-circuit impedances at the short-circuit location F and short-circuit impedances of individual electrical equipment. According to the calculation with symmetrical components positive-sequence, negative-sequence and zero-sequence short-circuit impedances shall be considered.

8.3.1 *Short-circuit impedances at the short-circuit location F*

The positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ at the short-circuit location F is obtained according to Figure 4a, page 27, when a symmetrical system of voltages of positive-sequence phase order is applied to the short-circuit location F and all synchronous and asynchronous machines are replaced by their internal impedances. When calculating short-circuit currents in accordance with Clause 9, all line capacitances and parallel admittances of non-rotating loads are neglected.

For the calculation of balanced three-phase short circuits, the positive-sequence impedance is the only relevant impedance. In this case $\underline{Z}_k = \underline{Z}_{(1)}$ (see Sub-clauses 3.20.1 and 3.20.4).

The negative-sequence short-circuit impedance $\underline{Z}_{(2)}$ at the short-circuit location F is obtained according to Figure 4b, page 27, when a symmetrical system of voltages of negative-sequence phase order is applied to the short-circuit location F. When calculating short-circuit currents in accordance with Clause 9, all line capacitances and parallel admittances of non-rotating loads are neglected.

The values of positive-sequence and negative-sequence impedances can differ from each other only in the case of rotating machines. In this section, where far-from-generator short circuits are calculated, it is generally allowed to take $\underline{Z}_{(2)} = \underline{Z}_{(1)}$.

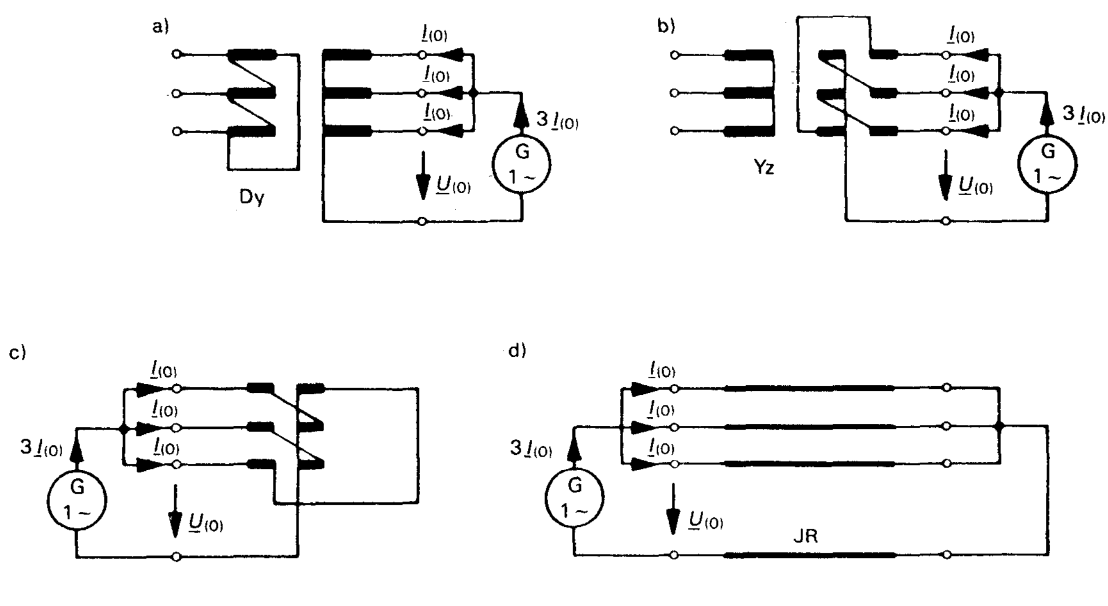
The zero-sequence short-circuit impedance $\underline{Z}_{(0)}$ at the short-circuit location F is obtained according to Figure 4c, page 27, if an a.c. voltage is applied between the short-circuited lines and the common returns (e.g. earth system, neutral conductor, earth wires, cable sheaths, cable armouring).

When calculating unbalanced short-circuit currents in medium or high-voltage systems and applying an equivalent voltage source at the short-circuit location, the line zero-sequence capacitances and zero-sequence parallel admittances of non-rotating loads are to be considered for isolated neutral systems and resonant earthed systems.

Neglecting the line zero-sequence capacitances in earthed neutral systems leads to results which are higher than the real values of the short-circuit currents. The deviation depends on several parameters of the system, for example the length of the line between transformers with neutral earthing.

In low-voltage systems, line capacitances and parallel admittances of non-rotating loads can be neglected.

Except for special cases, the zero-sequence short-circuit impedances differ from the positive-sequence short-circuit impedances.



a) Transformer of vector group Dy.
b) Transformer of vector group Yz.
c) Neutral-earthing transformer in zig-zag connection.
d) Line (overhead line or cable); JR: joint return.

FIG. 5. – Measuring of zero-sequence short-circuit impedances of electrical equipment (examples).

8.3.2 *Short-circuit impedances of electrical equipment*

In network feeders, transformers, overhead lines, cables, reactors and similar equipment, positive-sequence and negative-sequence short-circuit impedances are equal:

$$\underline{Z}_{(1)} = \underline{U}_{(1)} / \underline{I}_{(1)} = \underline{Z}_{(2)} = \underline{U}_{(2)} / \underline{I}_{(2)}$$

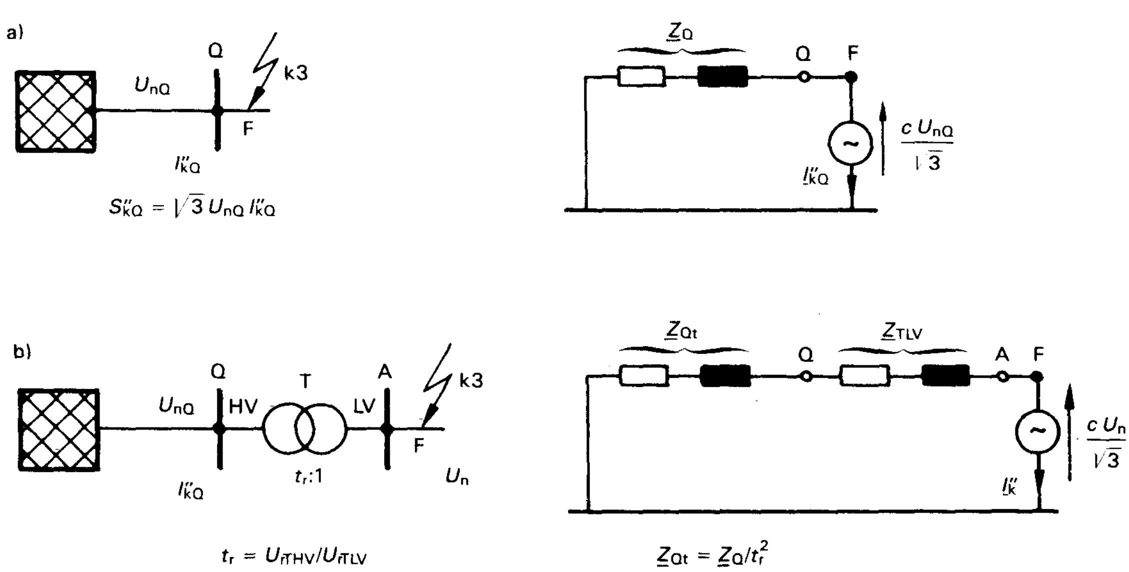
When calculating the zero-sequence short-circuit impedance of a line, for instance (see Figure 5d, page 33), $\underline{Z}_{(0)} = \underline{U}_{(0)} / \underline{I}_{(0)}$ is determined by assuming an a.c. voltage between the three paralleled conductors and the joint return (e.g. earth, earthing device, neutral conductor, earth wire, cable sheath and cable armouring). In this case, the three-fold zero-sequence current flows through the joint return.

Normally the zero-sequence short-circuit impedances differ from the positive-sequence short-circuit impedances: $\underline{Z}_{(0)}$ may be larger than, equal to or smaller than $\underline{Z}_{(1)}$.

8.3.2.1 *Network feeders*

If a short circuit in accordance with Figure 6a, page 35, is fed from a network in which only the initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at the feeder connection point Q is known, then the equivalent impedance Z_Q of the network (positive-sequence short-circuit impedance) at the feeder connection point Q should be determined by:

$$Z_Q = \frac{cU_{nQ}^2}{S''_{kQ}} = \frac{cU_{nQ}}{\sqrt{3}\, I''_{kQ}} \tag{5a}$$



a) Without transformer.

b) With transformer.

FIG. 6. – System diagram and equivalent circuit diagram for network feeders.

If a short circuit in accordance with Figure 6b, page 35, is fed by a transformer from a medium or high-voltage network in which only the initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at the feeder connection point Q is known, then the equivalent impedance Z_{Qt} referred to the low-voltage side of the transformer may be determined by:

$$Z_{Qt} = \frac{cU^2_{nQ}}{S''_{kQ}} \cdot \frac{1}{t^2_r} = \frac{cU_{nQ}}{\sqrt{3}\, I''_{kQ}} \cdot \frac{1}{t^2_r} \tag{5b}$$

where:

U_{nQ} = nominal system voltage at the feeder connection point Q
S''_{kQ} = initial symmetrical short-circuit apparent power at the feeder connection point Q
I''_{kQ} = initial symmetrical short-circuit current at the feeder connection point Q
c = voltage factor (see Sub-clause 3.16, Table I and Equation (2))
t_r = rated transformation ratio at which the tap-changer is in the main position (see also Sub-clause 8.4)

In the case of high-voltage feeders with nominal voltages above 35 kV fed by overhead lines, the equivalent impedance $\underline{Z}_Q$ may be considered as a reactance, i. e. $\underline{Z}_Q = 0 + jX_Q$. In other cases, if no accurate value is known for the resistance R_Q of network feeders, one may substitute $R_Q = 0.1\, X_Q$ where $X_Q = 0.995\, Z_Q$.

The initial symmetrical short-circuit power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} on the high-voltage side of the supply transformers shall be given by the supply company.

In general, the equivalent zero-sequence short-circuit impedance of network feeders is not required for calculations. In special cases, however, it may be necessary to consider this impedance.

8.3.2.2 *Transformers*

The positive-sequence short-circuit impedances of two-winding transformers $\underline{Z}_T = R_T + jX_T$ can be calculated from the rated transformer data as follows:

$$Z_T = \frac{u_{kr}}{100\%} \cdot \frac{U^2_{rT}}{S_{rT}} \tag{6}$$

$$R_T = \frac{u_{Rr}}{100\%} \cdot \frac{U^2_{rT}}{S_{rT}} = \frac{P_{krT}}{3I^2_{rT}} \tag{7}$$

$$X_T = \sqrt{Z^2_T - R^2_T} \tag{8}$$

where:

U_{rT} = rated voltage of the transformer on the high-voltage or low-voltage side
I_{rT} = rated current of the transformer on the high-voltage or low-voltage side
S_{rT} = rated apparent power of the transformer
P_{krT} = total loss of the transformer in the windings at rated current
u_{kr} = rated short-circuit voltage, in per cent
u_{Rr} = rated ohmique voltage, in per cent

The necessary data may be taken from rating plates or obtained from the manufacturer.

The resistive component can be calculated from the total loss in the windings at the rated current.

The ratio X/R generally increases with transformer size. For large transformers the resistance is so small that the impedance may be assumed to consist only of reactance when calculating short-circuit current magnitude. Resistance must be considered if the peak short-circuit current i_p or the decaying aperiodic component i_{DC} is to be calculated.

The zero-sequence short-circuit impedances $\underline{Z}_{(0)T} = R_{(0)T} + jX_{(0)T}$ of transformers with two or more windings may be obtained from the manufacturer.

Note. – It is sufficient for transformers with tap-changers to determine Z_T in accordance with formula (6) for the main position and to convert the impedances, currents and voltages according to Sub-clause 8.4 using the rated transformation ratio t_r corresponding to the tap-changer in the main position.

Special considerations are necessary, only if:

- a single fed short-circuit current is calculated and the short-circuit current has the same direction as the operational current before the short-circuit occurs (short circuit on the low-voltage side of one transformer or parallel transformers with tap changers according to Figure 3, page 25, or Figure 6b, page 35),
- it is possible to change the transformation ratio of a transformer with the tap changer in a wide range, $U_{THV} = U_{rTHV}(1 \pm p_T)$ with $p_T > 0.05$,
- the minimum short-circuit voltage $u_{k\,min}$ is considerably lower than the rated short-circuit voltage in the main position ($u_{k\,min} < u_{kr}$),
- the voltage during operation is considerably higher than the nominal system voltage ($U \geq 1.05\,U_n$).

In the case of three-winding transformers, the positive-sequence short-circuit impedances $\underline{Z}_A$, $\underline{Z}_B$ and $\underline{Z}_C$ referring to Figure 7, page 41, can be calculated by the three short-circuit impedances (related to side A of the transformer):

$$Z_{AB} = \frac{u_{krAB}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTAB}} \quad \text{(side C open)} \tag{9a}$$

$$Z_{AC} = \frac{u_{krAC}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTAC}} \quad \text{(side B open)} \tag{9b}$$

$$Z_{BC} = \frac{u_{krBC}}{100\%} \cdot \frac{U_{rTA}^2}{S_{rTBC}} \quad \text{(side A open)} \tag{9c}$$

with the formulae:

$$\underline{Z}_A = \frac{1}{2}(\underline{Z}_{AB} + \underline{Z}_{AC} - \underline{Z}_{BC}) \tag{10a}$$

$$\underline{Z}_B = \frac{1}{2}(\underline{Z}_{BC} + \underline{Z}_{AB} - \underline{Z}_{AC}) \tag{10b}$$

$$\underline{Z}_C = \frac{1}{2}(\underline{Z}_{AC} + \underline{Z}_{BC} - \underline{Z}_{AB}) \tag{10c}$$

where:

U_{rTA} = rated voltage
S_{rTAB} = rated apparent power between sides A and B
S_{rTAC} = rated apparent power between sides A and C
S_{rTBC} = rated apparent power between sides B and C
u_{krAB} = rated short-circuit voltage, given in percent, between sides A and B
u_{krAC} = rated short-circuit voltage, given in percent, between sides A and C
u_{krBC} = rated short-circuit voltage, given in percent, between sides B and C

8.3.2.3 *Overhead lines and cables*

The positive-sequence short-circuit impedances $\underline{Z}_L = R_L + jX_L$ may be calculated from the conductor data, such as the cross sections and the centre-distances of the conductors.

For measurement of the zero-sequence short-circuit impedances $\underline{Z}_{(0)} = R_{(0)} + jX_{(0)}$, see Sub-clause 8.3.2 and Figure 5d, page 33. Sometimes it is possible to calculate the zero-sequence impedances with the ratios $R_{(0)L}/R_L$ et $X_{(0)L}/X_L$.

The impedances $\underline{Z}_{(1)L}$ and $\underline{Z}_{(0)L}$ of low-voltage and high-voltage cables depend on national techniques and standards and may be taken from text-books or manufacturer's data.

The effective resistance per unit length R'_L of overhead lines at the medium conductor temperature 20 °C may be calculated from the nominal cross section q_n and the resistivity ϱ:

$$R'_L = \frac{\varrho}{q_n} \qquad (11)$$

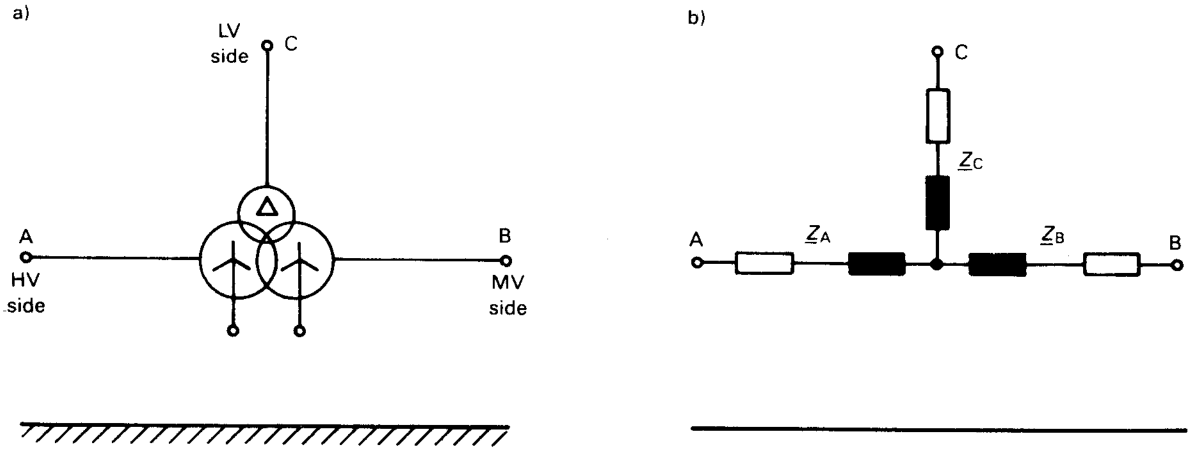
with:

$\varrho = \frac{1}{54} \frac{\Omega\,\mathrm{mm}^2}{\mathrm{m}}$ for copper

$\varrho = \frac{1}{34} \frac{\Omega\,\mathrm{mm}^2}{\mathrm{m}}$ for aluminium

and

$\varrho = \frac{1}{31} \frac{\Omega\,\mathrm{mm}^2}{\mathrm{m}}$ for aluminium alloy



a) Denotation of winding connections.
b) Equivalent circuit diagram (positive-sequence system).

FIG. 7. – Three-winding transformer (example).

The reactance per unit length X'_L for overhead lines may be calculated, assuming transposition, from:

$$X'_L = 2\pi f \frac{\mu_0}{2\pi} \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) = f \mu_0 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \tag{12a}$$

where:

$d = \sqrt[3]{d_{L1\,L2}\, d_{L2\,L3}\, d_{L3\,L1}}$ geometric mean distance between conductors, respectively the centre of bundles

r = radius of a single conductor. In the case of conductor bundles, r is to be substituted by $\sqrt[n]{nrR^{n-1}}$, with the bundle radius R

n = number of bundled conductors; for single conductors $n = 1$

Taking $\mu_0 = 4\pi \cdot 10^{-4}$ H/km as the permeability of a vacuum, equation (12a) may be simplified as follows:

$$\text{for } f = 50\,\text{Hz},\ X'_L = 0.0628 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \Omega/\text{km} \tag{12b}$$

$$\text{for } f = 60\,\text{Hz},\ X'_L = 0.0754 \left(\frac{0.25}{n} + \ln \frac{d}{r} \right) \Omega/\text{km} \tag{12c}$$

8.3.2.4 *Short-circuit current limiting reactors*

The positive-sequence, the negative-sequence and the zero-sequence short-circuit impedances are equal, assuming geometric symmetry. Short-circuit current limiting reactors shall be treated as a part of the short-circuit impedance.

8.3.2.5 *Motors*

Synchronous motors are to be treated as synchronous generators (see Section Two).

Asynchronous motors in low-voltage and medium-voltage systems supply short-circuit currents to the short-circuit location. In the case of three-phase balanced short circuits, the short-circuit currents of asynchronous motors decay rapidly.

It is not necessary to take into account asynchronous motors or groups of asynchronous motors which have a total rated current less than 1% of the initial symmetrical short-circuit current I''_k calculated without the influence of motors. The supplement of short-circuit currents of asynchronous motors to the current I''_k may be neglected if:

$$\Sigma I_{rM} \leq 0.01\, I''_k \tag{13}$$

where:

ΣI_{rM} = sum of the rated currents of motors in the neighbourhood of the short-circuit location (see Section Two, Sub-clause 11.5.3.5)

I''_k = short-circuit current at the short-circuit location without the influence of motors

In other cases see Section Two.

8.4 *Conversion of impedances, currents and voltages*

When calculating short-circuit currents in systems with different voltage levels, it is necessary to convert impedances, currents and voltages from one level to the other (e. g. see Figure 3b, page 25). For per unit or other similar unit systems no conversion is necessary, if these systems are coherent.

The impedances of the equipment in superimposed or subordinated networks are to be divided or multiplied by the square of the rated transformation ratio t_r or in special cases by the square of the transformation ratio t, corresponding to the actual position if it is known.

Voltages and currents are to be converted by the rated transformation ratio t_r or t.

9. Calculation of short-circuit currents

9.1 *Calculation method for balanced short circuits*

9.1.1 *Single fed three-phase short circuit*

9.1.1.1 *Initial symmetrical short-circuit current I''_k*

In accordance with Figure 3, page 25, the three-phase initial symmetrical short-circuit current I''_k becomes:

$$I''_k = \frac{cU_n}{\sqrt{3}\sqrt{R_k^2 + X_k^2}} = \frac{cU_n}{\sqrt{3}\, Z_k} \qquad (14)$$

where:

$cU_n/\sqrt{3}$ = equivalent voltage source (see Clause 6)

$R_k = R_{Qt} + R_T + R_L$ = sum of series-connected resistances in accordance with Figure 3b, page 25, R_L is the line resistance for a conductor temperature of 20 °C (see Sub-clause 8.3.2)

$X_k = X_{Qt} + X_T + X_L$ = sum of series-connected reactances in accordance with Figure 3b (see Sub-clause 8.3.2)

$Z_k = \sqrt{R_k^2 + X_k^2}$ = short-circuit impedance (see Sub-clause 8.3.1)

Resistances of the order of $R_k < 0.3 X_k$ may be neglected. The impedance of the system feeder $\underline{Z}_{Qt} = R_{Qt} + jX_{Qt}$, referred to the voltage of that transformer side where the short circuit occurs, is to be calculated according to equations (5a) and (5b) and additional information in Sub-clause 8.3.2.1.

The scope of Section One supports the following equation:

$$I_k = I_b = I''_k \qquad (15)$$

9.1.1.2 *Peak short-circuit current i_p*

Because the short circuit is fed by a series circuit, the peak short-circuit current can be expressed by:

$$i_p = \varkappa \sqrt{2}\, I''_k \qquad (16)$$

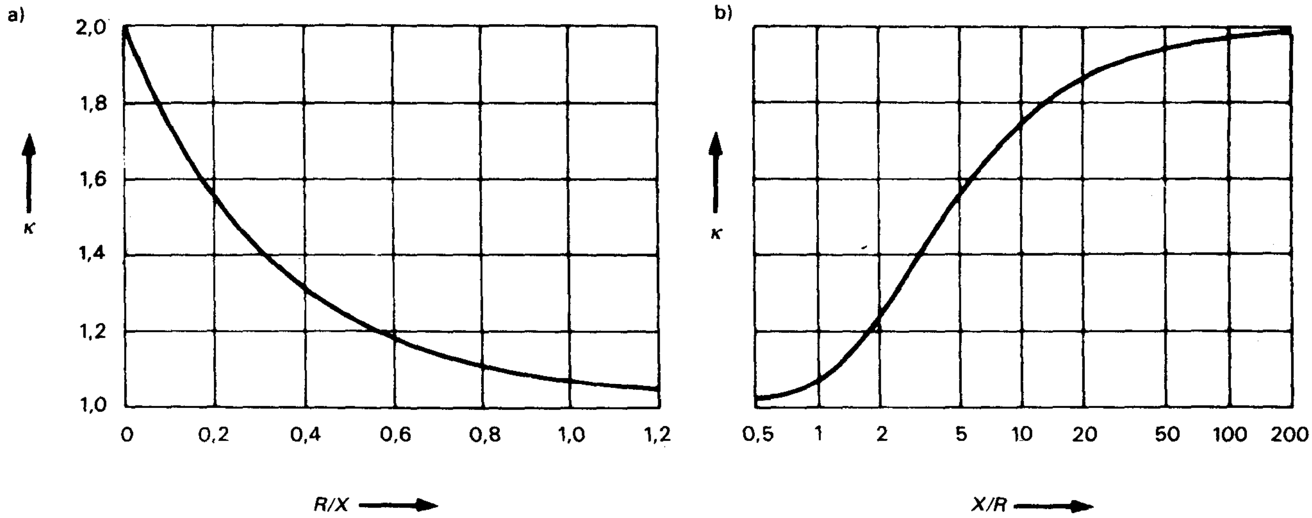


FIG. 8. – Factor $\varkappa$ for series circuits as a function of:
a) ratio R/X; b) ratio X/R.

The factor $\varkappa$ for the ratios R/X and X/R is taken from Figure 8.

The factor $\varkappa$ may also be calculated by the approximate equation:

$$\varkappa \approx 1.02 + 0.98\, e^{-3R/X}$$

9.1.2 *Three-phase short circuit fed from non-meshed sources*

9.1.2.1 *Initial symmetrical short-circuit current I''_k*

The initial symmetrical short-circuit current I''_k, the symmetrical breaking current I_b and the steady-state short-circuit current I_k at the short-circuit location F, fed from sources which are not meshed with one another in accordance with Figure 9, page 49, may be composed of the various separate branch short-circuit currents which are independent of each other:

$$I''_k = I''_{kT1} + I''_{kT2} \quad (17)$$

$$I_k = I_b = I''_k \quad (18)$$

The branch short-circuit currents are to be calculated like a single-fed three-phase short-circuit current in accordance with Sub-clause 9.1.1.

Note. – The short-circuit current at the short-circuit location F is the phasor sum of the branch short-circuit currents. In most cases the phase angles of the branch short-circuit currents are nearly the same. The short-circuit current at F is then equal to the algebraic sum of the branch short-circuit currents.

Impedances between the short-circuit location F and the busbar B, where the branch short-circuit currents flow together as shown in Figure 9, may be neglected if they are smaller than $0.05\, U_n/(\sqrt{3}\; I''_{kB})$, where I''_{kB} is the initial symmetrical short-circuit current on the busbar determined by equation (17) with a three-phase busbar short circuit. In all other cases, calculations are made in accordance with Sub-clause 9.1.3.

9.1.2.2 *Peak short-circuit current* i_p

The peak short-circuit current i_p at the short-circuit location F, fed from sources which are not meshed with one another in accordance with Figure 9, may be composed of the branch short-circuit currents i_{pT1} and i_{pT2}:

$$i_p = i_{pT1} + i_{pT2} \tag{19}$$

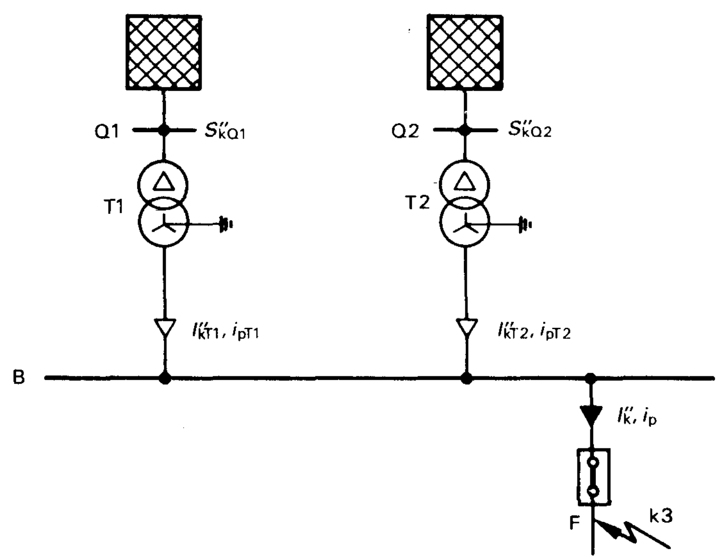


FIG. 9. – System diagram illustrating a short circuit fed from several sources which are independent of one another. (In some cases the impedance between busbar B and the short-circuit location F may be neglected.)

9.1.3 *Three-phase short circuits in meshed networks*

9.1.3.1 *Initial symmetrical short-circuit current* I''_k

In accordance with the example shown in Figure 10, page 51, the equivalent voltage source $cU_n/\sqrt{3}$ is established at the short-circuit location as the only active voltage in the network.

The calculation is to be carried out in accordance with Sub-clause 8.3.1, especially with Figure 4a, page 27 (positive-sequence short-circuit impedance at the short-circuit location F). It is generally necessary to ascertain the short-circuit impedance $\underline{Z}_k = \underline{Z}_{(1)}$, by network transformation (e. g. series connection, parallel connection and deltastar transformation) considering the positive-sequence short-circuit impedances of electrical equipment (see Sub-clause 8.3.2).

All impedances are referred to the low-voltage side of the transformers (see Figure 10). The network feeder is treated in accordance with Sub-clause 8.3.2.1.

$$I''_k = \frac{cU_n}{\sqrt{3}\,Z_k} = \frac{cU_n}{\sqrt{3}\,\sqrt{R_k^2 + X_k^2}} \tag{20}$$

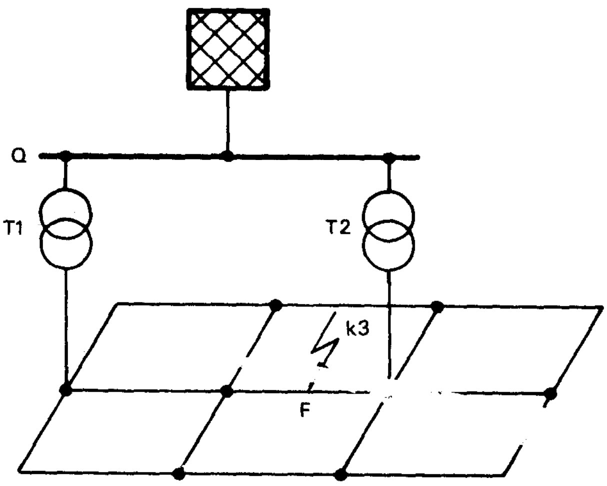
where:

$cU_n/\sqrt{3}$ = equivalent voltage source (see Clause 6)

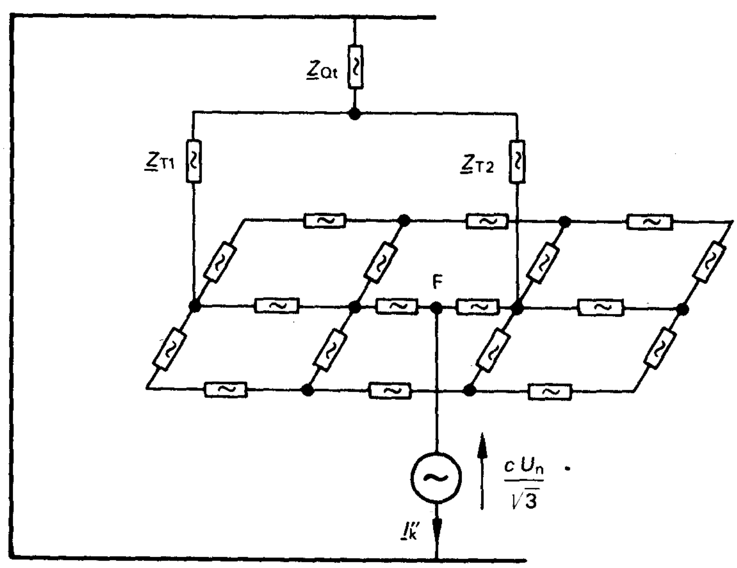
Z_k = short-circuit impedance, according to Sub-clause 8.3.1 and Figure 4a, page 27

For the calculation of I_b and I_k, see Equation (15).

a)



b)



a) System diagram.

b) Equivalent circuit diagram with the equivalent voltage source in accordance with Clause 6.
$\underline{Z}_{Qt}$, $\underline{Z}_{T1}$, $\underline{Z}_{T2}$ = impedances referred to the low-voltage side of the transformers.

FIG. 10. – Illustration of the calculation of the initial symmetrical short-circuit current $\underline{I}''_k$ in a meshed network. The short-circuit current at the short-circuit location F is supplied by the feeder connection point Q through transformers T1 and T2.

9.1.3.2 *Peak short-circuit current* i_p

For the calculation of the peak short-circuit current i_p in meshed networks Equation (16) is used and one of the following approximations A, B, or C is chosen to find a suitable value for $\varkappa$. If high accuracy is not needed, the Method A is sufficient.

Method A – Uniform ratio R/X or X/R: use $\varkappa = \varkappa_a$.

The factor $\varkappa_a$ is determined from Figure 8, page 47, taking the smallest ratio of R/X or the largest ratio X/R of all branches of the network.

It is only necessary to choose the branches which together carry 80% of the current at the nominal voltage corresponding to the short-circuit location. Any branch may be a series combination of several elements.

In low-voltage networks the value $\varkappa_a$ is limited to 1.8.

Method B – Ratio R/X or X/R at the short-circuit location:

The factor $\varkappa$ is given by:

$$\varkappa = 1.15\,\varkappa_b \qquad (21)$$

where 1.15 is a safety factor to cover inaccuracies caused by using the ratio R/X from a meshed network reduction with complex impedances.

The factor $\varkappa_b$ is found from Figure 8 for the ratio R/X given by the short-circuit impedance $\underline{Z}_k = R_k + jX_k$ at the short-circuit location F, calculated with the frequency $f = 50$ Hz or $f = 60$ Hz.

In low-voltage networks the product $1.15\varkappa_b$ is limited to 1.8 and in high-voltage networks to 2.0.

Method C – Equivalent frequency f_c: use $\varkappa = \varkappa_c$.

The factor $\varkappa_c$ is found from Figure 8 for the ratio:

$$\frac{R}{X} = \frac{R_c}{X_c} \cdot \frac{f_c}{f} \qquad (22a)$$

$$\frac{X}{R} = \frac{X_c}{R_c} \cdot \frac{f}{f_c} \qquad (22b)$$

where:

$\underline{Z}_c = R_c + jX_c$

$R_c = \mathrm{Re}\,\{\underline{Z}_c\} \neq R$ at power frequency
Equivalent effective resistance for the equivalent frequency f_c as seen from the short-circuit location

$X_c = \mathrm{Im}\,\{\underline{Z}_c\} \neq X$ at power frequency
Equivalent effective reactance for the equivalent frequency f_c as seen from the short-circuit location

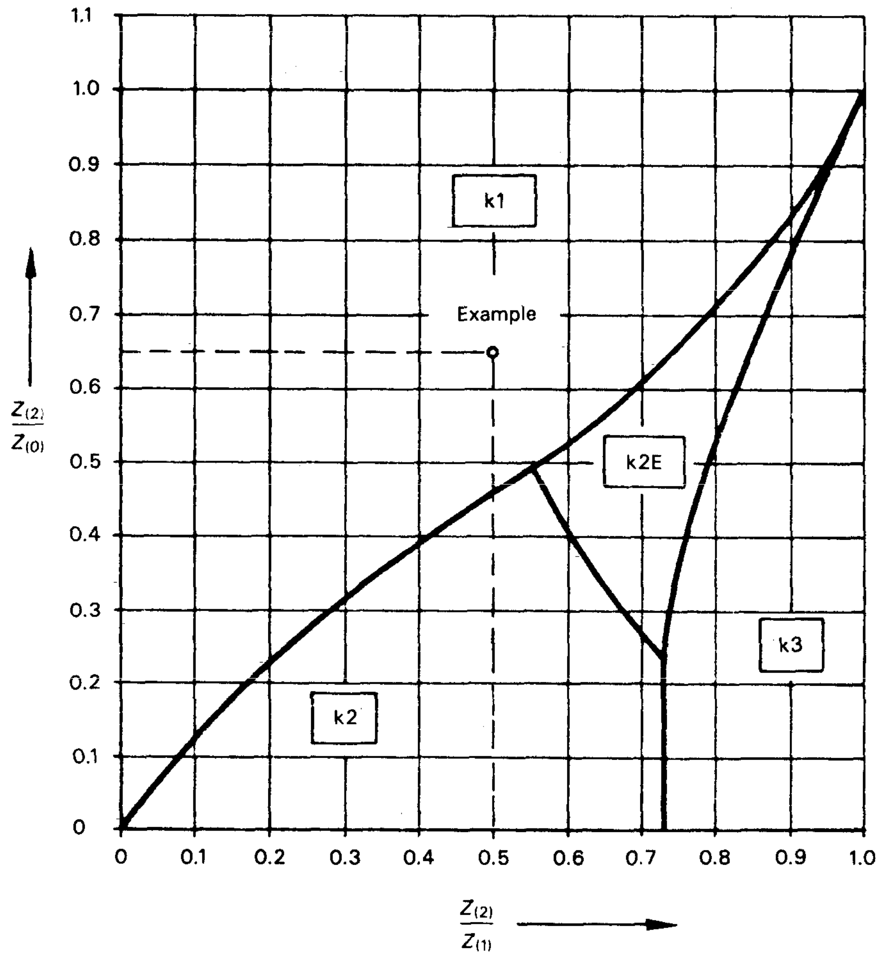
The equivalent impedance $\underline{Z}_c = R_c + j2\pi f_c L_c$ is the impedance as seen from the short-circuit location if an equivalent voltage source with the frequency $f_c = 20$ Hz (for a nominal frequency 50 Hz) or 24 Hz (for a nominal frequency 60 Hz) is applied there as the only active voltage.

9.2 *Calculation method for line-to-line and line-to-earth short circuits*

The types of short circuit considered are given in Figures 2b to 2d, page 23.

Figure 11, page 55, shows which type of short circuit leads to the highest short-circuit currents if the a.c. component decays, i. e. if $Z_{(2)}/Z_{(1)} < 1$ (see Section Two).

In Section One $Z_{(2)}/Z_{(1)} = 1$ is valid.



It is anticipated that the differences between R/X-ratios for positive-sequence and zero-sequence systems are small.

Example:

$Z_{(2)}/Z_{(1)} = 0.5$
$Z_{(2)}/Z_{(0)} = 0.65$ } The single phase circuit ($k1$) will give the highest short-circuit current.

FIG. 11. – Chart indicating the type of short-circuit giving the highest current.

9.2.1 *Line-to-line short circuit without earth connection*

9.2.1.1 *Initial short-circuit current I''_{k2}*

Independent of system configuration, the initial short-circuit current of a line-to-line short circuit without earth connection (see Figure 2b, page 23) is calculated by:

$$I''_{k2} = \frac{cU_n}{|\underline{Z}_{(1)} + \underline{Z}_{(2)}|} = \frac{cU_n}{2|\underline{Z}_{(1)}|} \quad \text{with } \underline{Z}_{(1)} = \underline{Z}_{(2)} \tag{23}$$

$\underline{Z}_{(1)} = \underline{Z}_k$ is the positive-sequence short-circuit impedance at the short-circuit location F (see Figure 4a, page 27).

The ratio I''_{k2} to I''_k according to Equations (20) and (23) is:

$$\frac{I''_{k2}}{I''_k} = \frac{\sqrt{3}}{2} \tag{24}$$

In the case of a far-from-generator short circuit, the steady-state short-circuit current I_{k2} and the short-circuit breaking current I_{b2} are equal to the initial short-circuit current I''_{k2}:

$$I_{k2} = I_{b2} = I''_{k2} \tag{25}$$

9.2.1.2 *Peak short-circuit current i_{p2}*

The peak short-circuit current can be expressed by:

$$i_{p2} = \varkappa \sqrt{2}\, I''_{k2} \tag{26}$$

The factor $\varkappa$ is calculated according to Sub-clause 9.1.1.2 or 9.1.3.2 depending on the system configuration. The same value as used in the case of a three-phase short circuit may be taken.

9.2.2 *Line-to-line short circuit with earth connection*

9.2.2.1 *Initial short-circuit currents I''_{k2E} and I''_{kE2E}*

According to Figure 2c, page 23, one has to distinguish between the currents I''_{k2E} and I''_{kE2E}.

To calculate the value of I''_{k2E}, the following formulae are given:

$$I''_{k2E\ L2} = cU_n \frac{|1 + \underline{a}^2 + \underline{Z}_{(0)}/\underline{Z}_{(1)}|}{|\underline{Z}_{(1)} + 2\,\underline{Z}_{(0)}|} \tag{27a}$$

$$I''_{k2E\ L3} = cU_n \frac{|1 + \underline{a} + \underline{Z}_{(0)}/\underline{Z}_{(1)}|}{|\underline{Z}_{(1)} + 2\,\underline{Z}_{(0)}|} \tag{27b}$$

with $\underline{Z}_{(1)} = \underline{Z}_{(2)}$.

$\underline{a}$ and $\underline{a}^2$ are given in Sub-clause 8.2, Equation (4).

The initial short-circuit current I''_{kE2E}, flowing to earth and/or grounded wires according to Figure 2c, page 23, is calculated by:

$$I''_{kE2E} = \frac{\sqrt{3}\, cU_n}{|\underline{Z}_{(1)} + 2\,\underline{Z}_{(0)}|} \tag{28}$$

9.2.2.2 *Peak short-circuit current i_{p2E}*

It is not necessary to calculate i_{p2E} because either:

$$i_{p3} \geqslant i_{p2E} \text{ or } i_{p1} \geqslant i_{p2E}.$$

9.2.3 *Line-to-earth short circuit*

9.2.3.1 *Initial short-circuit current I''_{k1}*

The initial short-circuit current of a line-to-earth short circuit according to Figure 2d, page 23, is calculated by:

$$I''_{k1} = \frac{\sqrt{3}\, cU_n}{|\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)}|} = \frac{\sqrt{3}\, cU_n}{|2\,\underline{Z}_{(1)} + \underline{Z}_{(0)}|} \tag{29}$$

In the case of a far-from-generator short circuit, the steady-state short-circuit current I_{k1} and the breaking current I_{b1} are equal to the initial short-circuit current I''_{k1} (see also Equations (15) and (25)):

$$I_{k1} = I_{b1} = I''_{k1} \tag{30}$$

9.2.3.2 *Peak short-circuit current* i_{p1}

The peak short-circuit current can be expressed by:

$$i_{p1} = \varkappa \sqrt{2}\, I''_{k1} \tag{31}$$

The factor $\varkappa$ is calculated according to Sub-clauses 9.1.1.2 or 9.1.3.2 depending on the system configuration. For simplification, the same value as used in the case of a three-phase short circuit may be taken.

9.3. *The minimum short-circuit currents*

9.3.1 *General*

When calculating minimum short-circuit currents, it is necessary to introduce the following conditions:

- voltage factor c for the calculation of minimum short-circuit current according to Table I;
- choose the system configuration and, in some cases, the minimum contribution from sources and network feeders, which lead to a minimum value of short-circuit current at the short-circuit location;
- motors are to be neglected;
- resistances R_L of lines (overhead lines and cables, phase conductors and neutral conductors) are to be introduced at a higher temperature:

$$R_L = [1 + \frac{0.004}{°C}\,(\theta_e - 20\,°C)] \cdot R_{L20} \tag{32}$$

where R_{L20} is the resistance at a temperature of 20 °C and θ_e in °C the conductor temperature at the end of the short circuit. The factor 0.004/°C is valid for copper, aluminium and aluminium alloy.

9.3.2 *Initial symmetrical short-circuit current* I''_k

When calculating three-phase short-circuit currents according to Sub-clause 9.1, the minimum initial short-circuit current is given by:

$$I''_{k\,min} = \frac{cU_n}{\sqrt{3}\, Z_k} \tag{33}$$

$\underline{Z}_k = \underline{Z}_{(1)}$ is the short-circuit impedance under the conditions of Sub-clause 9.3.1.

The value of the voltage factor c depends on many influences, for example operational voltage of cables or overhead lines, location of short circuit. If there are no national standards, the values of Table I may be used.

When calculating unbalanced short circuits according to Sub-clause 9.2, the equivalent voltage source $cU_n/\sqrt{3}$ and impedances $\underline{Z}_{(1)}$ and $\underline{Z}_{(0)}$ under the conditions of Sub-clause 9.3.1 are chosen.

SECTION TWO – SYSTEMS WITH SHORT-CIRCUIT CURRENTS HAVING DECAYING A.C. COMPONENTS (NEAR-TO-GENERATOR SHORT CIRCUITS)

10. General

This section gives procedures for calculations in systems with short-circuit currents having decaying a.c. components. The influence of motors is also taken into account.

Procedures for the calculation of short-circuit currents of synchronous and asynchronous motors are given if their contribution is higher than 5% of the initial symmetrical short-circuit current I''_k without motors (see Sub-clause 13.2.1).

11. Short-circuit parameters

11.1 *General*

In the calculation of the short-circuit currents in systems supplied by generators, power-station units and motors (near-to-generator short circuits), it is of interest not only to know the initial symmetrical short-circuit current I''_k and the peak short-circuit current i_p, but also the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k.

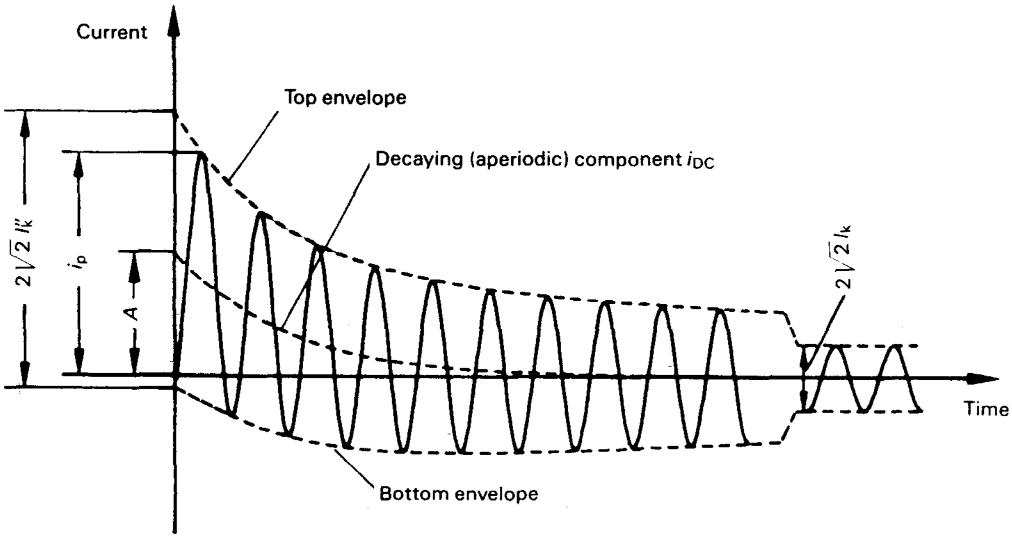
In general the symmetrical short-circuit breaking current I_b is smaller than the initial symmetrical short-circuit current I''_k. Normally the steady-state short-circuit current I_k is smaller than the symmetrical short-circuit breaking current I_b.

Frequently, especially when dealing with the mechanical effects of short-circuit currents, it will be necessary to determine the asymmetrical short-circuit breaking current from the a.c. breaking current and the superimposed d.c. breaking current. The decaying aperiodic component i_{DC} can be calculated according to Clause 5.

In the case of a near-to-generator short circuit the prospective short-circuit current can be considered as the sum of the following two components:

- the a.c. component with decaying amplitude during the short circuit,
- the aperiodic component beginning with an initial value A and decaying to zero.

In a near-to-generator short circuit, the short-circuit current behaves generally as shown in Figure 12, page 63. In some special cases it could happen that the decaying short-circuit current reaches zero for the first time, some periods after the short circuit took place. This is possible if the d.c. time constant of a synchronous machine is larger than the subtransient time constant. This phenomenon is not dealt with in detail by short-circuit currents calculated in this standard.



I_k'' = initial symmetrical short-circuit current
i_p = peak short-circuit current
I_k = steady-state short-circuit current
i_{DC} = decaying (aperiodic) component of short-circuit current
A = initial value of the aperiodic component i_{DC}

FIG. 12. – Short-circuit current of a near-to-generator short circuit (schematic diagram).

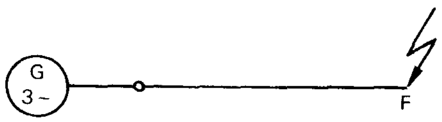
Short-circuit currents may have one or more sources as shown in Figure 13, page 65. The figure also specifies which clause of this section describes the short-circuit current calculation. The main sub-clauses for the calculation of the three-phase short-circuit currents are:

- 12.2.1: for the case shown in Item 1) of Figure 13a } single fed three-phase short-circuit,
- 12.2.2: for the case shown in Item 2) of Figure 13a } single fed three-phase short-circuit,
- 12.2.3: for the cases shown in Figures 13b, 13c respectively, if the given inequality is fulfilled (three-phase short-circuit fed from non-meshed sources),
- 12.2.4: for the general case shown in Figure 13d (three-phase short circuit in meshed networks).

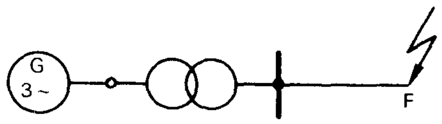
a) Single fed short circuit.

Calculation according to Sub-clauses 12.2.1, 12.2.2, 12.3 and 12.4.

1. Short circuit fed from one generator (without transformer).

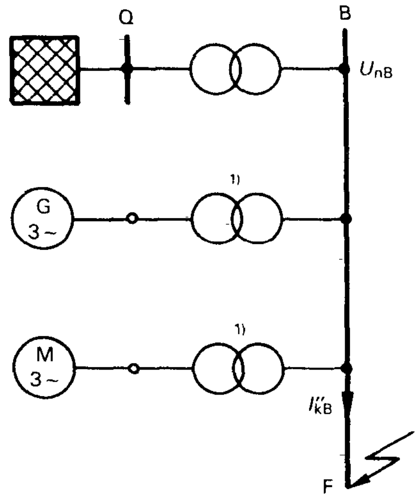


2. Short circuit fed from one power-station unit (generator and unit transformer).



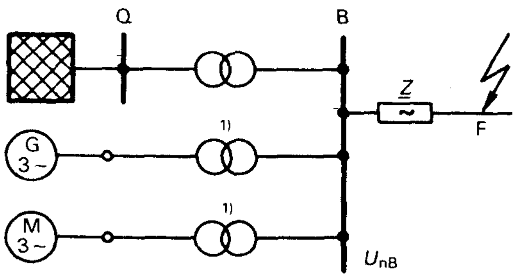
b) Short circuit fed from non-meshed sources.

Calculation according to Sub-clauses 12.2.3, 12.3 and 12.4.



c) Short circuit fed from several sources with the common impedance $\underline{Z}$.

Calculation according to Sub-clauses 12.2.3, 12.2.4, 12.3 and 12.4.



$\underline{Z}$ can be neglected if

$$Z < 0.05 \frac{U_{nB}}{\sqrt{3}\, I''_{kB}}$$

I''_{kB} is calculated according to Figure 13b

d) Short circuit in meshed networks.

Calculation according to Sub-clauses 12.2.4, 12.3 and 12.4.

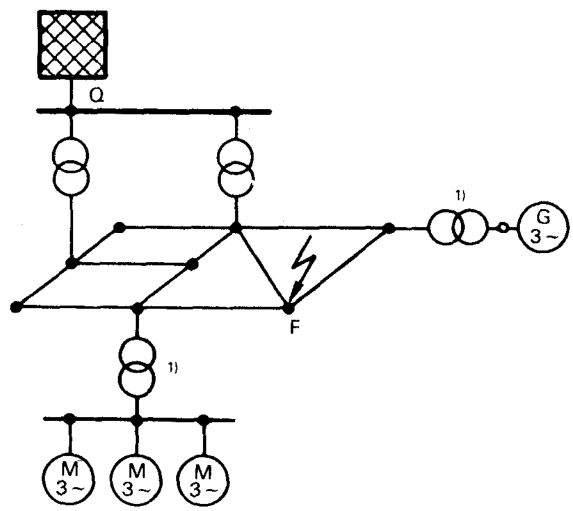


FIG. 13. – Various short-circuit source connections.

11.2 *Balanced short circuit*

The details of Sub-clause 8.1 are valid.

11.3 *Unbalanced short circuit*

The details of Sub-clause 8.2 are valid.

---

[1] Generators and motors can also be connected without transformers.

11.4 *Equivalent voltage source at the short-circuit location*

It is possible in all cases to determine the short-circuit current at the short-circuit location F by means of an equivalent voltage source $cU_n / \sqrt{3}$, if correction factors are introduced for the impedances of generators and for the impedances of generators and transformers of power-station units (see Sub-clauses 11.5.3.6, 11.5.3.7, 11.5.3.8 and Clause 12). Details for the equivalent voltage source $cU_n / \sqrt{3}$ are given in Clause 6 and Table I.

In this method the equivalent voltage source $cU_n / \sqrt{3}$ at the short-circuit location is the only active voltage of the system. The internal voltages of all synchronous and asynchronous machines are set to zero. Therefore the synchronous machines are only effective with their subtransient impedances and the asynchronous motors are only effective with their impedances calculated from their locked-rotor currents.

Furthermore in this method all line capacitances and parallel admittances of non-rotating loads except those of the zero-sequence system shall be neglected (see Figure 15, page 77, and Figure 20, page 87).

Details for consideration of motors are given in Clause 13.

11.5 *Short-circuit impedances*

In addition to Sub-clause 8.3.2, impedances of generators and motors are introduced. Additional calculations are given for power-station units in Sub-clauses 11.5.3.7 and 11.5.3.8. The short-circuit impedances of network feeders, network transformers, overhead lines and cables as well as short-circuit limiting reactors are valid.

11.5.1 *Short-circuit impedances at the short-circuit location F*

For the calculation of the initial symmetrical short-circuit current in a near-to-generator short circuit Sub-clause 8.3.1 and Figure 4, page 27, are valid.

11.5.2 *Short-circuit impedances of electrical equipment*

The general considerations made in Sub-clause 8.3.2 are valid. Motors and generators are dealt with in Sub-clauses 11.5.3.5 to 11.5.3.8.

11.5.3 *Calculation of short-circuit impedances of electrical equipment*

11.5.3.1 *Network feeders*

The details given in Sub-clause 8.3.2.1 are valid, except for the special case given in Sub-clause 12.2.3.1.

11.5.3.2 *Transformers*

The details given in Sub-clause 8.3.2.2 are valid. Unit transformers of power-station units are excluded and dealt with in Sub-clauses 11.5.3.7 and 11.5.3.8.

11.5.3.3 *Overhead lines and cables*

Details given in Sub-clause 8.3.2.3 are valid.

11.5.3.4 *Short-circuit current limiting reactors*

Details given in Sub-clause 8.3.2.4 are valid.

11.5.3.5 *Motors*

When calculating three-phase initial symmetrical short-circuit currents I''_k, synchronous motors and synchronous compensators are treated as synchronous generators (see Sub-clauses 11.5.3.6, 11.5.3.7, 11.5.3.8 and 13.1).

The impedance $\underline{Z}_M = R_M + jX_M$ of asynchronous motors in the positive- and negative-sequence system can be determined by:

$$Z_M = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3}\, I_{rM}} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} \tag{34}$$

where:

U_{rM} = rated voltage of the motor
I_{rM} = rated current of the motor
S_{rM} = rated apparent power of the motor $S_{rM} = P_{rM}/(\eta_r \cos \varphi_r)$
I_{LR}/I_{rM} = ratio of the locked-rotor current (Sub-clause 3.11) to the rated current of the motor

The following may be used with sufficient accuracy:

$R_M/X_M = 0.10$, with $X_M = 0.995\, Z_M$ for high-voltage motors with powers P_{rM} per pair of poles $\geq$ 1 MW,
$R_M/X_M = 0.15$, with $X_M = 0.989\, Z_M$ for high-voltage motors with powers P_{rM} per pair of poles < 1 MW,
$R_M/X_M = 0.42$, with $X_M = 0.922\, Z_M$ for low-voltage motor groups with connection cables.

Details for consideration or omission of asynchronous motors or groups of asynchronous motors for calculation of short-circuit currents are given in Sub-clause 13.2.1.

Static converter fed drives are treated for the calculation of short-circuit currents in a similar way as asynchronous motors. The following applies for static converter fed drives:

Z_M = as in Equation (34)
U_{rM} = rated voltage of the static converter transformer on the network side or rated voltage of the static converter, if no transformer is present
I_{rM} = rated current of the static converter transformer on the network side or rated current of the static converter, if no transformer is present
I_{LR}/I_{rM} = 3
R_M/X_M = 0.10 with $X_M = 0.995\, Z_M$

11.5.3.6 *Generators directly connected to systems*

When calculating three-phase initial symmetrical short-circuit currents in systems fed directly from generators without unit transformers, for example in industrial networks or in low-voltage networks, the following impedance has to be used in the positive-sequence system:

$$\underline{Z}_{GK} = K_G \underline{Z}_G = K_G\,(R_G + jX''_d) \tag{35}$$

with the correction factor:

$$K_G = \frac{U_n}{U_{rG}} \cdot \frac{c_{max}}{1 + x''_d \sin \varphi_{rG}} \tag{36}$$

where:

c_{max} = voltage factor according to Table I

U_n = nominal voltage of the system

U_{rG} = rated voltage of the generator

$\underline{Z}_{GK}$ = corrected impedance of the generator

$\underline{Z}_G$ = impedance of the generator ($\underline{Z}_G = R_G + jX''_d$)

x''_d = subtransient reactance of the generator referred to rated impedance ($x''_d = X''_d / Z_{rG}$)

φ_{rG} = phase angle between $\underline{I}_{rG}$ and $\underline{U}_{rG}/\sqrt{3}$

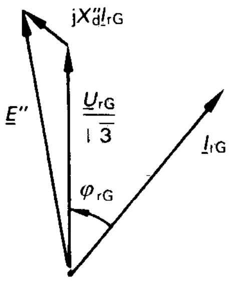


FIG. 14. – Phasor diagram of a synchronous generator at rated conditions.

Using the equivalent voltage source $cU_n/\sqrt{3}$ according to Sub-clause 12.2.1.1 instead of the subtransient voltage E'' of the synchronous generator (see Figure 14), the correction factor K_G (Equation (36)) for the calculation of the corrected impedance $\underline{Z}_{GK}$ (Equation (35)) of the generator has to be introduced.

The following values of sufficient accuracy may be used:

$R_G = 0.05\ X''_d$ for generators with $U_{rG} > 1$ kV and $S_{rG} \geq 100$ MVA

$R_G = 0.07\ X''_d$ for generators with $U_{rG} > 1$ kV and $S_{rG} < 100$ MVA

$R_G = 0.15\ X''_d$ for generators with $U_{rG} \leq 1000$ V

In addition to the decay of the d.c. component, the factors 0.05, 0.07 and 0.15, also take account of the decay of the a.c. component of the short-circuit current during the first half-period after the short circuit took place. The influence of various winding-temperatures on R_G is not considered.

Note. – The effective resistance of the stator of synchronous machines lies generally much below the given values for R_G.

For the impedances of synchronous generators in the negative-sequence system and the zero-sequence system the following applies:

$$\underline{Z}_{(2)G} = \underline{Z}_{GK} = K_G \underline{Z}_G \tag{37}$$

For salient-pole synchronous machines with differing values of X''_d and X''_q, $X_{(2)G} = \frac{1}{2}(X''_d + X''_q)$.

$$\underline{Z}_{(0)G} = K_G\ (R_{(0)G} + jX_{(0)G}) \tag{38}$$

For the calculation of short-circuit currents for line-to-line and line-to-earth short circuits (Sub-clause 12.3) the correction factor according to Equation (36) shall be taken into account.

11.5.3.7 *Generators and unit transformers of power-station units*

In this case correction factors for the impedances of generators and transformers of power-station units have to be introduced:

$$\underline{Z}_{G,\,PSU} = K_{G,\,PSU}\,\underline{Z}_G \tag{39}$$

with the correction factor:

$$K_{G,\,PSU} = \frac{c_{max}}{1 + x''_d \sin \varphi_{rG}} \tag{40}$$

$$\underline{Z}_{T,\,PSU} = K_{T,\,PSU}\,\underline{Z}_{TLV} \tag{41}$$

with the correction factor:

$$K_{T,\,PSU} = c_{max} \tag{42}$$

where:

$\underline{Z}_{G,\,PSU}$; $\underline{Z}_{T,\,PSU}$ = corrected impedances of generators (G) and unit transformers (T) of power-station units
$\underline{Z}_G$ = impedance of the generator $\underline{Z}_G = R_G + jX''_d$ (see Sub-clause 11.5.3.6)
$\underline{Z}_{TLV}$ = impedance of the unit transformer related to the low-voltage side (see Sub-clause 8.3.2.2)
x''_d, φ_{rG} = (see Sub-clause 11.5.3.6)

If necessary the impedances $\underline{Z}_{G,\,PSU}$ and $\underline{Z}_{T,\,PSU}$ are converted by the fictitious transformation ratio t_f to the high-voltage side (see Sub-clause 12.2.2).

For the calculation of short-circuit currents at short circuits between generator and unit transformer of a power-station unit the equivalent voltage source $cU_{rG}/\sqrt{3}$ at the short-circuit location is to be introduced. In this case the rated voltage of the generator is chosen, because the nominal system voltage cannot be determined. These cases are dealt with in Sub-clause 12.2.3.1.

Notes 1. – Equations (40) and (42) are valid if $U_Q = U_{nQ}$ and $U_G = U_{rG}$. Special considerations are recommended if for a power-station unit having a transformer with a tap changer the operational voltage U_{Qmin} is permanently higher than U_{nQ} ($U_{Qmin} > U_{nQ}$), and/or U_G differs from U_{rG} ($U_G > U_{rG}$) or for a power-station unit having a transformer without a tap changer the voltage U_G of the generator is permanently higher than U_{rG} ($U_G > U_{rG}$).

2. – Values for correction factors for negative-sequence impedances and zero-sequence impedances at unbalanced short circuits are under consideration.

11.5.3.8 *Power-station units*

For the calculation of short-circuit currents of power-station units for short circuits on the high-voltage side it is not necessary to deal with the correction factors according to Sub-clause 11.5.3.7. In this case the following formula for the correction of the impedance of the whole power-station unit (PSU) is used:

$$\underline{Z}_{PSU} = K_{PSU}\,(t_r^2\,\underline{Z}_G + \underline{Z}_{THV}) \tag{43}$$

with the correction factor:

$$K_{PSU} = \left(\frac{t_f}{t_r}\right)^2 \cdot \frac{c_{max}}{1 + (x''_d - x_T)\sin\varphi_{rG}} = \frac{U^2_{nQ}}{U^2_{rG}} \cdot \frac{U^2_{rTLV}}{U^2_{rTHV}} \cdot \frac{c_{max}}{1 + (x''_d - x_T)\sin\varphi_{rG}} \tag{44}$$

where:

$\underline{Z}_{PSU}$ = corrected impedance of power-station unit related to the high-voltage side
$\underline{Z}_{G}$ = impedance of the generator $\underline{Z}_G = R_G + jX''_d$ (see Sub-clause 11.5.3.6)
$\underline{Z}_{THV}$ = impedance of the unit transformer related to the high-voltage side (see Sub-clause 8.3.2.2)
U_{nQ} = nominal system voltage at the connection point Q of the power-station unit
t_r = rated transformation ratio at which the tap-changer is in the main position
t_f = fictitious transformation ratio $t_f = U_n / U_{rG} = U_{nQ} / U_{rG}$
x''_d, φ_{rG} = (see Sub-clause 11.5.3.6)
x_T = reactance of the unit transformer related to U^2_{rT}/S_{rT}, $x_T = X_T / (U^2_{rT}/S_{rT})$

Notes 1. – Equation (44) is valid if $U_Q = U_{nQ}$ and $U_G = U_{rG}$. Special considerations are recommended if for a power-station unit having a transformer with a tap changer the operational voltage U_{Qmin} is permanently higher than U_{nQ} ($U_{Qmin} > U_{nQ}$), and/or U_G differs from U_{rG} ($U_G > U_{rG}$) or for a power-station unit having a transformer without a tap changer the voltage U_G of the generator is permanently higher than U_{rG} ($U_G > U_{rG}$).

2. – Values for correction factors for negative-sequence impedances and zero-sequence impedances at unbalanced short circuits are under consideration.

11.6 *Conversion of impedances, currents and voltages*

The details given in Sub-clause 8.4 remain valid. Exceptions in the Sub-clauses 12.2.2.1 and 12.2.3.1 are to be regarded.

12. Calculation of short-circuit currents

12.1 *General*

For the calculation of the initial symmetrical short-circuit current I''_k, the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k at the short-circuit location, the system may be converted by transformations into an equivalent short-circuit impedance $\underline{Z}_k$. This procedure is not allowed when calculating the peak short-circuit current i_p. In this case it is necessary to distinguish between systems with and without parallel branches (see Sub-clauses 9.1.1.2. 9.1.2.2 and 9.1.3.2).

12.2 *Calculation method for balanced short circuits*

12.2.1 *Short circuit fed from one generator*

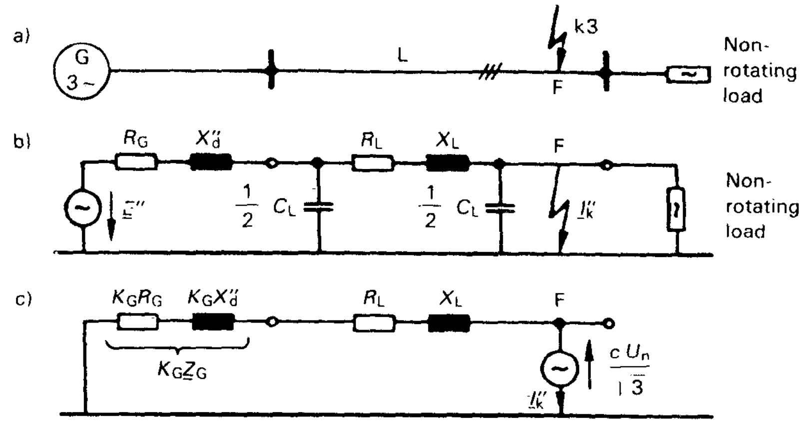
12.2.1.1 *Initial symmetrical short-circuit current I''_k*

The initial symmetrical short-circuit current for the examples of item 1) of Figure 13a, page 65, and of Figure 15, page 77, is calculated with the equivalent source voltage $cU_n/\sqrt{3}$ at the short-circuit location and the short-circuit impedance $\underline{Z}_k = R_k + jX_k$:

$$I''_k = \frac{cU_n}{\sqrt{3}\, Z_k} = \frac{cU_n}{\sqrt{3}\,\sqrt{R^2_k + X^2_k}} \tag{45}$$

For calculation of the maximum short-circuit current, the value of the voltage factor c is chosen according to Table I.

Note. = Normally it can be presumed that the rated voltage U_{rG} of the generator is 5% higher than the nominal system voltage U_n.



a) System diagram.

b) Equivalent circuit (positive-sequence system) with the subtransient voltage E'' of the generator.

c) Equivalent circuit for the calculation with the equivalent voltage source (see Clause 6 and Sub-clause 11.4) and the impedances according to Sub-clause 11.5.3 and especially to Sub-clause 11.5.3.6.

FIG. 15. – Example for the calculation of the initial symmetrical short-circuit current $\underline{I}''_k$ for a short circuit fed directly from one generator.

12.2.1.2 *Peak short-circuit current i_p*

The calculation of the peak short-circuit current is done as shown in Sub-clause 9.1.1.2. For the generator the corrected resistance $K_G R_G$ and the corrected reactance $K_G X''_d$ is used.

12.2.1.3 *Symmetrical short-circuit breaking current I_b*

The decay to the symmetrical short-circuit breaking current is taken account of with the factor μ.

$$I_b = \mu\, I''_k \tag{46}$$

where μ is dependent on the minimum time delay t_{min} (see Sub-clause 3.23) and the ratio I''_k / I_{rG}.

The values of μ of the following equations apply to the case where medium voltage turbine generators, salient-pole generators and synchronous compensators are excited by rotating exciters or by static converter exciters (provided that for static exciters the minimum time delay is less than 0.25 s and the maximum excitation-voltage is less than 1.6 times the rated load excitation-voltage). For all other cases μ is taken to be $\mu = 1$ if the exact value is unknown.

$$\begin{aligned}
\mu &= 0.84 + 0.26\, e^{-0.26\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.02 \text{ s} \\
\mu &= 0.71 + 0.51\, e^{-0.30\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.05 \text{ s} \\
\mu &= 0.62 + 0.72\, e^{-0.32\, I''_{kG}/I_{rG}} \text{ for } t_{min} = 0.10 \text{ s} \\
\mu &= 0.56 + 0.94\, e^{-0.38\, I''_{kG}/I_{rG}} \text{ for } t_{min} \geq 0.25 \text{ s}
\end{aligned} \tag{47}$$

The values I''_{kG} (partial short-circuit current at the terminals of the generator) and I_{rG} are related to the same voltage. In the case of asynchronous motors, replace I''_{kG} / I_{rG} by I''_{kM} / I_{rM} (see Table II).

If $I''_{kG} / I_{rG} \leq 2$, apply $\mu = 1$ at every minimum time delay t_{min}.

The factor μ may also be obtained from Figure 16 taking the abscissa for three-phase short circuit. For other values of minimum time delay, linear interpolation between curves is acceptable.

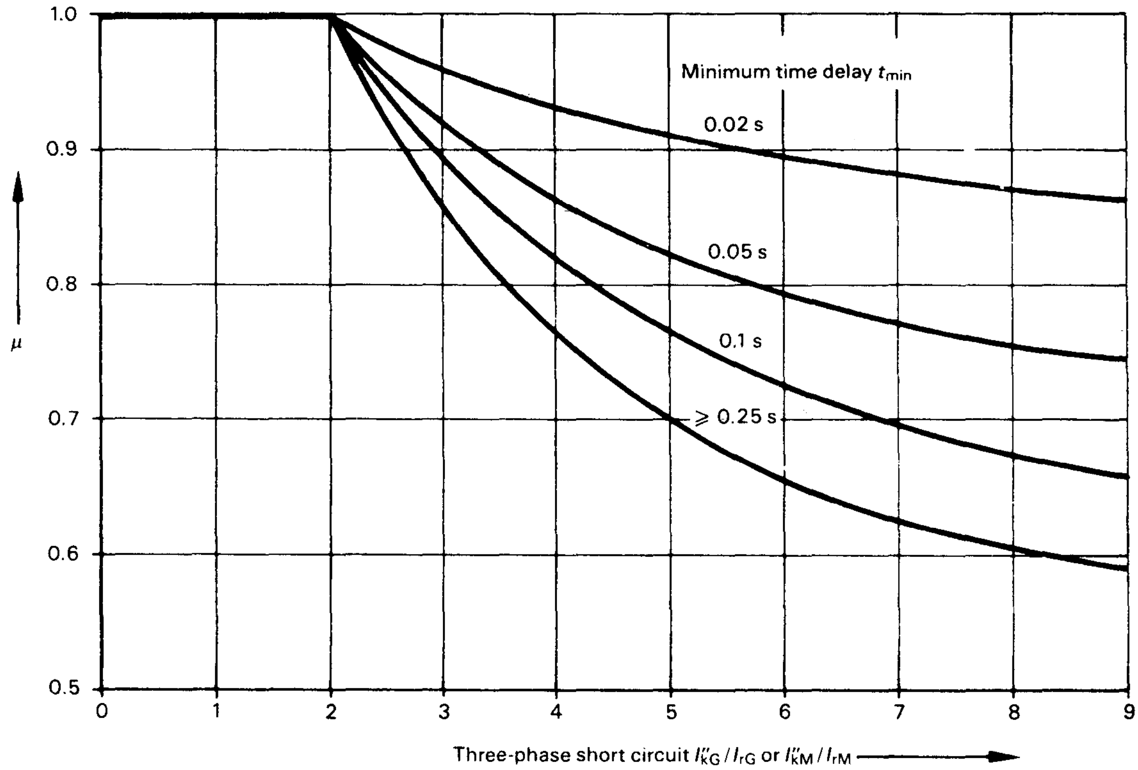


FIG. 16. – Factor μ for the calculation of short-circuit breaking curr :nt I_b.

Figure 16 can also be used for compound excited low-voltage generators with a minimum time delay $t_{min} \leq 0.1$ s. The calculation of low-voltage breaking currents after a time delay $t_{min} >$ 0.1 s is not included in these procedures; generator manufacturers may be able to provide information.

12.2.1.4 *Steady-state short-circuit current* I_k

Because the magnitude of the steady-state short-circuit I_k depends upon saturation influences and switching-condition changes in the system its calculation is less accurate than that of the initial symmetrical short-circuit current I''_k. The methods of calculation given here can be regarded as a sufficient estimate for the upper and lower limits, in the case when the short circuit is fed by one generator or one synchronous machine respectively.

a) Maximum steady-state short-circuit current $I_{k\,max}$

The following may be set at the highest excitation of the synchronous generator for the maximum steady-state short-circuit current:

$$I_{k\,max} = \lambda_{max} \cdot I_{rG} \tag{48}$$

λ_{max} may be obtained from Figures 17 or 18 for turbine generators or salient-pole machines. $x_{d\,sat}$ (sat = saturated) is the reciprocal of the short-circuit ratio.

λ_{max}-curves of Series One are based on the highest possible excitation-voltage according to either 1.3 times the rated excitation at rated load and power factor for turbine generators (see Figure 17a) or 1.6 times the rated excitation for salient-pole machines (see Figure 18a).

λ_{max}-curves of Series Two are based on the highest possible excitation-voltage according to either 1.6 times the rated excitation at rated load and power factor for turbine generators (see Figure 17b) or 2.0 times the rated excitation for salient-pole machines (see Figure 18b).

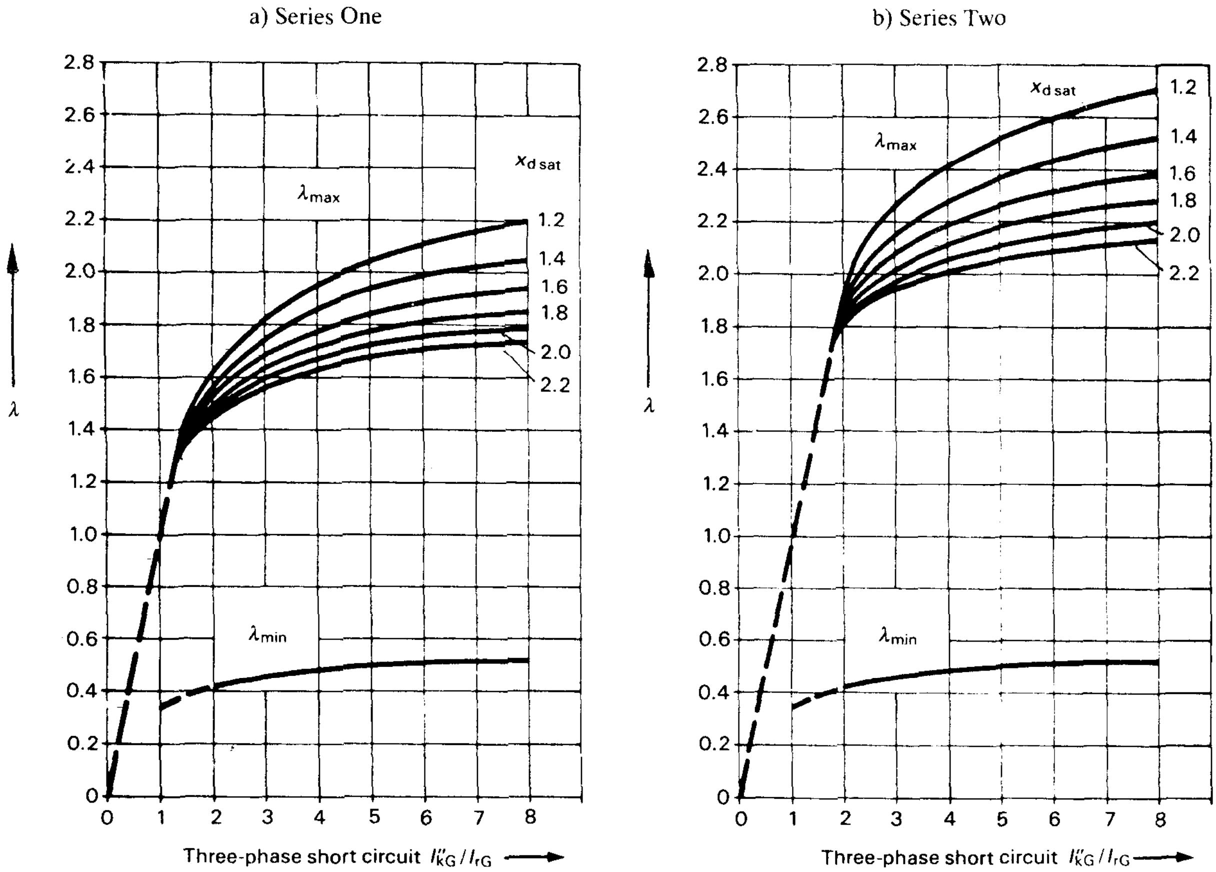


FIG. 17. – Factors λ_{max} and λ_{min} for turbine generators. (Definitions of Series One and Series Two are given in the text.)

b) Minimum steady-state short-circuit current $I_{k\,min}$

For the minimum steady-state short-circuit current, constant no-load excitation of the synchronous machine is assumed.

$$I_{k\,min} = \lambda_{min}\, I_{rG} \tag{49}$$

λ_{min} may be obtained from Figure 17 or 18 for turbine generators or salient-pole machines.

Note. – For bus fed static exciters without current forcing the minimum steady-state short-circuit current for a three-phase bus short circuit is zero.

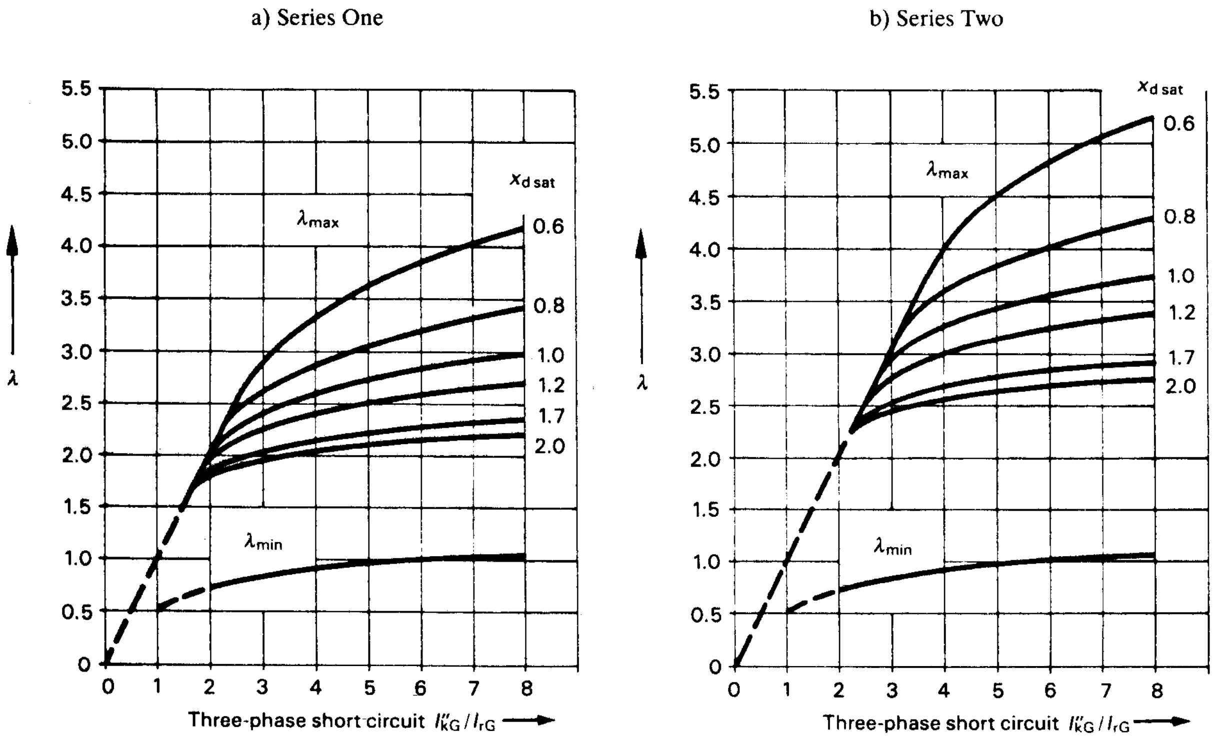
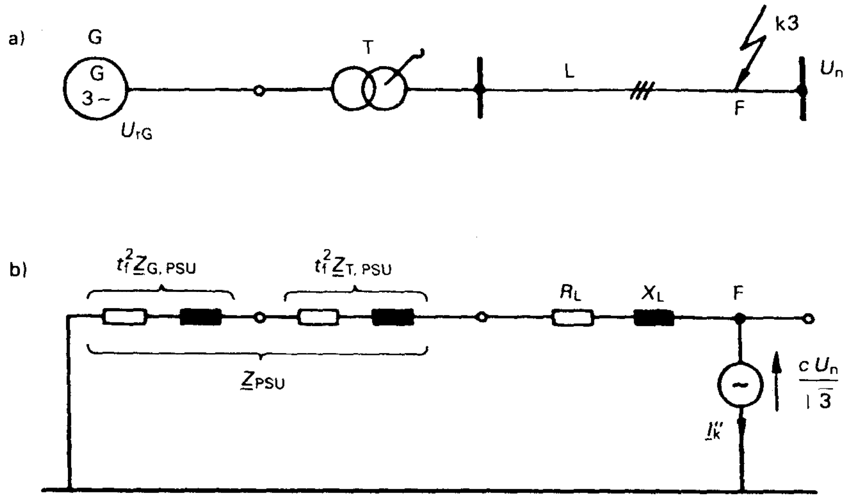


FIG. 18. – Factors λ_{max} and λ_{min} for salient-pole machines. (Definitions of Series One and Two are given in the text.)

12.2.2 *Short circuit fed from one power-station unit*

12.2.2.1 *Initial symmetrical short-circuit current* I''_k

For the examples in Item 2) of Figure 13a, page 65, and in Figure 19 the initial symmetrical short-circuit current is calculated with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location and the corrected impedances of the generator and the transformer of the power-station unit (Sub-clauses 11.5.3.7 or 11.5.3.8) in series with a line impedance $\underline{Z}_L = R_L + jX_L$ according to Sub-clause 8.3.2.3.



a) System diagram.

b) Equivalent circuit diagram of the positive-sequence system for the calculation with the equivalent voltage source at the short-circuit location and the corrected impedances of the generator and the transformer of the power-station unit.

FIG. 19. – Example of the calculation of the initial symmetrical short-circuit current I_k'' fed from one power-station unit.

For the calculation of the initial symmetrical short-circuit current Equation (45) should be used.

The short-circuit impedance for the example in Figure 19 is given by the following in accordance with Sub-clause 11.5.3.7:

$$\underline{Z}_k = R_k + jX_k = t_f^2 \underline{Z}_{G,PSU} + t_f^2 \underline{Z}_{T,PSU} + \underline{Z}_L \quad (50)$$

$\underline{Z}_{G,PSU}$ is taken from Equation (39) and $\underline{Z}_{T,PSU}$ from Equation (41). Both impedances are to be transformed to the high-voltage side with the fictitious transformation ratio $t_f = U_n / U_{rG}$.

Following Sub-clause 11.5.3.8 the short-circuit impedance for the example in Figure 19 is given by:

$$\underline{Z}_k = R_k + jX_k = \underline{Z}_{PSU} + \underline{Z}_L \quad (51)$$

$\underline{Z}_{PSU}$ is taken from Equation (43).

12.2.2.2 *Peak short-circuit current i_p*

The calculation is done as shown in Sub-clause 9.1.1.2. For power-station units the corrected resistances and the corrected reactances according to Sub-clause 11.5.3.7 and 11.5.3.8 are used.

12.2.2.3 *Symmetrical short-circuit breaking current I_b*

The calculation of the symmetrical short-circuit breaking current is done as shown in Sub-clause 12.2.1.3 with μ according to Equation (47) or Figure 16, page 79. Insert the transformed value $I_{kPSUt}'' = t_r I_{kPSU}''$ in place of I_{kG}''.

12.2.2.4 *Steady-state short-circuit current* I_k

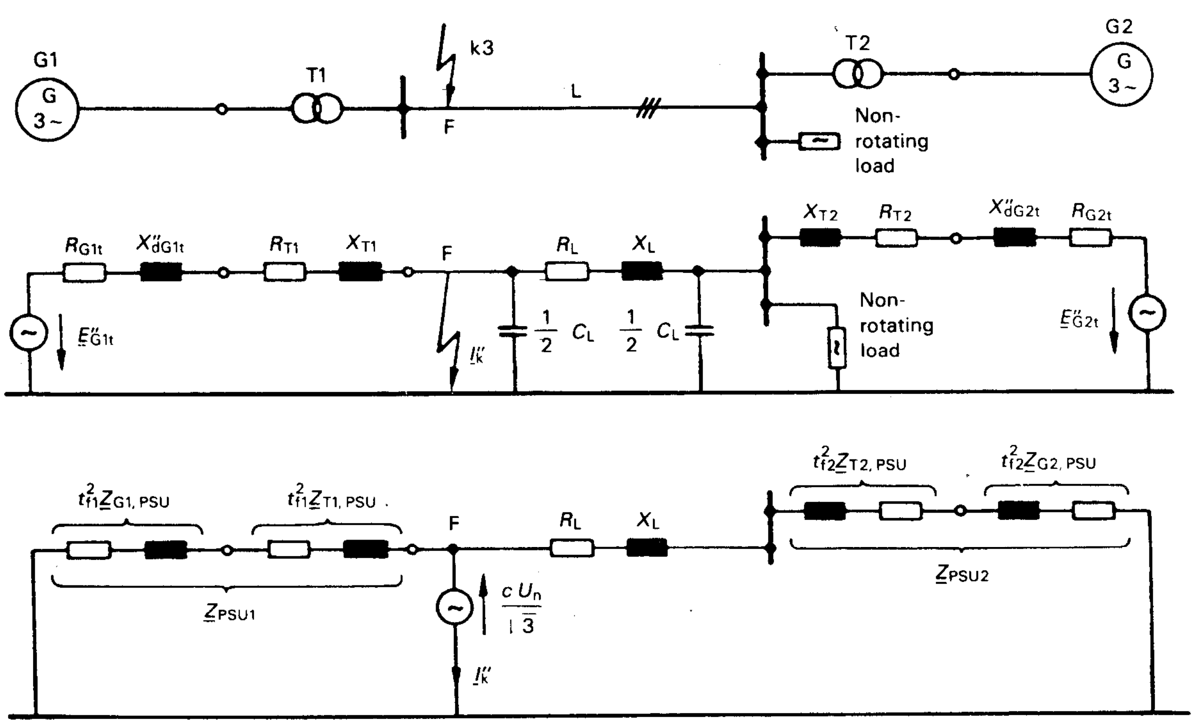
The calculation can be done as shown in Sub-clause 12.2.1.4, if the short circuit is fed by one power-station unit. Insert the transformed value $I''_{kPSUt} = t_r I''_{kPSU}$ in place of I''_{kG}.

12.2.3 *Three-phase short circuit fed from non-meshed sources*

12.2.3.1 *General*

In addition to short circuits fed from non-meshed sources (see Figure 13b, page 65), all short circuits directly fed through a common impedance $\underline{Z}$, can be calculated by the procedure given in this sub-clause, if $Z < 0.05\ U_{nB} / (\sqrt{3}\ I''_{kB})$ holds (see Figure 13c, page 65).

In general the equivalent voltage source $cU_n/\sqrt{3}$ is introduced (see Figure 20c) at the short-circuit location. U_n is the nominal voltage of the system in which the short circuit occurs. Generators, feeding the short circuit directly (without transformers) are to be treated as given in Sub-clause 11.5.3.6, power-station units according to Sub-clauses 11.5.3.7 or 11.5.3.8 and 12.2.2 and asynchronous motors as shown in Sub-clause 11.5.3.5, taking into account Clause 13.



a) System diagram.

b) Equivalent circuit diagram of the positive-sequence system with the subtransient voltages E''.

c) Equivalent circuit diagram of the positive-sequence system for the calculation with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location.

FIG. 20. – Example of the calculation of the initial symmetrical short-circuit current $\underline{I}''_k$ fed from non-meshed sources.

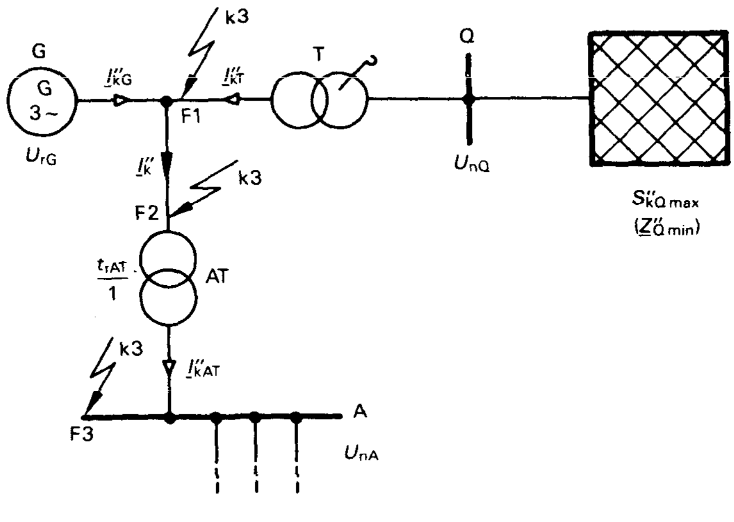


FIG. 21. – Short-circuit currents and partial short-circuit currents for three-phase short circuits between generator and transformer of a power-station unit and at the auxiliary busbar A (see also Sub-clause 12.2.4.1).

For calculating the partial short-circuit currents I''_{kG} and I''_{kT} at a short circuit in F1 in Figure 21, the initial symmetrical short-circuit currents are given by:

$$I''_{kG} = \frac{cU_{rG}}{\sqrt{3}\,|\underline{Z}_{G,\,PSU}|} = \frac{cU_{rG}}{\sqrt{3}\,K_{G,\,PSU}\,|\underline{Z}_{G}|} \tag{52}$$

$$I''_{kT} = \frac{cU_{rG}}{\sqrt{3}\left|\underline{Z}_{T,\,PSU} + \frac{1}{t_f^2}\,\underline{Z}_{Q\,min}\right|} \tag{53}$$

where:

$\underline{Z}_{G,\,PSU}$ = according to Sub-clause 11.5.3.7, Equation (39)

$\underline{Z}_{T,\,PSU}$ = according to Sub-clause 11.5.3.7, Equation (41)

$t_f = U_{nQ}/U_{rG}$ = fictitious transformation ratio, Sub-clause 11.6

$\underline{Z}_{Q\,min}$ = minimum value of the impedance of the network feeder, corresponding to $S''_{kQ\,max}$

For $S''_{kQ\,max}$ the maximum possible value expected during the life time of the power station is to be introduced.

For the calculation of the short-circuit current I''_k at the short-circuit location F2, for example at the connection to the high-voltage side of the auxiliary transformer AT in Figure 21, it is sufficient to take:

$$I''_k = c\,\frac{U_{rG}}{\sqrt{3}}\left|\frac{1}{\underline{Z}_{G,\,PSU}} + \frac{1}{\underline{Z}_{T,\,PSU} + \frac{1}{t_f^2}\,\underline{Z}_{Q\,min}}\right| = c\,\frac{U_{rG}}{\sqrt{3}}\,\frac{1}{|\underline{Z}_{rsl}|} \tag{54}$$

The short-circuit current I''_{kAT} at the short-circuit location F3 has to be treated according to Sub-clause 12.2.4.1.

12.2.3.2 *Initial symmetrical short-circuit current I''_k*

The initial symmetrical short-circuit current at the short-circuit location F can be calculated from the sum of the partial short-circuit currents as shown in Figure 22. Motors are taken into account by the application of Clause 13.

$$\underline{I}''_k = \underline{I}''_{k\,PSU} + \underline{I}''_{kT} + \underline{I}''_{kM} + \ldots \tag{55}$$

A simpler result, to be on the safe side, is gained by using the algebraic sum of values instead of the geometric sum.

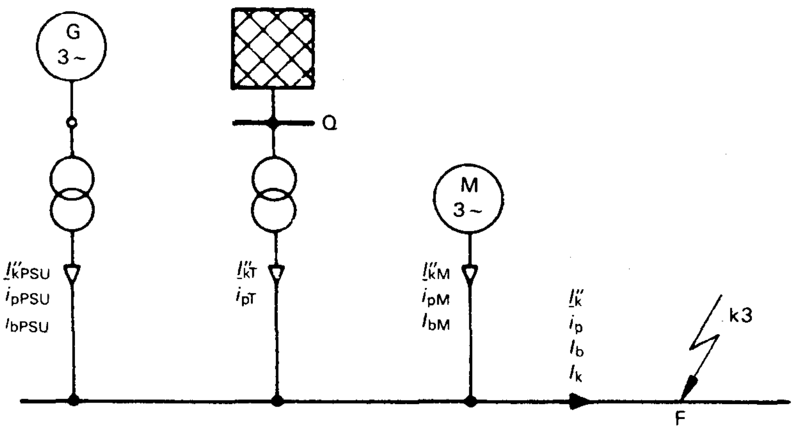


FIG. 22. – Explanation of the calculation of $\underline{I}''_k$, i_p, I_b and I_k for a three-phase short circuit fed from non-meshed sources according to equations (55) to (58).

12.2.3.3 *Peak short-circuit current i_p, symmetrical short-circuit breaking current I_b and steady-state short-circuit current I_k*

If the three-phase short circuit is fed from several non-meshed sources according to Figure 22 the components of the peak short-circuit current i_p and the symmetrical short-circuit breaking current I_b at the short-circuit location F are added:

$$i_p = i_{pPSU} + i_{pT} + i_{pM} + \ldots \tag{56}$$

$$I_b = I_{bPSU} + I''_{kT} + I_{bM} + \ldots \tag{57}$$

$$I_k = I_{bPSU} + I''_{kT} + \ldots \tag{58}$$

The simple formulae (57) and (58) give results which are on the safe side.

The partial short-circuit currents should be calculated as follows:

- network feeders according to Sub-clause 8.3.2.1,
- generators *without* transformers between the generator and the short-circuit location as in Sub-clause 12.2.1,
- power-station units as in Sub-clause 12.2.2, taking into account Sub-clauses 11.5.3.7 and 11.5.3.8,
- motors as in Sub-clause 11.5.3.5 and Clause 13.

This directive does not apply to the steady-state short-circuit current I_k. It is assumed that generators fall out of step and produce a steady-state short-circuit current $I_{kG} \approx I_{bG}$ or $I_{kPSU} \approx I_{bPSU}$. For network feeders $I_k = I_b = I''_k$ is valid. There is no motor supplement to the three-phase steady-state short-circuit current (see Table II).

12.2.4 *Three-phase short circuit in meshed networks*

12.2.4.1 *Initial symmetrical short-circuit current* I''_k

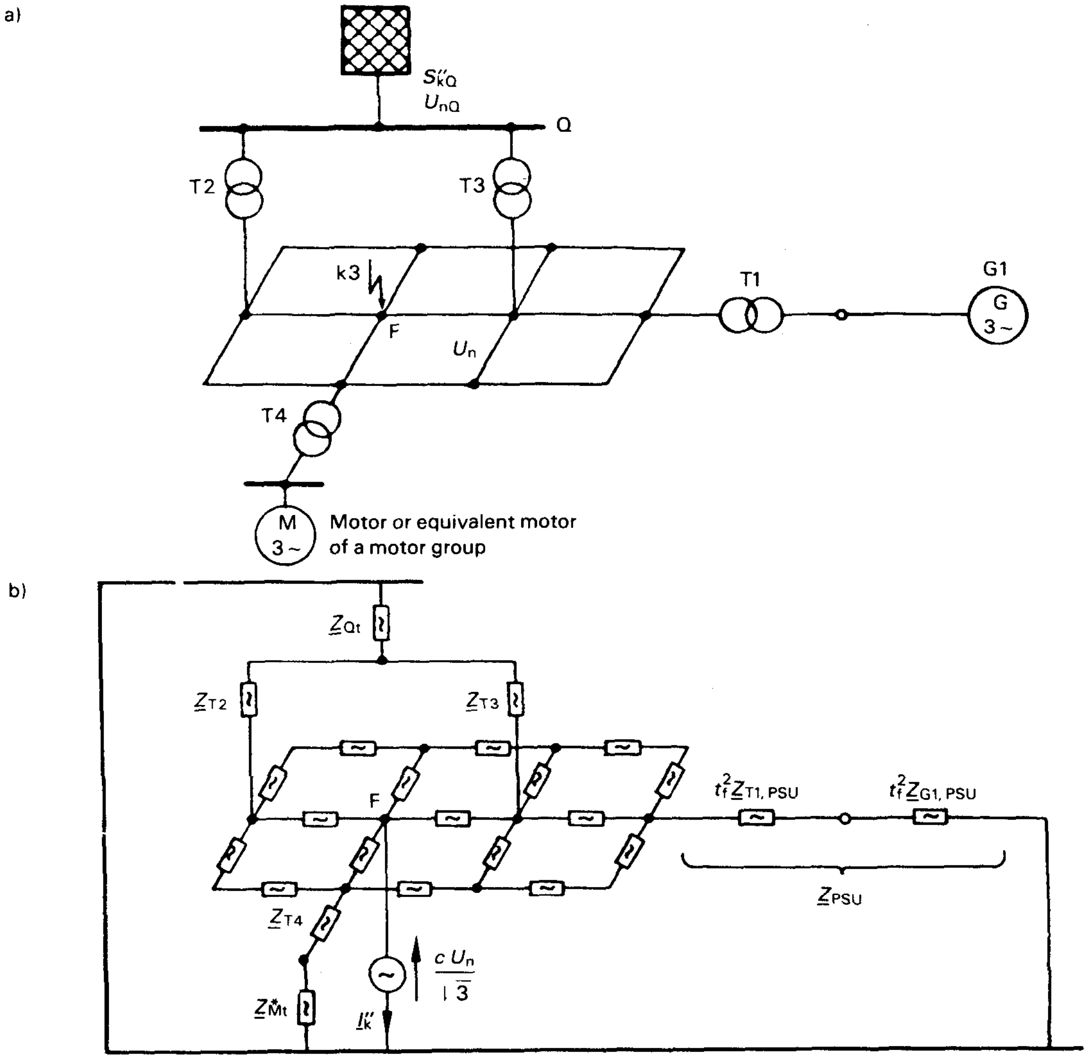
The initial symmetrical short-circuit current is calculated with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location. Equation (45) is used. The impedances of electrical equipment are calculated according to Sub-clause 11.5.3 (see also Sub-clause 12.2.2). For the calculation of the partial short-circuit current I''_{kAT} in Figure 21, page 89 (short-circuit location F3), it is permitted to take $\underline{Z}_{rsl}$ from Equation (54) and to transform this impedance by t^2_{rAT}.

The impedances in systems connected beyond transformers to the system in which the short circuit occurs have to be transformed by the square of the rated transformation ratio. If there are several transformers with slightly differing rated transformation ratios t_{r1}, t_{r2}, ... t_{rn}, between two systems, the arithmetic mean value can be used.

Figures 13d, page 65, and 23 show examples for meshed networks with several sources.

12.2.4.2 *Peak short-circuit current* i_p

The calculation can be done as given in Sub-clause 9.1.3.2.



a) System diagram.

b) Equivalent circuit diagram for the calculation with the equivalent voltage source $cU_n/\sqrt{3}$ at the short-circuit location.

* Impedance of a motor or an equivalent motor of a motor group.

FIG. 23. – Example of the calculation of the initial symmetrical short-circuit current $\underline{I}''_k$ in a meshed network fed from several sources.

12.2.4.3 *Symmetrical short-circuit breaking current* I_b

The following may be set for the short-circuit breaking current in meshed networks:

$$I_b = I''_k \tag{59}$$

Currents calculated with Equation (59) are larger than the real symmetrical short-circuit breaking currents.

Note. – A more accurate calculation can be done with the following equations:

$$\underline{I}_b = \underline{I}''_k - \sum_i \frac{\Delta \underline{U}''_{Gi}}{\frac{cU_n}{\sqrt{3}}} (1 - \mu_i) \underline{I}''_{kGi} - \sum_j \frac{\Delta \underline{U}''_{Mj}}{\frac{cU_n}{\sqrt{3}}} (1 - \mu_j q_j) \underline{I}''_{kMj} \tag{60}$$

$$\Delta \underline{U}''_{Gi} = j\, X''_{di}\, \underline{I}''_{kGi} \tag{61}$$

$$\Delta \underline{U}''_{Mj} = j\, X_{Mj}\, \underline{I}''_{kMj} \tag{62}$$

where:

$\frac{cU_n}{\sqrt{3}}$ = equivalent voltage source at the short-circuit location

$\underline{I}''_k$, $\underline{I}_b$ = initial symmetrical short-circuit current, symmetrical short-circuit breaking current with influence of all network feeders, synchronous machines and asynchronous motors

$\Delta \underline{U}''_{Gi}$, $\Delta \underline{U}''_{Mj}$ = initial voltage difference at the connection points of the synchronous machine i and the asynchronous motor j

$\underline{I}''_{kGi}$, $\underline{I}''_{kMj}$ = parts of the initial symmetrical short-circuit current of the synchronous machine i and the asynchronous motor j

μ = (see Sub-clause 12.2.1.3 and Figure 16, page 79) with I''_{kGi}/I_{rGi} or I''_{kMj}/I_{rMj} respectively

q = (see Sub-clause 13.2.1 and Figure 25, page 103)

The values of Equations (61) and (62) are related to the same voltage.

12.2.4.4 *Steady-state short-circuit current I_k*

The steady-state short-circuit current I_k may be calculated by:

$$I_k = I''_{k\not{M}} \tag{63}$$

$I''_{k\not{M}}$ is the initial symmetrical short-circuit current calculated without motors.

12.3 *Calculation method for line-to-line and line-to-earth short circuits*

The details given in Sub-clause 9.2 remain valid.

12.4 *The minimum short-circuit currents*

12.4.1 *General*

The details given in Sub-clause 9.3 remain valid. In addition, consider Sub-clauses 12.4.2 to 12.4.4. Careful reflection is necessary for the impedance correction factors in the equations (36), (40), (42) and (44), especially in the case of underexcited operation.

12.4.2 *Initial symmetrical short-circuit current I''_k*

12.4.2.1 *Short-circuit fed from one generator*

If a short circuit is fed from one generator as shown in Figure 15, page 77, apply Sub-clause 12.2.1 and introduce a voltage factor c_{min} according to Table I for the calculation of the minimum short-circuit current.

This procedure is also applied for short circuits, which are fed by several similar generators, operated at one point in parallel.

12.4.2.2 *Short circuit in meshed networks*

For the calculation use Sub-clause 12.2.4 and a voltage factor c_{min} according to Table I.

12.4.3 *Steady-state short-circuit current $I_{k\,min}$ fed from generators with compound excitation*

The calculation for the minimum steady-state short-circuit current in a near-to-generator short circuit, fed by one or several similar and parallel working generators with compound excitation, is done as follows:

$$I_{k\,min} = \frac{c_{min} / U_n}{\sqrt{3}\ \sqrt{R_k^2 + X_k^2}} \qquad (64)$$

For the effective reactance of the generators introduce:

$$X_{dP} = \frac{U_{rG}}{\sqrt{3}\ I_{kP}} \qquad (65)$$

I_{kp} is the steady-state short-circuit current of a generator with a three-phase terminal short circuit.

This value I_{kP} should be obtained from the manufacturer.

12.4.4 *Initial short-circuit currents at unbalanced short circuits*

The initial short-circuit currents at unbalanced short circuits are calculated according to Sub-clauses 9.2 and 12.3. Use the voltage factor c_{min} according to Table I.

13. Influence of motors

13.1 *Synchronous motors and synchronous compensators*

When calculating the initial symmetrical short-circuit current I''_k, the peak short-circuit current i_p, the symmetrical short-circuit breaking current I_b and the steady-state short-circuit current I_k, the synchronous motors and synchronous compensators are treated in the same way as synchronous generators.

Exceptions are: no modification for internal voltage; motors may have constant field voltage and no regulators. Motors and compensators with terminal-fed static exciters do not contribute to I_k.

13.2 *Asynchronous motors*

13.2.1 *General*

High-voltage motors and low-voltage motors contribute to the initial symmetrical short-circuit current I''_k, to the peak short-circuit i_p, to the symmetrical short-circuit breaking current I_b, and for unbalanced short circuits also to the steady-state short-circuit current I_k.

High-voltage motors have to be considered in the calculation of short circuit. Low-voltage motors are to be taken into account in auxiliaries of power-stations and in industrial and similar installations, for example in networks of chemical and steel industries and pump-stations.

Motors in low-voltage public power supply systems may be neglected.

In the calculation of short-circuit currents those high-voltage and low-voltage motors may be neglected, which, according to the circuit diagram (interlocking) or to the process (reversible drives), are not switched in at the same time.

High-voltage and low-voltage motors which are connected through two-winding transformers to the network in which the short circuit occurs, may be neglected in the calculation of currents for a short circuit at the feeder connection point Q (see Figure 24), if:

$$\frac{\Sigma P_{rM}}{\Sigma S_{rT}} \leqslant \frac{0.8}{\left| \frac{c\,100\,\Sigma S_{rT}}{S''_{kQ}} - 0.3 \right|} \qquad (66)$$

where:

ΣP_{rM} = sum of the rated active powers of the high-voltage and the low-voltage motors which should be considered

ΣS_{rT} = sum of the rated apparent powers of all transformers, through which the motors are directly fed

S''_{kQ} = initial symmetrical short-circuit power at the feeder connection point Q without supplement of the motors

The estimation according to Equation (66) is not allowed in the case of three-winding transformers.

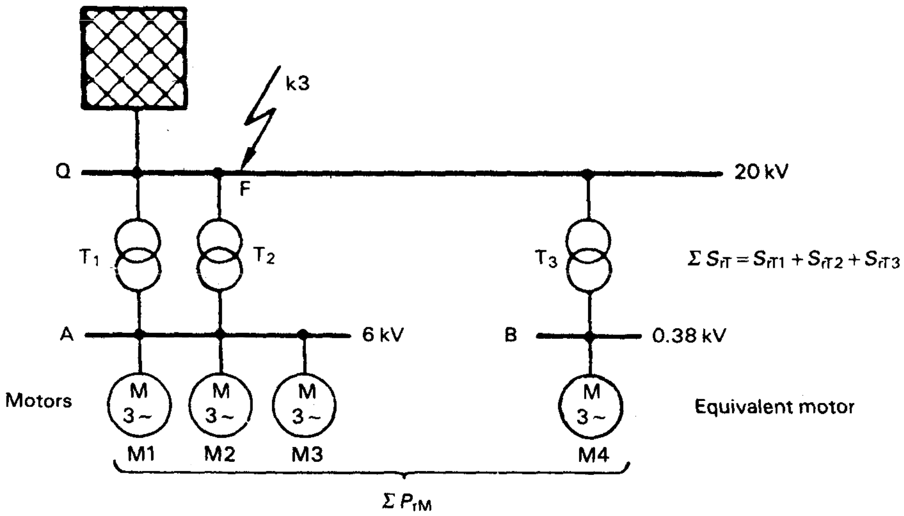


FIG. 24. – Example for the estimation of the contribution from the asynchronous motors in relation to the total short-circuit current.

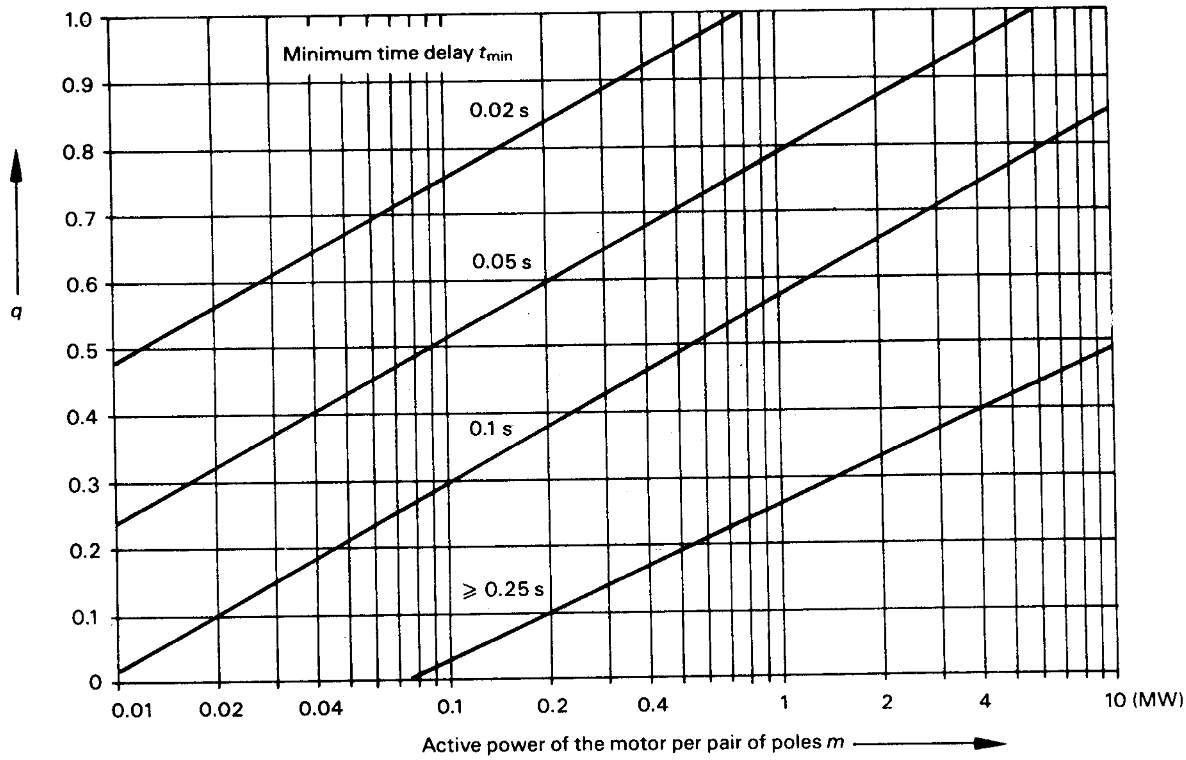


FIG. 25. – Factor q for the calculation of the symmetrical short-circuit breaking current of asynchronous motors.

The factor q for the calculation of the symmetrical short-circuit breaking current for asynchronous motors may be determined as a function of the minimum time delay t_{min}:

$$\left.\begin{aligned} q &= 1.03 + 0.12 \ln m \text{ for } t_{min} = 0.02 \text{ s} \\ q &= 0.79 + 0.12 \ln m \text{ for } t_{min} = 0.05 \text{ s} \\ q &= 0.57 + 0.12 \ln m \text{ for } t_{min} = 0.10 \text{ s} \\ q &= 0.26 + 0.10 \ln m \text{ for } t_{min} \geqslant 0.25 \text{ s} \end{aligned}\right\} \begin{array}{l} \text{with } m\text{:} \\ \text{the rated active power of motors (MW)} \\ \text{per pair of poles} \end{array} \qquad (67)$$

If the calculation in Equation (67) provides larger values than 1 for q, assume that $q = 1$. The factor q may also be obtained from Figure 25.

Low-voltage motors are usually connected to the busbar by cables with different lengths and cross-sections. For simplification of the calculation, groups of motors including their connection cables may be combined to an equivalent motor, see motor M4 in Figure 24.

For these equivalent asynchronous motors including their connection cables the following may be used:

Z_M	= (according to Equation (34))
I_{rM}	= sum of the rated currents of all motors in a group of motors (equivalent motor)
I_{LR}/I_{rM}	= 5
R_M/X_M	= 0.42, respectively $\varkappa_M = 1.3$
m	= 0.05 MW if nothing definite is known

For a short circuit at the busbar B in Figure 24, page 101, the partial short-circuit current of the low-voltage motor group M4 may be neglected, if the following condition holds:

$$I_{rM4} < 0.01\ I''_{k\not{M}4} \qquad (68)$$

I_{rM4} is the rated current of the equivalent motor M4. $I''_{k\not{M}4}$ is the initial symmetrical short-circuit current at the short-circuit location B without supplement of the equivalent motor M4.

In the case of a short circuit on the high-voltage side (e. g. short-circuit locations Q or A in Figure 24) it is possible to simplify the calculation of Z_M according to Equation (34) with the rated current of the transformer T3 ($I_{rT3,\,LV}$) in Figure 24 instead of the rated current I_{rM4} of the equivalent motor M4.

13.2.2 *Terminal short circuit of asynchronous motors*

In the case of balanced and line-to-line short circuits at the terminals of asynchronous motors the currents I''_k, i_p, I_b and I_k are evaluated as shown in Table II. For solid grounded systems the influence of motors on the line-to-earth short-circuit current cannot be neglected.

13.2.3 *Short circuit beyond an impedance*

For the calculation of the initial short-circuit currents according to Sub-clauses 12.2.3 and 12.2.4, asynchronous motors are substituted by their impedances Z_M according to Equation (34) in the positive-sequence and negative-sequence system.

TABLE II

Calculation of short-circuit currents of asynchronous motors in the case of a short circuit at the terminals

Short circuit	Balanced short circuit	Line-to-line short circuit
Initial symmetrical short-circuit current	$I''_{k3M} = \dfrac{cU_n}{\sqrt{3}\, Z_M}$ (69)	$I''_{k2M} = \dfrac{\sqrt{3}}{2} I''_{k3M}$ (73)
Peak short-circuit current	$i_{p3M} = \varkappa_M \sqrt{2}\, I''_{k3M}$ (70)	$i_{p2M} = \dfrac{\sqrt{3}}{2} i_{p3M}$ (74)
	High-voltage motors: $\varkappa_M = 1.65$ (corresponding to $R_M/X_M = 0.15$) for motor powers per pair of poles < 1 MW $\varkappa_M = 1.75$ (corresponding to $R_M/X_M = 0.10$) for motor powers per pair of poles $\geqslant 1$ MW Low-voltage motor groups with connection cables $\varkappa_M = 1.3$ (corresponding to $R_M/X_M = 0.42$)	
Symmetrical short-circuit breaking current	$I_{b3M} = \mu\, q\, I''_{k3M}$ (71)	$I_{b2M} \approx \dfrac{\sqrt{3}}{2} I''_{k3M}$ (75)
	μ according to equation (47) or Figure 16, page 79, with I''_{kM}/I_{rM} q according to equation (67) or Figure 25, page 103	
Steady-state short-circuit current	$I_{k3M} = 0$ (72)	$I_{k2M} \approx \dfrac{1}{2} I''_{k3M}$ (76)

13.3 *Static converter fed drives*

Static converter fed drives (e. g. as in rolling mill drives) are considered for three-phase short circuits only, if the rotational masses of the motors and the static equipment provide reverse transfer of energy for deceleration (a transient inverter operation) at the time of short circuit. Then they contribute only to the initial symmetrical short-circuit current I''_k and to the peak short-circuit current i_p. They do not contribute to the symmetrical short-circuit breaking current I_b.

Apply Sub-clause 11.5.3.5 for the equivalent motor of the static converter fed drive.

14. Consideration of non-rotating loads and capacitors

Calculation methods are given in Sub-clauses 12.2 and 12.3 which allow, as stated in Clause 6, line capacitances and parallel admittances of non-rotating loads to be neglected.

14.1 *Parallel capacitors*

Regardless of the time of short-circuit occurrence, the discharge current of the capacitors may be neglected for the calculation of the peak short-circuit currents.

14.2 *Series capacitors*

The effect of capacitors in series can be neglected in the calculation of short-circuit currents, if they are equipped with voltage-limiting devices in parallel, acting if a short circuit occurs.

APPENDIX A

CALCULATION OF SHORT-CIRCUIT CURRENTS

A1. Example 1: Calculation of short-circuit currents in a low-voltage system

A.1.1 *Problem*

A low-voltage system with $U_n = 380$ V and $f = 50$ Hz is given in Figure A1. The short-circuit currents I''_k and i_p shall be determined at the short-circuit locations F1 to F3 according to Section One (Systems with short-circuit currents having no a.c. component decay). The equipment data for the positive-sequence, negative-sequence and zero-sequence systems are given in Table A1.

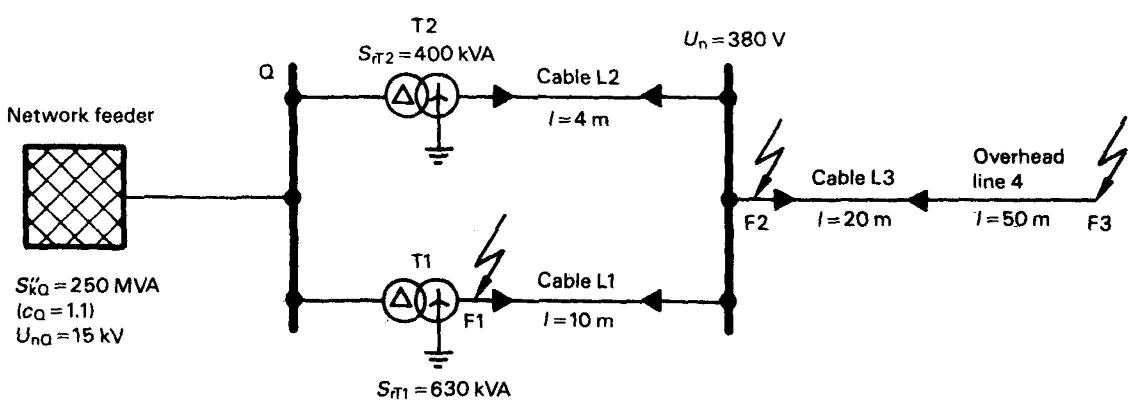


FIG. A1. – Low-voltage system with short-circuit locations F1, F2 and F3. Example 1.

A1.2 *Determination of the positive-sequence impedances*

A1.2.1 *Network feeder*

According to Equation (5b) with $c_Q = 1.1$ (see Table I) it follows that:

$$Z_{Qt} = \frac{c_Q U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{t_r^2} = \frac{1.1 \cdot (15\,\text{kV})^2}{250\,\text{MVA}} \cdot \frac{1}{(15\,\text{kV}/0.4\,\text{kV})^2} = 0.704\,\text{m}\Omega$$

$$\left.\begin{aligned} X_{Qt} &= 0.995\, Z_{Qt} \doteq 0.700\,\text{m}\Omega \\ R_{Qt} &= 0.1\, X_{Qt} = 0.070\,\text{m}\Omega \end{aligned}\right\} \quad Z_{Qt} = (0.070 + \text{j}\,0.700)\,\text{m}\Omega$$

A1.2.2 *Transformers*

According to equation (6), (7) and (8) it follows that:

Transformer T1:

$$Z_{T1} = \frac{u_{krT1}}{100\%} \cdot \frac{U_{rT1}^2}{S_{rT1}} = \frac{4\%}{100\%} \cdot \frac{(400\ \text{V})^2}{630\ \text{kVA}} = 10.16\ \text{m}\Omega$$

$$R_{T1} = \frac{P_{krT1}}{3\,I_{rT1}^2} = \frac{P_{krT1}\,U_{rT1}^2}{S_{rT1}^2} = \frac{6.5\ \text{kW} \cdot (400\ \text{V})^2}{(630\ \text{kVA})^2} = 2.62\ \text{m}\Omega$$

$$X_{T1} = \sqrt{Z_{T1}^2 - R_{T1}^2} = 9.82\ \text{m}\Omega$$

$$\underline{Z}_{T1} = (2.62 + \text{j}\ 9.82)\ \text{m}\Omega$$

Transformer T2:

According to the calculation for transformer T1 it follows that:

$$S_{rT2} = 400\ \text{kVA},\ U_{rT2} = 400\ \text{V},\ u_{krT2} = 4\%\ \text{and}\ P_{krT2} = 4.6\ \text{kW:}$$

$$\underline{Z}_{T2} = (4.60 + \text{j}\ 15.32)\ \text{m}\Omega$$

A1.2.3 *Lines (cables and overhead lines)*

Line impedances: $\underline{Z}_L = \underline{Z}'_L l$

Line L1 (two parallel cables):

$$\underline{Z}_{L1} = \frac{1}{2}\,(0.077 + \text{j}\ 0.079)\ \frac{\Omega}{\text{km}} \cdot 10\ \text{m} = (0.385 + \text{j}\ 0.395)\ \text{m}\Omega$$

Line L2 (two parallel cables):

$$\underline{Z}_{L2} = \frac{1}{2}\,(0.208 + \text{j}\ 0.068)\ \frac{\Omega}{\text{km}} \cdot 4\ \text{m} = (0.416 + \text{j}\ 0.136)\ \text{m}\Omega$$

Line L3 (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):

$$R'_{L4} = \frac{\varrho}{q_n} = \frac{\Omega\ \text{mm}^2}{54\ \text{m} \cdot 50\ \text{mm}^2} = 0.3704\ \frac{\Omega}{\text{km}}\ ;\ r = 1.14\ \sqrt{q_n/\pi} = 4.55\ \text{mm}$$

$$X'_{L4} = 2\pi f\,\frac{\mu_0}{2\pi}\left(0.25 + \ln\frac{d}{r}\right) = 2\pi\ 50\ \text{s}^{-1}\,\frac{4\pi \cdot 10^{-4}\ \text{Vs}}{2\pi\ \text{Akm}}\left(0.25 + \ln\frac{0.4\ \text{m}}{0.455 \cdot 10^{-2}\ \text{m}}\right) = 0.297\frac{\Omega}{\text{km}}$$

$$\underline{Z}_{L4} = (R'_{L4} + \text{j}\ X'_{L4})\ l = (0.3704 + \text{j}\ 0.297)\ \frac{\Omega}{\text{km}} \cdot 50\ \text{m} = (18.52 + \text{j}\ 14.85)\ \text{m}\Omega$$

TABLE AI

Data of equipment for Example 1 and positive-sequence, negative-sequence and zero-sequence short-circuit impedances

Equipment	Data of equipment	Data and equations for the calculation of $\underline{Z}_{(1)}$ and $\underline{Z}_{(0)}$	$\underline{Z}_{(1)} = \underline{Z}_{(2)}$ (mΩ)	$\underline{Z}_{(0)}$ (mΩ)
Network feeder Q	$U_{nQ} = 15$ kV; $c_Q = 1.1$; $S''_{kQ} =$ 250 MVA $R_Q = 0.1 \cdot X_Q$ with $X_Q =$ 0.995 Z_Q	(5b)	$\underline{Z}_{Qt} =$ 0.070 + j 0.700	
Transformers T1	S_{rT} = 630 kVA; U_{rTHV} = 15 kV; U_{rTLV} = 0.4 kV u_{kr} = 4%; P_{krT} = 6.5 kW; Dy 5	(6) to (8)	$\underline{Z}_{T1} =$ 2.62 + j 9.82	$\underline{Z}_{(0)T1} =$ 2.62 + j 9.33
T2	S_{rT} = 400 kVA; U_{rTHV} = 15 kV; U_{rTLV} = 0.4 kV u_{kr} = 4%; P_{krT} = 4.6 kW; Dy 5	(6) to (8)	$\underline{Z}_{T2} =$ 4.60 + j 15.32	$\underline{Z}_{(0)T2} =$ 4.60 + j 14.55
Lines L1	Two parallel four-core cables l = 10 m; 4 × 240 mm² Cu $\underline{Z}'_L = (0.077 + j\,0.079)\ \frac{\Omega}{km}$	Data and ratios $\frac{R_{(0)L}}{R_L}$; $\frac{X_{(0)L}}{X_L}$ given by the manufacturer	$\underline{Z}_{L1} =$ 0.385 + j 0.395	$\underline{Z}_{(0)L1} =$ 1.425 + j 0.715
L2	Two parallel three-core cables l = 4 m; 3 × 150 mm² Al $\underline{Z}'_L = (0.208 + j\,0.068)\ \frac{\Omega}{km}$		$\underline{Z}_{L2} =$ 0.416 + j 0.136	$\underline{Z}_{(0)L2} =$ 1.760 + j 0.165
L3	Four-core cable l = 20 m; 4 × 70 mm² Cu $\underline{Z}'_L = (0.271 + j\,0.087)\ \frac{\Omega}{km}$		$\underline{Z}_{L3} =$ 5.420 + j 1.740	$\underline{Z}_{(0)L3} =$ 16.26 + j 7.76
L4	Overhead line l = 50 m; q_n = 50 mm² Cu; d = 0.4 m $\underline{Z}'_L = (0.3704 + j\,0.297)\ \frac{\Omega}{km}$	(11), (12a)	$\underline{Z}_{L4} =$ 18.52 + j 14.85	$\underline{Z}_{(0)L4} =$ 37.04 + j 44.55

A1.3 *Determination of the zero-sequence impedances*

A1.3.1 *Transformers*

For the transformers T1 and T2 with the vector group Dy5 the following relations are given by the manufacturer:

$$R_{(0)T} = R_T;\ X_{(0)T} = 0.95\ X_T$$

Transformer T1:

$$\underline{Z}_{(0)T1} = R_{(0)T1} + jX_{(0)T1} = (2.62 + j\ 9.33)\ \text{m}\Omega$$

Transformer T2:

$$\underline{Z}_{(0)T2} = R_{(0)T2} + jX_{(0)T2} = (4.60 + j\ 14.55)\ \text{m}\Omega$$

A1.3.2 *Lines (cables and overhead lines)*

The zero-sequence impedances are to be calculated with the relations $R_{(0)L}/R_L$ and $X_{(0)L}/X_L$ obtained from the manufacturer.

- Line L1: $R_{(0)L} = 3.7\ R_L$; $X_{(0)L} = 1.81\ X_L$ with return circuit by the fourth conductor and surrounding conductor:

$$\underline{Z}_{(0)L1} = (3.7\ R_{L1} + \text{j}\ 1.81\ X_{L1}) = (1.425 + \text{j}\ 0.715)\ \text{m}\Omega$$

- Line L2: $R_{(0)L} = 4.23\ R_L$; $X_{(0)L} = 1.21\ X_L$ with return circuit by sheath:

$$\underline{Z}_{(0)L2} = (4.23\ R_{L2} + \text{j}\ 1.21\ X_{L2}) = (1.76 + \text{j}\ 0.165)\ \text{m}\Omega$$

- Line L3: $R_{(0)L} = 3\ R_L$; $X_{(0)L} = 4.46\ X_L$ with return circuit by the fourth conductor, sheath and earth:

$$\underline{Z}_{(0)L3} = (3\ R_{L3} + \text{j}\ 4.46\ X_{L3}) = (16.26 + \text{j}\ 7.76)\ \text{m}\Omega$$

- Line L4: Overhead line with $R_{(0)L} = 2\ R_L$; $X_{(0)L} = 3\ X_L$, when calculating the maximum short-circuit currents:

$$\underline{Z}_{(0)L4} = (2\ R_{L4} + \text{j}\ 3\ X_{L4}) = (37.04 + \text{j}\ 44.55)\ \text{m}\Omega$$

A1.4 *Calculation of the short-circuit currents I''_k and i_p for balanced short circuits at the short-circuit locations F1, F2 and F3*

A1.4.1 *Short-circuit location F1*

Short-circuit impedance at the short-circuit location F1 according to Figure A2:

$$\underline{Z}_k = \underline{Z}_{Qt} + \frac{\underline{Z}_{T1}\,(\underline{Z}_{T2} + \underline{Z}_{L1} + \underline{Z}_{L2})}{\underline{Z}_{T1} + \underline{Z}_{T2} + \underline{Z}_{L1} + \underline{Z}_{L2}} = (1.857 + \text{j}\ 6.771)\ \text{m}\Omega$$

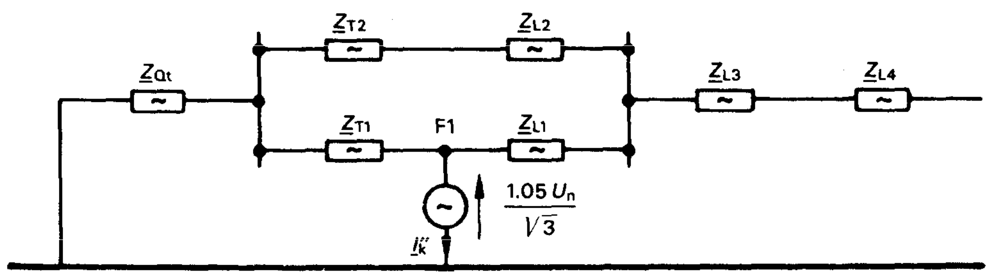


FIG. A2. – Positive-sequence system (according to Figure A1, page 109) for the calculation of I''_k and i_p at the short-circuit location F1.

Maximum initial symmetrical short-circuit current according to Equation (20) with $c = 1.05$ (see Table I):

$$I''_k = \frac{cU_n}{\sqrt{3}\ Z_k} = \frac{1.05 \cdot 380\ \text{V}}{\sqrt{3}\ 7.021\ \text{m}\Omega} = 32.81\ \text{kA}$$

Peak short-circuit current i_p according to Sub-clause 9.1.3.2. Because the calculation of $\underline{Z}_k$ is carried out with complex values, it is sufficient to choose the conservative Method B or for higher accuracy Method C of Sub-clause 9.1.3.2.

Method B (impedance ratio at the short-circuit location, Equation (21)):

From the short-circuit impedance $\underline{Z}_k = R_k + \mathrm{j}\, X_k$ the ratio $R_k/X_k = 1.857\ \mathrm{m}\Omega / 6.771\ \mathrm{m}\Omega = 0.274$ can be found and with the equation for $\varkappa$ in Sub-clause 9.1.1.2 it follows that:

$$\varkappa_b = 1.02 + 0.98\ \mathrm{e}^{-3 \cdot 0.274} = 1.45$$

$$i_{p,b} = 1.15 \cdot \varkappa_b \sqrt{2}\ I''_k = 1.15 \cdot 1.45 \sqrt{2} \cdot 32.81\ \mathrm{kA} = 77.37\ \mathrm{kA}$$

Method C (equivalent frequency f_c, Equation (16) with R/X according to Equation (22a)):

The impedance $\underline{Z}_c = R_c + \mathrm{j}\, X_c$ is calculated according to the comments of Method C of Sub-clause 9.1.3.2 with an equivalent source voltage of the frequency $f_c = 20$ Hz ($f_n = 50$ Hz). The calculation procedure is similar to the calculation of $\underline{Z}_k$, but taking the following values:

$$\underline{Z}_{Qt,c} = (0.070 + \mathrm{j}\, 0.280)\ \mathrm{m}\Omega$$

$$\underline{Z}_{T1,c} = (2.62 + \mathrm{j}\, 3.928)\ \mathrm{m}\Omega;\ \underline{Z}_{T2,c} = (4.60 + \mathrm{j}\, 6.128)\ \mathrm{m}\Omega$$

$$\underline{Z}_{L1,c} = (0.385 + \mathrm{j}\, 0.158)\ \mathrm{m}\Omega;\ \underline{Z}_{L2,c} = (0.416 + \mathrm{j}\, 0.0544)\ \mathrm{m}\Omega$$

$$\underline{Z}_c = \underline{Z}_{Qt,c} + \frac{\underline{Z}_{T1,c}\,(\underline{Z}_{T2,c} + \underline{Z}_{L1,c} + \underline{Z}_{L2,c})}{\underline{Z}_{T1,c} + \underline{Z}_{T2,c} + \underline{Z}_{L1,c} + \underline{Z}_{L2,c}} = (1.85 + \mathrm{j}\, 2.718)\ \mathrm{m}\Omega$$

$$\frac{R}{X} = \frac{R_c}{X_c} \cdot \frac{f_c}{f_n} = \frac{1.85\ \mathrm{m}\Omega}{2.718\ \mathrm{m}\Omega} \cdot \frac{20\ \mathrm{Hz}}{50\ \mathrm{Hz}} = 0.272$$

$$\varkappa_c = 1.02 + 0.98\ \mathrm{e}^{-3 \cdot 0.272} = 1.453$$

$$i_{p,c} = \varkappa_c \sqrt{2}\ I''_k = 1.453 \sqrt{2} \cdot 32.81\ \mathrm{kA} = 67.42\ \mathrm{kA}$$

In order to interpret this result, the ratios R/X of the parallel branches $\underline{Z}_{T1}$ and $\underline{Z}_{T2} + \underline{Z}_{L1} + \underline{Z}_{L2}$ are to be considered. These can be calculated as:

$$\frac{R_{T1}}{X_{T1}} = 0.27$$

$$\frac{R_{T2} + R_{L1} + R_{L2}}{X_{T2} + X_{L1} + X_{L2}} = 0.34$$

Additionally, two-thirds of the short-circuit current are taken by the transformer T1.

The breaking current I_b and the steady state short-circuit current I_k at all three short-circuit locations need not be calculated since they are equal to the corresponding initial symmetrical short-circuit current I''_k (see Equation (15)).

A1.4.2 *Short-circuit location F2*

$$\underline{Z}_{k} = \underline{Z}_{Qt} + \frac{(\underline{Z}_{T1} + \underline{Z}_{L1})(\underline{Z}_{T2} + \underline{Z}_{L2})}{\underline{Z}_{T1} + \underline{Z}_{T2} + \underline{Z}_{L1} + \underline{Z}_{L2}} = (1.953 + j\,6.852)\ \text{m}\Omega$$

$$I''_{k} = \frac{cU_{n}}{\sqrt{3}\ Z_{k}} = \frac{1.05 \cdot 380\ \text{V}}{\sqrt{3} \cdot 7.125\ \text{m}\Omega} = 32.33\ \text{kA}$$

The peak short-circuit current can be calculated from Sub-clause 9.1.3.2:

$$\underline{Z}_{c} = (1.951 + j\,2.742)\ \text{m}\Omega$$

This leads to R/X ratio of:

$$R/X = 0.2847$$

Using the equation for $\varkappa$ in Sub-clause 9.1.1.2:

$$\varkappa_{c} = 1.44$$

thus:

$$i_{p,c} = \varkappa_{c} \sqrt{2}\ I''_{k} = 1.44 \sqrt{2} \cdot 32.33\ \text{kA} = 65.84\ \text{kA}$$

The decisive ratio R/X is mostly determined by those of the branches $\underline{Z}_{T1} + \underline{Z}_{L1}$ and $\underline{Z}_{T2} + \underline{Z}_{L2}$ with $(R_{T1} + R_{L1})/(X_{T1} + X_{L1}) = 0.29$ and $(R_{T2} + R_{L2})/(X_{T2} + X_{L2}) = 0.32$. Moreover, these two relations are similar to $R_{k}/X_{k} = 1.953\ \Omega/6.852\ \Omega = 0.29 \rightarrow \varkappa_{b} = 1.43$.

A1.4.3 *Short-circuit location F3*

$$\underline{Z}_{k} = \underline{Z}_{Qt} + \frac{(\underline{Z}_{T1} + \underline{Z}_{L1})(\underline{Z}_{T2} + \underline{Z}_{L2})}{\underline{Z}_{T1} + \underline{Z}_{T2} + \underline{Z}_{L1} + \underline{Z}_{L2}} + \underline{Z}_{L3} + \underline{Z}_{L4} = (25.893 + j\,23.442)\ \text{m}\Omega$$

$$I''_{k} = \frac{cU_{n}}{\sqrt{3}\ Z_{k}} = \frac{1.05 \cdot 380\ \text{V}}{\sqrt{3} \cdot 34.93\ \text{m}\Omega} = 6.6\ \text{kA}$$

$$i_{p,c} = \varkappa_{c} \sqrt{2}\ I''_{k} = 1.05 \sqrt{2} \cdot 6.6\ \text{kA} = 9.89\ \text{kA}$$

with:

$$\underline{Z}_{c} = R_{c} + j\,X_{c} = \underline{Z}_{F2,c} + \underline{Z}_{L3,c} + \underline{Z}_{L4,c} = (1.951 + j\,2.742)\ \text{m}\Omega + (23.94 + j\,6.636)\ \text{m}\Omega = (25.89 + j\,9.38)\ \text{m}\Omega$$

$$\frac{R}{X} = \frac{R_{c}}{X_{c}} \cdot \frac{f_{c}}{f_{n}} = \frac{25.89\ \text{m}\Omega}{9.38\ \text{m}\Omega} \cdot \frac{20\ \text{Hz}}{50\ \text{Hz}} = 1.104$$

Calculated according to Equation (21) of Method B (see Sub-clause 9.1.3.2):

$$\frac{R_{k}}{X_{k}} = \frac{25.893\ \text{m}\Omega}{23.442\ \text{m}\Omega} = 1.1043$$

therefore:

$$\varkappa_{c} = 1.05 \approx \varkappa_{b}$$

A1.5 *Calculation of the short-circuit currents I''_{k1} and i_{p1} for line-to-earth short circuits at the short-circuit locations F1, F2 and F3*

A1.5.1 *Short-circuit location F1*

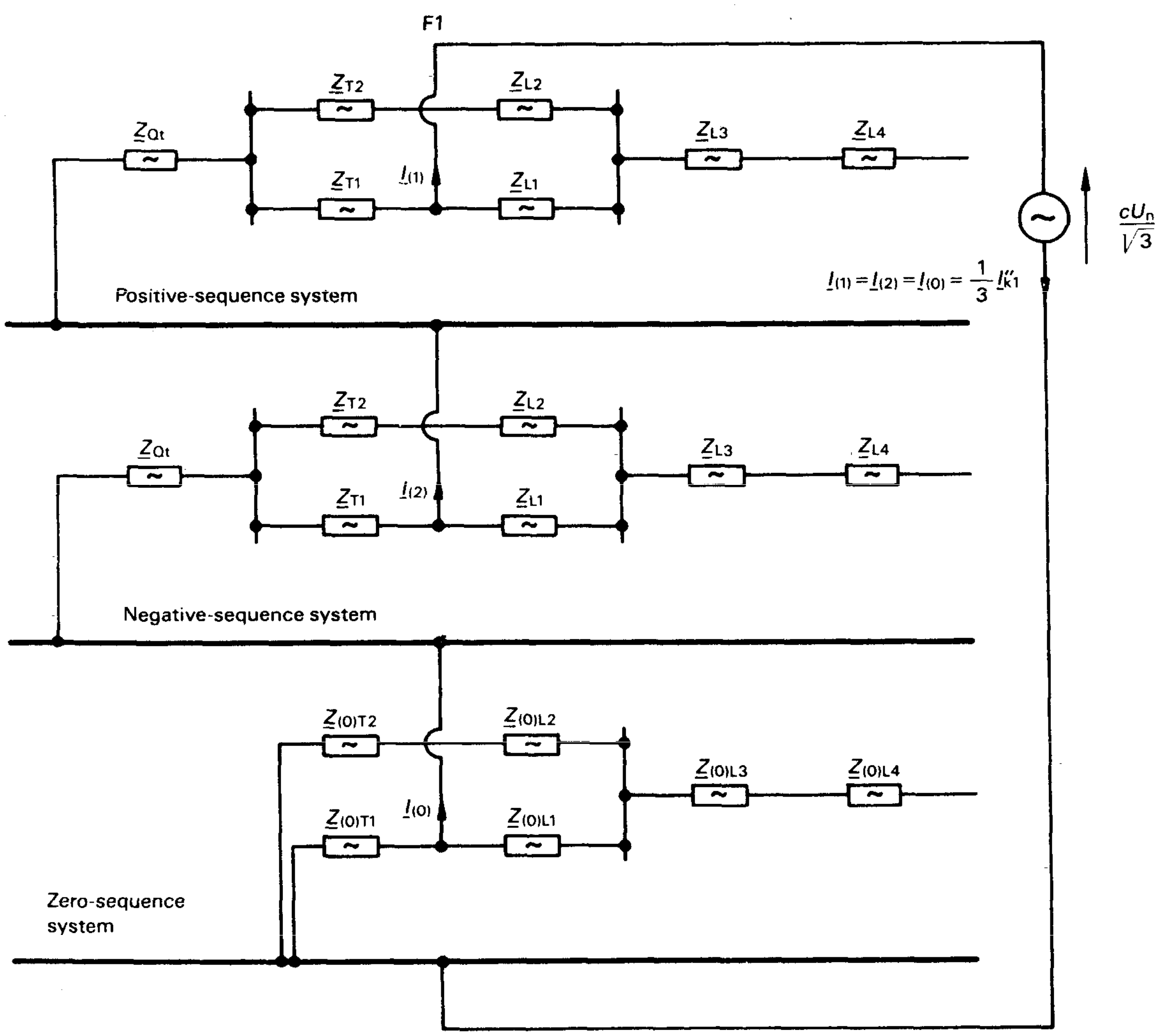


FIG. A3. – Positive-sequence, negative-sequence and zero-sequence systems with connections at the short-circuit location F1 for the calculation $\underline{I}''_{k1}$ at a line-to-earth short circuit.

Short-circuit impedances:

$$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_k = (1.857 + \text{j}\, 6.771)\ \text{m}\Omega$$

$$\underline{Z}_{(0)} = \frac{\underline{Z}_{(0)T1}\,(\underline{Z}_{(0)T2} + \underline{Z}_{(0)L1} + \underline{Z}_{(0)L2})}{\underline{Z}_{(0)T1} + \underline{Z}_{(0)T2} + \underline{Z}_{(0)L1} + \underline{Z}_{(0)L2}} = (2.099 + \text{j}\, 5.872)\ \text{m}\Omega$$

$$\underline{Z}_{(1)} + \underline{Z}_{(2)} + \underline{Z}_{(0)} = 2\underline{Z}_{(1)} + \underline{Z}_{(0)} = (5.813 + \text{j}\, 19.414)\ \text{m}\Omega$$

Initial short-circuit current for a line-to-earth short circuit according to Equation (29) (see Sub-clause 9.2.3.1):

$$I''_{k1} = \frac{\sqrt{3}\, cU_n}{|2\underline{Z}_{(1)} + \underline{Z}_{(0)}|} = \frac{\sqrt{3} \cdot 1.05 \cdot 380 \text{ V}}{20.266 \text{ m}\Omega} = 34.10 \text{ kA}, \; (I''_{k1}/I''_k = 1.04)$$

Peak short-circuit current i_{p1} according to Equation (31) of Sub-clause 9.2.3.2, calculated with the same value for $\varkappa_c$ as in the case of a balanced three-phase short circuit (see Sub-clause 9.1.3.2 for $\varkappa_c$):

$$i_{p1} = \varkappa_c \sqrt{2}\, I''_{k1} = 1.453 \cdot \sqrt{2} \cdot 34.10 \text{ kA} = 70.07 \text{ kA}$$

A1.5.2 *Short-circuit location F2*

$$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_k = (1.953 + \text{j}\, 6.852) \text{ m}\Omega$$

$$\underline{Z}_{(0)} = \frac{(\underline{Z}_{(0)T1} + \underline{Z}_{(0)L1})\,(\underline{Z}_{(0)T2} + \underline{Z}_{(0)L2})}{\underline{Z}_{(0)T1} + \underline{Z}_{(0)T2} + \underline{Z}_{(0)L1} + \underline{Z}_{(0)L2}} = (2.475 + \text{j}\, 5.970) \text{ m}\Omega$$

$$I''_{k1} = \frac{\sqrt{3}\, cU_n}{|2\underline{Z}_{(1)} + \underline{Z}_{(0)}|} = \frac{\sqrt{3} \cdot 1.05 \cdot 380 \text{ V}}{20.684 \text{ m}\Omega} = 33.41 \text{ kA}, \; (I''_{k1}/I''_k = 1.03)$$

$$i_{p1} = \varkappa_c \sqrt{2}\, I''_{k1} = 1.44 \sqrt{2} \cdot 33.41 \text{ kA} = 68.04 \text{ kA}$$

A1.5.3 *Short-circuit location F3*

$$\underline{Z}_{(1)} = \underline{Z}_{(2)} = \underline{Z}_k = (25.893 + \text{j}\, 23.442) \text{ m}\Omega$$

$$\underline{Z}_{(0)} = \frac{(\underline{Z}_{(0)T1} + \underline{Z}_{(0)L1})\,(\underline{Z}_{(0)T2} + \underline{Z}_{(0)L2})}{\underline{Z}_{(0)T1} + \underline{Z}_{(0)T2} + \underline{Z}_{(0)L1} + \underline{Z}_{(0)L2}} + \underline{Z}_{(0)L3} + \underline{Z}_{(0)L4} = (55.775 + \text{j}\, 58.280) \text{ m}\Omega$$

$$I''_{k1} = \frac{\sqrt{3}\, cU_n}{|2\underline{Z}_{(1)} + \underline{Z}_{(0)}|} = \frac{\sqrt{3} \cdot 1.05 \cdot 380 \text{ V}}{150.43 \text{ m}\Omega} = 4.59 \text{ kA}, \; (I''_{k1}/I''_k = 0.70)$$

$$i_{p1} = \varkappa_c \sqrt{2}\, I''_{k1} = 1.05 \sqrt{2} \cdot 4.59 \text{ kA} = 6.82 \text{ kA}$$

A1.6 *Collection of results*

TABLE AII

Collection of results for Example 1 (U_n = 380 V)

Short-circuit location	$\underline{Z}_{(1)} = \underline{Z}_k$	$\underline{Z}_{(0)}$	I''_k [1]	$i_{p,c}$	I''_{k1}	$i_{p1,c}$	I''_{k1}/I''_k
	(mΩ)	(mΩ)	(kA)	(kA)	(kA)	(kA)	–
F1	7.021	6.24	32.81	67.42	34.10	70.07	1.04
F2	7.125	6.46	32.33	65.84	33.41	68.04	1.03
F3	34.93	80.67	6.60	9.89	4.59	6.82	0.70

[1] In all cases $I''_k = I_b = I_k$ (far-from-generator short circuit).

A2. Example 2: Calculation of balanced short-circuit currents in a medium-voltage system, influence of motors

A2.1 *Problem*

A medium-voltage system 33 kV/6 kV (50 Hz) is given in Figure A4, page 127. The calculations are to be carried out without asynchronous motors according to Sub-clause 9.1 of Section One and with the influence of asynchronous motors according to Sub-clause 13.2 of Section Two.

The 33-kV-/6-kV-sub-station with two transformers each of S_{rT} = 15 MVA is fed through two three-core solid type 33-kV-cables from a network feeder with S''_{kQ} = 750 MVA and U_{nQ} = 33 kV.

As the short-circuit resistance is small in comparison with the short-circuit reactance ($R_k <$ 0.3 X_k, see Sub-clause 9.1.1.1) it is sufficiently accurate to calculate only the short-circuit reactances of the electrical equipment and the short-circuit reactance X_k at the short-circuit location F in Figure A4.

To demonstrate the difference, when calculating the short-circuit current I''_k with absolute quantities or with quantities of a per unit system, both calculations are carried out (see Sub-clause A2.3 for the calculation with per unit quantities). To show the difference between a real and a complex calculation and to demonstrate the decaying of the aperiodic component of the short-circuit current an additional calculation is given in Sub-clause A2.4.

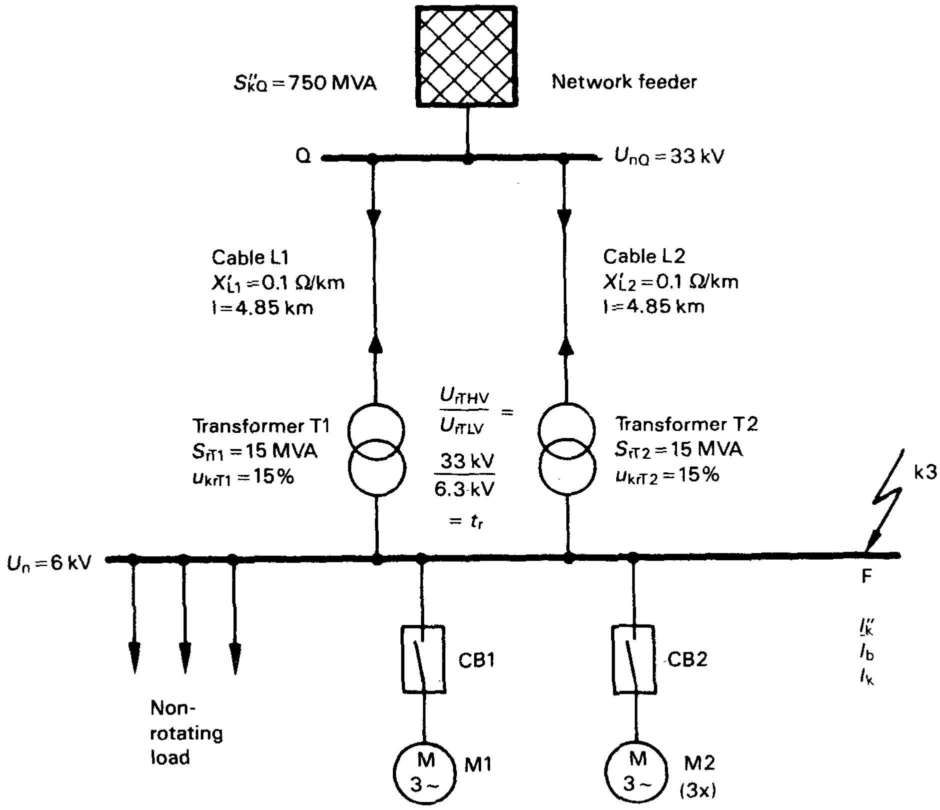
A2.2 *Calculation with absolute quantities*

Table AIII demonstrates the calculation of the short-circuit reactance X_k at the short-circuit location F in Figure A4 if the circuit breakers CB1 and CB2 are open (without influence of the asynchronous motors M1 and M2).

The initial symmetrical short-circuit current without the influence of the asynchronous motors M1 and M2 becomes with c = 1.1 (according to Table I for the maximum short-circuit currents):

$$I''_{k\,(\text{without M1, M2})} = \frac{c U_n}{\sqrt{3}\, X_k} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3} \cdot 0.2655\ \Omega} = 14.35\ \text{kA}$$

X_k is taken from Table AIII.



Asynchronous motor M1
P_{rM} = 5 MW; U_{rM} = 6 kV
cos φ_r = 0.86; η_r = 0.97
I_{LR}/I_{rM} = 4
pair of poles: 2

Three asynchronous motors, treated as an equivalent motor M2, each of them having the following data:
P_{rM} = 1 MW; U_{rM} = 6 kV
cos φ_r = 0.83; η_r = 0.94
I_{LR}/I_{rM} = 5.5
pair of poles: 1

FIG. A4. – Medium voltage 33 kV/6 kV system with asynchronous motors. Example 2.

TABLE AIII

Calculation of X_k (Ω) for Example 2, without the influence of asynchronous motors M1 and M2 (CB1 and CB2 are open)

No.	Equipment	Equations and calculations	Reactance (Ω)
1	Network feeder	Equation (5b): $X_{Qt} = \frac{cU_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{t_r^2} = \frac{1.1 \cdot (33\text{ kV})^2}{750\text{ MVA}} \cdot \frac{1}{(33\text{ kV}/6.3\text{ kV})^2}$	0.0582
2	Cable L1	$X_{L1t} = X'_{L1} \cdot l \cdot \frac{1}{t_r^2} = 0.1\frac{\Omega}{\text{km}} \cdot 4.85\text{ km} \cdot \frac{1}{(33\text{ kV}/6.3\text{ kV})^2}$	0.0177
3	Transformer T1	Equation (6) ($X_T \approx Z_T$) $X_{T1} = \frac{u_{krT1}}{100\%} \cdot \frac{U_{rT1LV}^2}{S_{rT1}} = \frac{15\%}{100\%} \cdot \frac{(6.3\text{ kV})^2}{15\text{ MVA}}$	0.3969
4	L1 + T1	$X_{L1t} + X_{T1} = X_{L2t} + X_{T2}$	0.4146
5	(L1 + T1) (L2 + T2) in parallel	Two equal branches in parallel $\frac{1}{2}(X_{L1t} + X_{T1})$	0.2073
6	Short-circuit reactance X_k	$X_k = X_{Qt} + \frac{1}{2}(X_{L1t} + X_{T1})$	0.2655

The initial symmetrical short-circuit current, without the influence of motors, at the short-circuit location (see Figure A4) is:

$$I''_{k\,(\text{without M1, M2})} = \frac{cU_n}{\sqrt{3} \cdot X_k} = \frac{1.1}{\sqrt{3}} \cdot \frac{6\text{ kV}}{0.2655\ \Omega} = 14.35\text{ kA}$$

According to Sub-clause 12.2.3 (three-phase short circuit fed from non-meshed sources and Equation (55) it is possible to add the partial symmetrical short-circuit current at the short-circuit location (see Figure A4, page 127):

$$\underline{I}''_k = \underline{I}''_{k\,(\text{without M1, M2})} + \underline{I}''_{kM1} + \underline{I}''_{kM2}$$

The partial short-circuit currents $\underline{I}''_{kM1}$ and $\underline{I}''_{kM2}$ (CB1 and CB2 are closed) are calculated from Equation (69) in Table II and Equation (34) in Sub-clause 11.5.3.5 for the short-circuit impedances of asynchronous motors.

Motor M1:

$$Z_{M1} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} = \frac{1}{4} \cdot \frac{(6\text{ kV})^2}{6\text{ MVA}} = 1.5\ \Omega$$

where:

$$S_{rM} = \frac{P_{rM}}{\cos\varphi_r\eta_r} = \frac{5\text{ MW}}{0.86 \cdot 0.97} = 6\text{ MVA}$$

Motor M2 (three motors with equal data → equivalent motor):

$$Z_{M2} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U_{rM}^2}{S_{rM}} = \frac{1}{3} \cdot \frac{1}{5.5} \cdot \frac{(6\text{ kV})^2}{1.28\text{ MVA}} = 1.705\ \Omega$$

where:

$$S_{rM} = \frac{P_{rM}}{\cos\varphi_r\eta_r} = \frac{1\text{ MW}}{0.83 \cdot 0.94} = 1.28\text{ MVA}$$

Partial short-circuit currents according to Equation (69):

$$I''_{kM1} = \frac{cU_n}{\sqrt{3}\ Z_{M1}} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3} \cdot 1.5\ \Omega} = 2.54\ \text{kA}$$

$$I''_{kM2} = \frac{cU_n}{\sqrt{3}\ Z_{M2}} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3} \cdot 1.705\ \Omega} = 2.23\ \text{kA}$$

Short-circuit current at the short-circuit location F in Figure A4, page 127, including the influence of the motors M1 and M2:

$$I''_k = I''_{k\,(\text{without M1, M2})} + I''_{kM1} + I''_{kM2} = (14.35 + 2.54 + 2.23)\ \text{kA}$$

$$I''_k = 19.12\ \text{kA}$$

The influence of the asynchronous motors raises the short-circuit current to 1.3 of the value without motors.

$$S''_k = \sqrt{3}\ U_n I''_k = \sqrt{3} \cdot 6\ \text{kV} \cdot 19.12\ \text{kA} = 198.7\ \text{MVA} \approx 200\ \text{MVA}$$

When calculating the partial short-circuit current fed from the network, Sub-clause 12.2.3.3 is used:

$$I_{k\,(\text{without M1, M2})} = I_{b\,(\text{without M1, M2})} = I''_{k\,(\text{without M1, M2})}$$

For the calculation of I_{b3M} the factor μ has to be determined according to Equation (47) and q according to Equation (67) with $t_{min} = 0.1$ s. With $I''_{kM1}/I_{rM1} = 4.40$ and $I''_{kM2}/I_{rM2} = 6.05$ the values $\mu_{M1} = 0.80$ and $\mu_{M2} = 0.72$ are calculated. With active power per pair of poles $m_{M1} =$ 2.5 MW and $m_{M2} = 1$ MW the values $q_{M1} = 0.68$ and $q_{M2} = 0.57$ are found.

According to Equation (71) the partial breaking currents are:

$$I_{b3M1} = \mu_{M1}\, q_{M1}\, I''_{kM1} = 0.80 \cdot 0.68 \cdot 2.54\ \text{kA} = 1.38\ \text{kA}$$

$$I_{b3M2} = \mu_{M2}\, q_{M2}\, I''_{kM2} = 0.72 \cdot 0.57 \cdot 2.23\ \text{kA} = 0.92\ \text{kA}$$

The symmetrical short-circuit breaking current becomes:

$$I_b = I_{b\,(\text{without M1, M2})} + I_{b3M1} + I_{b3M2} = (14.35 + 1.38 + 0.92)\ \text{kA} = 16.65\ \text{kA}$$

According to Equation (72) there is no contribution of the asynchronous motors to I_k:

$$I_k = I''_{k\,(\text{without M1, M2})} = 14.35\ \text{kA}$$

A2.3 *Calculation with per unit quantities*

For the calculation with per unit (p. u.) quantities two reference quantities (Index R) have to be chosen. For Example 2 those quantities shall be:

$$U_R = U_n = 6\ \text{kV or } 33\ \text{kV and } S_R = 100\ \text{MVA}$$

Per-unit (p. u.) quantities (with an asterisk [*] as a superscript) therefore are defined as follows:

$$*U = \frac{U}{U_R} ;\ *I = \frac{IU_R}{S_R} ;\ *Z = \frac{ZS_R}{U_R^2} ;\ *S = \frac{S}{S_R}$$

If the system is not coherent as indicated in Sub-clause 8.4, that means $U_{rTHV}/U_{rTLV} \neq U_{nHV}/U_{nLV}$, then the rated transformation ratio related to p. u. voltages becomes:

$$*t_r = \frac{U_{rTHV}}{U_{rTLV}} \cdot \frac{U_{R,6\,kV}}{U_{R,33\,kV}} = \frac{33\ kV}{6.3\ kV} \cdot \frac{6\ kV}{33\ kV} = 0.9524$$

The procedure for the calculation of the initial symmetrical short-circuit current without the influence of the motors is given in Table AIV in a similar manner as in Table AIII.

The initial symmetrical short-circuit current $*I''_{k\,(without\ M1,\ M2)}$ at the short-circuit location in Figure A4, page 127, is:

$$*I''_{k\,(without\ M1,\ M2)} = \frac{c^*U_n}{\sqrt{3}\ *X_k} = \frac{1.1 \cdot 1\ p.u.}{\sqrt{3} \cdot 0.7375\ p.u.} = 0.8611\ p.u.$$

From this the short-circuit current in kiloamperes is calculated:

$$I''_{k\,(without\ M1,\ M2)} = *I''_{k\,(without\ M1,\ M2)} \frac{S_R}{U_{R,\,6\,kV}} = 0.8611\ p.u. \frac{100\ MVA}{6\ kV} = 14.35\ kA$$

TABLE AIV

Calculation of $*X_k$ (per unit [p. u.]) for Example 2, without the influence of asynchronous motors M1 and M2 (CB1 and CB2 open)

No.	Equipment	Equations and calculations	Reactance (p. M.)
1	Network feeder	Equation (5b): $*X_{Qt} = \frac{c^*U_{nQ}^2}{*S_{kQ}} \cdot \frac{1}{*t_r^2} = \frac{1.1 \cdot (1\ p.u.)^2}{7.5\ p.u.} \cdot \frac{1}{0.9524^2}$	0.1617
2	Cable L1	$*X_{L1t} = *X'_{L1} \cdot l\ \frac{S_R}{U_{R,33\,kV}^2} \cdot \frac{1}{*t_r^2}$ $= 0.1\ \frac{\Omega}{km} \cdot 4.85\ km \frac{100\ MVA}{(33\ kV)^2} \cdot \frac{1}{0.9524^2}$	0.0491
3	Transformer T1	Equation (6) ($X_T \approx Z_T$) $*X_{T1} = \frac{u_{krT1}}{100\%} \cdot \frac{U_{rTLV}^2}{S_{rT1}} \cdot \frac{S_R}{U_{R,6\,kV}^2}$ $= \frac{15\%}{100\%} \cdot \frac{(6.3\ kV)^2}{15\ MVA} \cdot \frac{100\ MVA}{(6\ kV)^2}$	1.1025
4	L1 + T1	$*X_{L1t} + *X_{T1} = *X_{L2t} + *X_{T2}$	1.1516
5	(L1 + T1) (L2 + T2) in parallel	Two equal branches in parallel $\frac{1}{2}(*X_{L1t} + *X_{T1})$	0.5758
6	Short-circuit reactance $*X_k$	$*X_k = *X_{Qt} + \frac{1}{2}(*X_{L1t} + *X_{T1})$	0.7375

The short-circuit impedances in p. u. of the asynchronous motors are:

Motor M1:

$$*Z_{M1} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U^2_{rM}}{S_{rM}} \cdot \frac{S_R}{U^2_{R,6kV}} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{S_R}{S_{rM}}$$

$$*Z_{M1} = \frac{1}{4} \cdot \frac{100\ \text{MVA}}{6\ \text{MVA}} = 4.167\ \text{p. u.}$$

Motor M2:

$$*Z_{M2} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U^2_{rM}}{S_{rM}} \cdot \frac{S_R}{U^2_{R,6kV}} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{S_R}{S_{rM}}$$

$$*Z_{M2} = \frac{1}{3} \cdot \frac{1}{5.5} \cdot \frac{100\ \text{MVA}}{1.28\ \text{MVA}} = 4.735\ \text{p. u.}$$

Partial short-circuit currents according to Equation (69):

$$*I''_{kM1} = \frac{1.1\ *U_n}{\sqrt{3}\ *Z_{M1}} = \frac{1.1 \cdot 1\ \text{p. u.}}{\sqrt{3} \cdot 4.167\ \text{p. u.}} = 0.1524\ \text{p. u.} \rightarrow I''_{kM1} = 2.54\ \text{kA}$$

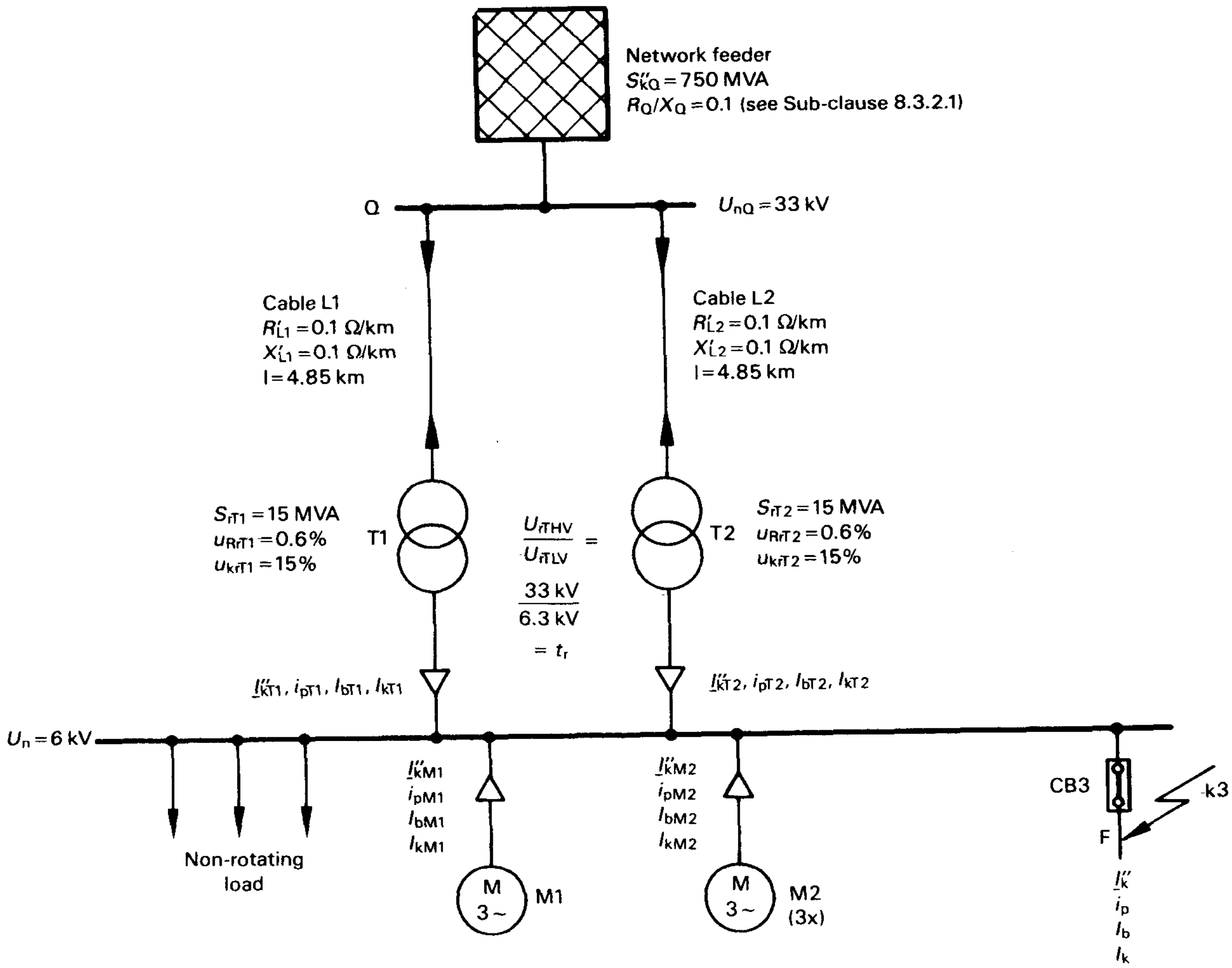
$$*I''_{kM2} = \frac{1.1\ *U_n}{\sqrt{3}\ *Z_{M2}} = \frac{1.1 \cdot 1\ \text{p. u.}}{\sqrt{3} \cdot 4.735\ \text{p. u.}} = 0.1341\ \text{p. u.} \rightarrow I''_{kM2} = 2.23\ \text{kA}$$

The results are the same as in Sub-clause A2.2.

A2.4 *Calculation with complex quantities*

In this Sub-clause the short-circuit calculation is done with complex quantities for the medium voltage system according to Figure A4, page 127.

The complex impedances of electrical equipment are calculated from the data given in Figure A5. This figure indicates the partial short-circuit currents of the branches and their addition at the short-circuit location.



Data of asynchronous motors M1 and M2 given in Figure A4

FIG. A5. – Medium voltage 33 kV/6 kV system with asynchronous motors (complex calculation for Example 2).

TABLE AV

Calculation of $\underline{Z}_{k\,(T1,\,T2)}$ for Example 2, with asynchronous motors M1 and M2 according to Figure A5

No.	Equipment	Equations et calculations	Impedance (Ω)
1	Network feeder	$Z_{Qt} = \frac{cU^2_{nQ}}{S''_{kQ}} \cdot \frac{1}{t^2_r} = 0.0582\ \Omega$ (see Table AIII) $X_{Qt} = 0.995\ Z_{Qt} = 0.0579\ \Omega$ $R_{Qt} = 0.1\ X_{Qt} = 0.0058\ \Omega$ } See Sub-clause 8.3.2.1 $\underline{Z}_{Qt} = R_{Qt} + jX_{Qt}$	0.0058 + j 0.0579
2	Cable L1	$R_{L1t} = R'_{L1}\, l\ \frac{1}{t^2_r} = 0.1 \frac{\Omega}{km} \cdot 4.85\ km \cdot \frac{1}{\left(\frac{33\ kV)}{6.3\ kV}\right)^2}$ $R_{L1t} = 0.0177\ \Omega$ $X_{L1t} = X'_{L1}\, l\ \frac{1}{t^2_r} = 0.0177\ \Omega$ (see Table AIII) $\underline{Z}_{L1t} = R_{L1t} + jX_{L1t}$	0.0177 + j 0.0177
3	Transformer T1	$Z_{T1} = \frac{u_{krT1}}{100\%} \cdot \frac{U^2_{rT1LV}}{S_{rT1}} = 0.3969\ \Omega$ (see Table AIII) Equation (7): $R_{T1} = \frac{u_{RrT1}}{100\%} \cdot \frac{U^2_{rT1LV}}{S_{rT1}} = \frac{0.6\%}{100\%} \cdot \frac{(6.3\ kV)^2}{15\ MVA}$ $R_{T1} = 0.015\ 88\ \Omega$ Equation (8): $X_{T1} = \sqrt{Z^2_{T1} - R^2_{T1}} = 0.3966\ \Omega$ $\underline{Z}_{T1} = R_{T1} + jX_{T1}$	0.01588 + j 0.3966
4	L1 + T1	$\underline{Z}_{L1t} + \underline{Z}_{T1} = \underline{Z}_{L2t} + \underline{Z}_{T2}$	0.03358 + j 0.4143
5	(L1 + T1) (L2 + T2) in parallel	$\frac{1}{2}(\underline{Z}_{L1t} + \underline{Z}_{T1})$	0.01679 + j 0.2072
6	Short-circuit impedance	$\underline{Z}_{k\,(T1,T2)} = \underline{Z}_{Qt} + \frac{1}{2}(\underline{Z}_{L1t} + \underline{Z}_{T1})$	0.02259 + j 0.2651

Short-circuit impedances of asynchronous motors M1 and M2:

Motor M1:

$$Z_{M1} = \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U^2_{rM}}{S_{rM}} = 1.5\ \Omega \qquad \text{(see Sub-clause A2.2)}$$

$$P_{rM}/p = 5\ \text{MW}/2 = 2.5\ \text{MW}\ [\geq 1\ \text{MW}]\ (p = 2 \text{ pairs of poles})$$

therefore:

$$X_M = 0.995\ Z_M \text{ et } R_M = 0.1\ X_M \qquad \text{(see Sub-clause 11.5.3.5)}$$

$$\underline{Z}_{M1} = (0.1493 + \text{j}\ 1.493)\ \Omega; |\underline{Z}_{M1}| = 1.5\ \Omega$$

Motor M2 (three motors with equal data → equivalent motor):

$$Z_{M2} = \frac{1}{3} \cdot \frac{1}{I_{LR}/I_{rM}} \cdot \frac{U^2_{rM}}{S_{rM}} = 1.705\ \Omega \qquad \text{(see Sub-clause A2.2)}$$

$$P_{rM}/p = 1\ \text{MW}/1 = \text{MW}\ [\geq 1\ \text{MW}]$$

therefore:

$$X_M = 0.995\ Z_M \text{ and } R_M = 0.1\ X_M$$

$$\underline{Z}_{M2} = (0.1696 + \text{j}\ 1.696)\ \Omega; |\underline{Z}_{M2}| = 1.705\ \Omega$$

Short-circuit current $\underline{I}''_k$ at the short-circuit location F in Figure A5, page 137, according to Equation (55) in Sub-clause 12.2.3.2:

$$\underline{I}''_k = (\underline{I}''_{kT1} + \underline{I}''_{kT2}) + \underline{I}''_{kM1} + \underline{I}''_{kM2}$$

$$\underline{I}''_{kT1} + \underline{I}''_{kT2} = \frac{cU_n}{\sqrt{3}\ \underline{Z}_{k(T1,T2)}} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3}\ (0.02259 + \text{j}\ 0.2651)\ \Omega} = (1.216 - \text{j}\ 14.27)\ \text{kA}$$

$$\underline{I}''_{kM1} = \frac{cU_n}{\sqrt{3}\ \underline{Z}_{M1}} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3}\ (0.1493 + \text{j}\ 1.493)\ \Omega} = (0.253 - \text{j}\ 2.527)\ \text{kA}$$

$$\underline{I}''_{kM2} = \frac{cU_n}{\sqrt{3}\ \underline{Z}_{M2}} = \frac{1.1 \cdot 6\ \text{kV}}{\sqrt{3}\ (0.1696 + \text{j}\ 1.696)\ \Omega} = (0.223 - \text{j}\ 2.225)\ \text{kA}$$

$$\underline{I}''_k = (1.692 - \text{j}\ 19.02)\ \text{kA}; |\underline{I}''_k| = 19.10\ \text{kA} \qquad \text{(see Sub-clause A2.2)}$$

Peak short-circuit current i_p at the short-circuit location F in Figure A5 according to Equation (56) in Sub-clause 12.2.3.3:

$$i_p = (i_{pT1} + i_{pT2}) + i_{pM1} + i_{pM2}$$

According to Sub-clause 9.1.1.2:

$$\text{T1, T2: } \frac{R}{X} = \frac{0.02259\ \Omega}{0.2651\ \Omega} = 0.0852$$

$$\varkappa = 1.02 + 0.98\ e^{-3 \cdot 0.0852} = 1.78$$

$$i_{pT1} + i_{pT2} = \sqrt{2}\ \varkappa\ (I''_{kT1} + I''_{kT2})$$

$$i_{pT1} + i_{pT2} = \sqrt{2} \cdot 1.78 \cdot 14.32\ \text{kA} = 36.05\ \text{kA}$$

$$\text{M1: } \frac{R}{X} = 0.1;\ \varkappa_{M1} = 1.75 \qquad \text{(see Table II)}$$

$$i_{pM1} = \sqrt{2}\ \varkappa_{M1}\ I''_{kM1} = \sqrt{2} \cdot 1.75 \cdot 2.54\ \text{kA} = 6.29\ \text{kA}$$

$$\text{M2: } \frac{R}{X} = 0.1;\ \varkappa_{M2} = 1.75$$

$$i_{pM2} = \sqrt{2}\ \varkappa_{M2}\ I''_{kM2} = \sqrt{2} \cdot 1.75 \cdot 2.24\ \text{kA} = 5.53\ \text{kA}$$

$$i_p = (36.05 + 6.29 + 5.53)\ \text{kA} = 47.87\ \text{kA}$$

Decaying aperiodic component i_{DC} according to Equation (1) at $f = 50$ Hz:

$$i_{DC} = (i_{DC,T1} + i_{DC,T2}) + i_{DC,M1} + i_{DC,M2}$$

$$i_{DC,T1} + i_{DC,T2} = \sqrt{2}\ (I''_{kT1} + I''_{kT2})\ e^{-2\pi\ ftR/X}$$

$$i_{DC,T1} + i_{DC,T2} = \sqrt{2} \cdot 14.32\ \text{kA}\ e^{-2\pi\ 50\ s^{-1} \cdot 0.0852 \cdot t}$$

$$i_{DC,M1} = \sqrt{2}\ I''_{kM1}\ e^{-2\pi\ ft\ R/X} = \sqrt{2} \cdot 2.54\ \text{kA}\ e^{-2\pi\ 50\ s^{-1} \cdot 0.1 \cdot t}$$

$$i_{DC,M2} = \sqrt{2}\ I''_{kM2}\ e^{-2\pi\ ft\ R/X} = \sqrt{2} \cdot 2.24\ \text{kA}\ e^{-2\pi\ 50\ s^{-1} \cdot 0.1 \cdot t}$$

Symmetrical short-circuit breaking current I_b according to Equation (57) in Sub-clause 12.2.3.3:

$$I_b = (I_{bT1} + I_{bT2}) + I_{bM1} + I_{bM2}$$

$$I_{bT1} + I_{bT2} = I''_{kT1} + I''_{kT2} = 14.32\ \text{kA}$$

(according to Sub-clause 12.2.3.3, far-from-generator short circuit)

$$I_{bM1} = \mu_{M1}\ q_{M1}\ I''_{kM1}$$

With a minimum time delay $t_{min} = 0.1$ s and the already calculated values for μ and q:

$$I_{bM1} = 0.80 \cdot 0.68 \cdot 2.54\ \text{kA} = 1.38\ \text{kA}$$

and corresponding for the motor M2:

$$I_{bM2} = 0.72 \cdot 0.57 \cdot 2.24 \text{ kA} = 0.92 \text{ kA}$$

$$I_b = (14.32 + 1.38 + 0.92) \text{ kA} = 16.62 \text{ kA} \qquad \text{(see Sub-clause A2.2)}$$

Asymmetrical short-circuit breaking current $I_{b\,asym}$ with the help of i_{DC}:

$$I_{b\,asym} = \sqrt{I_b^2 + \left(\frac{i_{DC}}{\sqrt{2}}\right)^2}$$

For $t_{min} = 0.1$ s ($f = 50$ Hz):

$$i_{DC} = \sqrt{2} \cdot 14.32 \text{ kA} \cdot 0.0688 + \sqrt{2} \cdot 2.54 \text{ kA} \cdot 0.0432 + \sqrt{2} \cdot 2.24 \text{ kA} \cdot 0.0432$$

$$i_{DC} = \sqrt{2}\,(0.985 + 0.110 + 0.097) \text{ kA} = \sqrt{2} \cdot 1.192 \text{ kA}$$

$$I_{b\,asym} = \sqrt{(16.62 \text{ kA})^2 + \left(\frac{\sqrt{2} \cdot 1.192 \text{ kA}}{\sqrt{2}}\right)^2}$$

$$I_{b\,asym} = \sqrt{276.2 + 1.42} \text{ kA} = 16.66 \text{ kA} \approx I_b$$

Steady-state short-circuit current I_k according to Equation (58):

$$I_k = (I_{kT1} + I_{kT2}) + I_{kM1} + I_{kM2}$$

$$I_{kT1} + I_{kT2} = I''_{kT1} + I''_{kT2} = 14.32 \text{ kA}$$

$$I_{kM1} = I_{kM2} = 0 \qquad \text{according to Equation (72)}$$

$$I_k = 14.32 \text{ kA}$$

A3. Example 3: Calculation of balanced short-circuit currents in the case of near-to-generator short circuits. Impedance correction factor

A3.1 *Problem*

The balanced short-circuit currents at the short-circuit locations F1 to F4 in Figure A6, page 147, are to be calculated according to Section Two.

A power-station unit (PSU) is connected to a 220 kV system with the actual, initial short-circuit power $S''_{kQ} = 8000$ MVA of the network feeder. The auxiliary transformer AT is of the three-winding type feeding two auxiliary busbars B and C with $U_n = 10$ kV.

The influence of asynchronous motors on the short-circuit currents is to be taken into account when calculating short-circuit currents at the short-circuit locations F2, F3 and F4. Low-voltage asynchronous motors shall be handled as motor groups. The terminal short-circuit currents of the high-voltage or low-voltage motors are calculated within the Tables AVI or AVII.

A3.2 *Short-circuit impedances of electrical equipment*

A3.2.1 *Network feeder*

According to Sub-clause 8.3.2.1 it follows, with $c = 1.1$ from the actual symmetrical short-circuit power at the feeder connection point, that:

$$Z_Q = \frac{cU_n^2}{S''_{kQ}} = \frac{1.1 \cdot (220\,\text{kV})^2}{8000\,\text{MVA}} = 6.655\ \Omega$$

$$\left. \begin{array}{l} X_Q = 0.995\, Z_Q = 0.995 \cdot 6.655\ \Omega = 6.622\ \Omega \\ R_Q = 0.1\, X_Q = 0.1 \cdot 6.622\ \Omega = 0.6622\ \Omega \end{array} \right\} \quad \underline{Z}_Q = (0.6622 + \text{j}\, 6.622)\ \Omega$$

For the calculation of the maximum short-circuit current at the short-circuit locations F2 and F3, $Z_{Q\,min}$ (corresponding to $S''_{kQ\,max}$) is found according to Sub-clause 12.2.3.1. $S''_{kQ\,max}$ is to be estimated from the future planning of the power-system.

$$Z_{Q\,min} = \frac{cU_{nQ}^2}{S''_{kQ\,max}} = \frac{1.1 \cdot (220\,\text{kV})^2}{20000\,\text{MVA}} = 2.662\ \Omega$$

$$\underline{Z}_{Q\,min} = (0.2649 + \text{j}\, 2.649)\ \Omega$$

A3.2.2 *Unit transformer*

From the data given in Figure A6, page 149, Equations (6) to (8) according to Sub-clause 8.3.2.2 yield:

$$Z_{THV} = \frac{u_{kr}}{100\%} \cdot \frac{U_{rTHV}^2}{S_{rT}} = \frac{15\%}{100\%} \cdot \frac{(240\,\text{kV})^2}{250\,\text{MVA}} = 34.56\ \Omega$$

$$R_{THV} = \frac{P_{krT}}{3\, I_{rTHV}^2} = P_{krT} \cdot \frac{U_{rTHV}^2}{S_{rT}^2} = 0.52\,\text{MW}\ \frac{(240\,\text{kV})^2}{(250\,\text{MVA})^2} = 0.479\ \Omega$$

$$X_{THV} = \sqrt{Z_{THV}^2 - R_{THV}^2} = 34.56\ \Omega$$

$$\underline{Z}_{THV} = (0.479 + \text{j}\, 34.56)\ \Omega$$

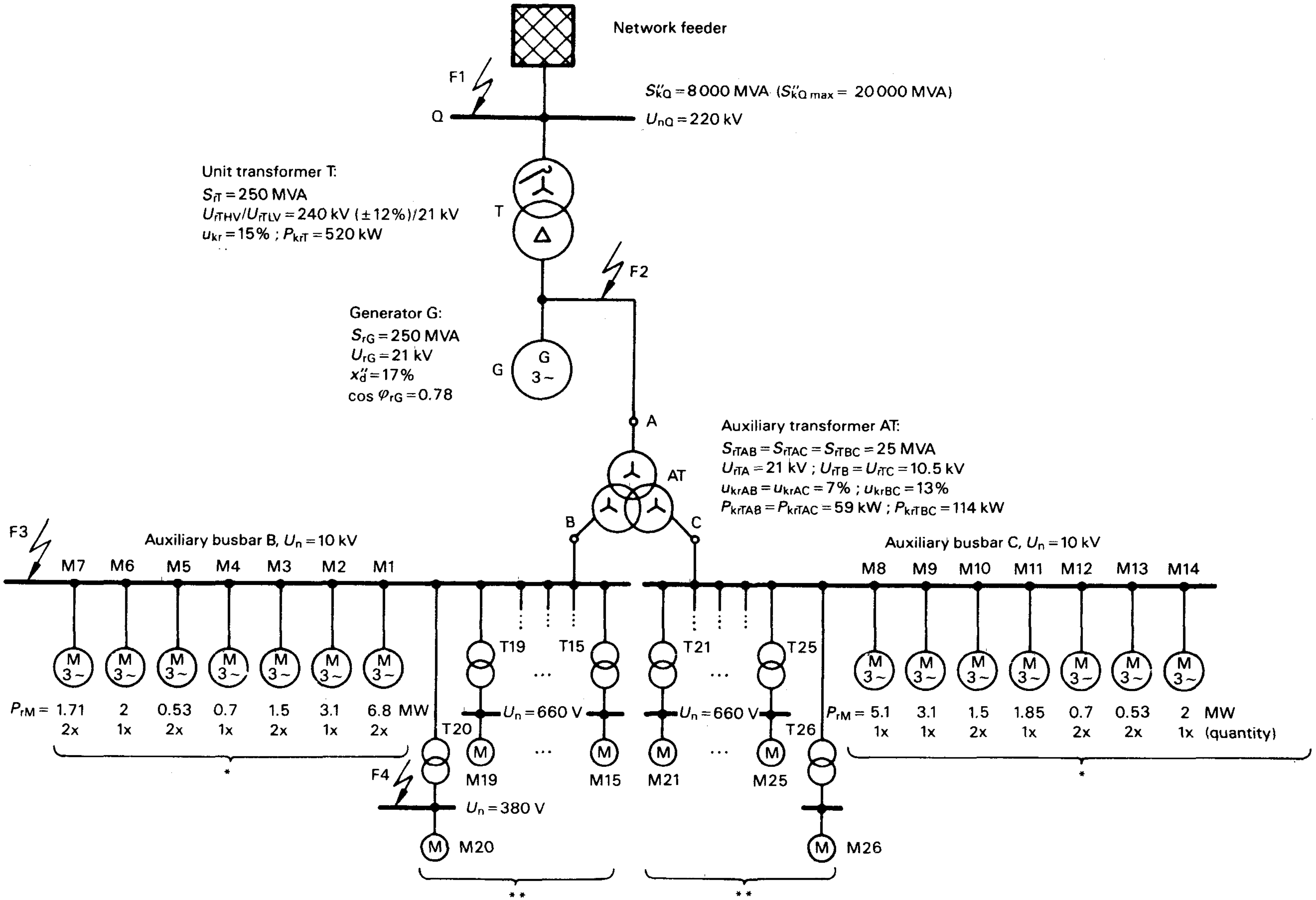
Converted to the low-voltage side of the unit transformer with $t_r = 240\,\text{kV}/21\,\text{kV}$:

$$X_{TLV} = X_{THV} \cdot \frac{1}{t_r^2} = 34.56\ \Omega\ \frac{1}{(240\,\text{kV}/21\,\text{kV})^2} = 0.2646\ \Omega;\ R_{TLV} = 0.00367\ \Omega$$

$$\underline{Z}_{TLV} = (0.00367 + \text{j}\, 0.2646)\ \Omega$$

A3.2.3 *Generator*

With the data given in Figure A6, the calculation according to Sub-clause 11.5.3.7 with $c = 1.1$ (see Table I) and $R_G = 0.05\, X''_d$ (see Sub-clause 11.5.3.6) can be performed as:



* For details see Table AVI.
** For details see Figure A8 and Table AVII.

FIG. A6. – Network feeder, power-station unit (PSU) – unit transformer and generator – with auxiliary transformer (AT), high-voltage and low-voltage asynchronous motors, Example 3.

$$\underline{Z}_G = R_G + j\,X''_d = X''_d\,(0.05 + j) = x''_d\,\frac{U^2_{rG}}{S_{rG}}\,(0.05 + j) = 0.17 \cdot \frac{(21\ \text{kV})^2}{250\ \text{MVA}}\,(0.05 + j)$$

$$\underline{Z}_G = (0.0150 + j\,0.2999)\ \Omega$$

The correction factor according to Sub-clause 11.5.3.7 can be found:

$$K_{G,\,PSU} = \frac{c_{max}}{1 + x''_d \sin \varphi_{rG}} = \frac{1.1}{1 + 0.17 \cdot 0.6258} = 0.9942$$

therefore:

$$\underline{Z}_{G,\,PSU} = K_{G,\,PSU}\,\underline{Z}_G = 0.9942\,(0.0150 + j\,0.2999)\ \Omega = (0.0149 + j\,0.2982)\ \Omega$$

In order to calculate the short-circuit current on the high-voltage side of the transformer (F1 in Figure A6, page 149) the equations in Sub-clause 11.5.3.8 are used with $c_{max} = 1.1$, $t_f = U_n / U_{rG} = 220\ \text{kV}/21\ \text{kV}$ and $t_r = 240\ \text{kV}/21\ \text{kV}$, and therefore:

$$K_{PSU} = \left(\frac{t_f}{t_r}\right)^2 \cdot \frac{c_{max}}{1 + (x''_d - x_T)\sin \varphi_{rG}} = \left(\frac{220\ \text{kV}}{21\ \text{kV}} \cdot \frac{21\ \text{kV}}{240\ \text{kV}}\right)^2 \cdot \frac{1.1}{1 + (0.17 - 0.15)\,0.6258}$$

$$K_{PSU} = 0.9129$$

$$\underline{Z}_{PSU} = K_{PSU}[t_r^2 \underline{Z}_G + \underline{Z}_{THV}] = 0.9129\ \left[\left(\frac{240\ \text{kV}}{21\ \text{kV}}\right)^2 (0.0150 + j0.2999)\,\Omega + (0.479 + j34.56)\,\Omega\right]$$

$$\underline{Z}_{PSU} = 0.9129\,[(1.959 + j\,39.17)\ \Omega + (0.479 + j\,34.56)\ \Omega] = (2.226 + j\,67.31)\ \Omega$$

A3.2.4 *Auxiliary transformer*

The positive-sequence short-circuit impedances $\underline{Z}_A$, $\underline{Z}_B$ and $\underline{Z}_C$ according to Figure 7, page 41, can be determined with the equations of Sub-clause 8.3.2.2. Substituting the data presented in Figure A6 in Equation (9), the positive-sequence short-circuit impedances of the transformer are calculated as follows (related to the 21 kV side A):

$$Z_{AB} = \frac{u_{krAB}}{100\%} \cdot \frac{U^2_{rTA}}{S_{rTAB}} = \frac{7\%}{100\%} \cdot \frac{(21\ \text{kV})^2}{25\ \text{MVA}} = 1.2348\ \Omega$$

$$Z_{AC} = Z_{AB}$$

$$Z_{BC} = \frac{u_{krBC}}{100\%} \cdot \frac{U^2_{rTA}}{S_{rTBC}} = \frac{13\%}{100\%} \cdot \frac{(21\ \text{kV})^2}{25\ \text{MVA}} = 2.2932\ \Omega$$

$$R_{AB} = R_{AC} = P_{krTAB}\,\frac{U^2_{rTA}}{S^2_{rTAB}} = 0.059\ \text{MW}\,\frac{(21\ \text{kV})^2}{(25\ \text{MVA})^2} = 0.04163\ \Omega$$

$$R_{BC} = P_{krTBC} \frac{U_{rTA}^2}{S_{rTBC}^2} = 0.114\ \text{MW} \frac{(21\ \text{kV})^2}{(25\ \text{MVA})^2} = 0.08044\ \Omega$$

$$X_{AB} = X_{AC} = \sqrt{Z_{AB}^2 - R_{AB}^2} = 1.2341\ \Omega$$

$$X_{BC} = \sqrt{Z_{BC}^2 - R_{BC}^2} = 2.2918\ \Omega$$

Using Equation (10) and referring the impedances to $U_{rTA} = 21$ kV:

$$\underline{Z}_A = \frac{1}{2}(\underline{Z}_{AB} + \underline{Z}_{AC} - \underline{Z}_{BC}) = \frac{1}{2}(0.00282 + j\,0.1764)\ \Omega = (0.00141 + j\,0.0882)\ \Omega$$

$$\underline{Z}_B = \frac{1}{2}(\underline{Z}_{BC} + \underline{Z}_{AB} - \underline{Z}_{AC}) = \frac{1}{2}(0.08044 + j\,2.2918)\ \Omega = (0.04022 + j\,1.1459)\ \Omega$$

$$\underline{Z}_C = \frac{1}{2}(\underline{Z}_{AC} + \underline{Z}_{BC} - \underline{Z}_{AB}) = \frac{1}{2}(0.08044 + j\,2.2918)\ \Omega = (0.04022 + j\,1.1459)\ \Omega$$

Converted to the 10.5 kV (side B or C) with $t_r = 21$ kV/10.5 kV, the impedances of the three-winding transformer AT are:

$$\underline{Z}_{ALV} = \underline{Z}_A \cdot \frac{1}{t_r^2}\ (0.000353 + j\,0.02205)\ \Omega$$

$$\underline{Z}_{BLV} = \underline{Z}_{CLV} = \underline{Z}_B \cdot \frac{1}{t_r^2}\ (0.0101 + j\,0.2865)\ \Omega$$

A3.2.5 *Low-voltage transformers 2.5 MVA and 1.6 MVA*

According to Figure A6, page 149, and Figure A8, page 165, there are five transformers with $S_{rT} = 2.5$ MVA and $U_{rTHV}/U_{rTLV} = 10$ kV/0.693 kV connected to each of the two auxiliary busbars 10 kV and in addition one transformer with $S_{rT} = 1.6$ MVA, $U_{rTHV}/U_{rTLV} = 10$ kV/0.4 kV. Each of these transformers feeds a group of low-voltage asynchronous motors.

With the equations in Sub-clause 8.3.2.2 and the data in Table AVII it follows that:

$$Z_{T15HV} = \frac{u_{krT15}}{100\%} \cdot \frac{U_{rT15HV}^2}{S_{rT15}} = \frac{6\%}{100\%} \cdot \frac{(10\ \text{kV})^2}{2.5\ \text{MVA}} = 2.4\ \Omega$$

$$R_{T15HV} = \frac{P_{krT15}}{3\,I_{rT15}^2} = P_{krT15} \frac{U_{rT15HV}^2}{S_{rT15}^2} = 0.0235\ \text{MW} \frac{(10\ \text{kV})^2}{(2.5\ \text{MVA})^2} = 0.376\ \Omega$$

$$X_{T15HV} = \sqrt{Z_{T15HV}^2 - R_{T15HV}^2} = 2.3704\ \Omega$$

$$\underline{Z}_{T15HV} = R_{T15HV} + j\,X_{T15HV} = (0.376 + j\,2.3704)\ \Omega$$

$$= \underline{Z}_{T16HV} \ldots Z_{T19HV}, \underline{Z}_{T21HV} \ldots \underline{Z}_{T25HV}$$

$$Z_{T20HV} = \frac{u_{krT20}}{100\%} \cdot \frac{U_{rT20HV}^2}{S_{rT20}} = \frac{6\%}{100\%} \cdot \frac{(10\ \text{kV})^2}{1.6\ \text{MVA}} = 3.75\ \Omega$$

$$R_{T20HV} = 0.0165 \text{ MW} \frac{(10 \text{ kV})^2}{(1.6 \text{ MVA})^2} = 0.6445 \ \Omega$$

$$X_{T20HV} = \sqrt{Z^2_{T20HV} - R^2_{T20HV}} = 3.694 \ \Omega$$

$$\underline{Z}_{T20HV} = R_{T20HV} + \text{j}\, X_{T20HV} = (0.6445 + \text{j}\, 3.694) \ \Omega = \underline{Z}_{T26HV}$$

Converted to the low-voltage side with $t_r = 10 \text{ kV}/0.4 \text{ kV}$:

$$\underline{Z}_{T20LV} = \underline{Z}_{T20HV} \cdot \frac{1}{t_r^2} = (1.031 + \text{j}\, 5.910) \text{ m}\Omega$$

A3.2.6 *Asynchronous motors*

Data and calculations of the short-circuit impedances of the high-voltage motors M1 to M14 according to Sub-clauses 11.5.3.5 and 13.2 are given in Table AVI.

Using Equations (69) and (34) and bearing in mind that U_{rM} is equal to U_n in this special case, the following expression can be found for I''_{k3M}:

$$I''_{k3M} = \frac{cU_n}{\sqrt{3}\, Z_M} = c \frac{U_n}{\sqrt{3}} \frac{I_{LR}}{I_{rM}} \cdot \frac{I_{rM}}{U_{rM}/\sqrt{3}} = c \frac{I_{LR}}{I_{rM}} \cdot I_{rM}$$

Data and calculation of the short-circuit impedances of the low-voltage motor groups including their supply cables according to Sub-clauses 11.5.3.5 and 13.2 are given in Figure A8, page 165, and Table AVII.

TABLE AVI

Data of high-voltage motors and their partial short-circuit currents at the short-circuit location on busbars B or C respectively

Auxiliary busbar		B								C								
Motor No. (see Figure A6)		1	2	3	4	5	6	7	Σ (1…7)	8	9	10	11	12	13	14	Σ (8…14)	Remarks
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	–	Data given from the manufacturer
Quantity of motors	–	2	1	2	1	2	1	2	–	1	1	2	1	2	2	1	–	
U_{rM}	kV	—	—	—	10	—	—	—	–	—	—	—	10	—	—	—	–	
$\cos\varphi_r$	–	0.89	0.85	0.88	0.85	0.75	0.85	0.95	–	0.87	0.85	0.88	0.85	0.85	0.75	0.85	–	
η_r	–	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}	–	—	—	—	4	—	—	—	–	—	—	—	4	—	—	—	–	
Pair of poles p	–	2	2	1	3	5	3	3	–	3	2	1	3	3	5	3	–	
S_{rM} (ΣS_{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	Calculated with $S_{rM} = P_{rM}/\cos\varphi_r\eta_r$
I_{rM} (ΣI_{rM})	kA	0.904	0.220	0.205	0.05	0.086	0.141	0.242	1.85	0.348	0.219	0.204	0.131	0.10	0.086	0.141	1.23	Calculated with $I_{rM} = S_{rM}/(\sqrt{3}\,U_{rM})$
I''_{k3M}/I_{rM}	–	—	—	—	4.4	—	—	—	–	—	—	—	4.4	—	—	—	–	See Sub-clause A3.2.6
m	MW	3.4	1.55	1.5	0.23	0.11	0.67	0.57	–	1.7	1.55	1.5	0.62	0.23	0.11	0.67	–	$m = P_{rM}/p$
R_M/X_M	–	0.1	0.1	0.1	0.15	0.15	0.15	0.15	–	0.1	0.1	0.1	0.15	0.15	0.15	0.15	–	according to Sub-clause 11.5.3.5
$\varkappa_M$	–	1.75	1.75	1.75	1.65	1.65	1.65	1.65	–	1.75	1.75	1.75	1.65	1.65	1.65	1.65	–	[1]
μ (t_{min} = 0.1 s)	–	—	—	—	0.796	—	—	—	–	—	—	—	0.796	—	—	—	–	$\mu = 0.62 + 0.72e^{-0.32 I''_{k3M}/I_{rM}}$ [2]
q (t_{min} = 0.1 s)	–	0.72	0.62	0.62	0.39	0.31	0.52	0.50	–	0.63	0.62	0.62	0.51	0.39	0.31	0.52	–	$q = 0.57 + 0.12\,ln\,m$ [3]
I''_{k3M}	kA	3.98	0.97	0.90	0.22	0.38	0.62	1.06	8.14	1.53	0.96	0.90	0.58	0.44	0.38	0.62	5.41	$I''_{k3M} = (I''_{k3M}/I_{rM})\,I_{rM}$
i_{p3M}	kA	9.85	2.40	2.23	0.51	0.89	1.45	2.47	19.8	3.79	2.38	2.23	1.35	1.03	0.89	1.45	13.12	$i_{p3M} = \varkappa_M \sqrt{2}\,I''_{k3M}$, Equation (70)
I_{b3M}	kA	2.28	0.48	0.44	0.07	0.09	0.26	0.42	4.04	0.77	0.47	0.44	0.24	0.14	0.09	0.26	2.41	$I_{b3M} = q\mu I''_{k3M}$, Equation (71)
Z_M	Ω	1.60	6.58	7.06	28.74	16.78	10.2	5.97	0.78	4.15	6.56	7.06	11.01	14.45	16.78	10.2	1.17	Calculated with Equation (34)
X_M	Ω	0.995 Z_M			0.989 Z_M				0.777	0.995 Z_M			0.989 Z_M				1.165	According to Sub-clause 11.5.3.5
R_M	Ω	0.1 X_M			0.15 X_M				0.08	0.1 X_M			0.15 X_M				0.138	

[1] The values for $\varkappa_M$ are given in Table II of Sub-clause 13.2.2.

[2] Equation (47), t_{min} = 0.1 s.

[3] Equation (67), t_{min} = 0.1 s.

A3.3 *Calculation of short-circuit currents*

A3.3.1 *Short circuit at the short-circuit location F1*

The calculation is done according to Sub-clause 12.2.3. It is not necessary to take the asynchronous motors into account (see Sub-clause 13.2.1, contribution of motors smaller than 5%).

The initial symmetrical short-circuit current is calculated according to Equation (55):

$$\underline{I}''_k = \underline{I}''_{kPSU} + \underline{I}''_{kQ}$$

$$\underline{I}''_{kPSU} = \frac{1.1 \cdot U_n}{\sqrt{3}\,\underline{Z}_{PSU}} = \frac{1.1 \cdot 220\text{ kV}}{\sqrt{3}\,(2.226 + \text{j}\,67.31)\,\Omega} = (0.0686 - \text{j}\,2.073)\text{ kA}; |\underline{I}''_{kPSU}| = 2.075\text{ kA}$$

$$I''_{kQ} = \frac{S''_{kQ}}{\sqrt{3}\,U_n} = \frac{8000\text{ MVA}}{\sqrt{3}\cdot 220\text{ kV}} = 20.99\text{ kA}$$

$$\underline{I}''_{kQ} = \frac{1.1 \cdot U_n}{\sqrt{3}\,\underline{Z}_Q} = \frac{1.1 \cdot 220\text{ kV}}{\sqrt{3}\,(0.6622 + \text{j}\,6.622)\,\Omega} = (2.088 - \text{j}\,20.89)\text{ kA}; |\underline{I}''_{kQ}| = 20.99\text{ kA}$$

$$\underline{I}''_{k} = \underline{I}''_{kPSU} + \underline{I}''_{kQ} = (2.157 - j\,22.96)\ \text{kA};\ |\underline{I}''_{k}| = 23.06\ \text{kA}$$

Equation (56):

$$i_p = i_{pPSU} + i_{pQ}$$

Power-station unit:

$$R/X = R_{PSU}/X_{PSU} = 2.226\ \Omega/67.31\ \Omega = 0.033 \rightarrow \varkappa_{PSU} = 1.91$$

$$i_{pPSU} = \varkappa_{PSU}\sqrt{2}\ I''_{kPSU} = 1.91 \cdot \sqrt{2} \cdot 2.075\ \text{kA} = 5.605\ \text{kA}$$

Network feeder:

$$R_Q/X_Q = 0.1;\ \varkappa_Q = 1.75$$

$$i_{pQ} = \varkappa_Q\sqrt{2}\ I''_{kQ} = 1.75 \cdot \sqrt{2} \cdot 20.99\ \text{kA} = 51.95\ \text{kA}$$

$$i_p = 5.605\ \text{kA} + 51.95\ \text{kA} = 57.56\ \text{kA}$$

Equation (57), $t_{min} = 0.1$ s:

$$I_b = I_{bPSU} + I_{bQ} = I_{bPSU} + I''_{kQ}$$

Power-station unit (see Sub-clauses 12.2.3.3 and 12.2.2.3):

$$I_{bPSU} = \mu I''_{kPSU};\ \mu = \mu_{0.1s} = 0.62 + 0.72\ e^{-0.32\, I''_{kG}/I_{rG}} = 0.859$$

with:

$$I''_{kG}/I_{rG} = I''_{kPSUt}/I_{rG} = t_z\, I''_{kPSU}/I_{rG} = (240\ \text{kV}/21\ \text{kV}) \cdot 2.075\ \text{kA}/6.873\ \text{kA} = 3.45$$

$$I_{bPSU} = 0.859 \cdot 2.075\ \text{kA} = 1.78\ \text{kA}$$

$$I_b = I_{bPSU} + I''_{kQ} = 1.78\ \text{kA} + 20.99\ \text{kA} = 22.77\ \text{kA}$$

A3.3.2 *Short circuit at the short-circuit location F2*

First of all, according to Figure 21, page 89, the initial symmetrical short-circuit current at the short-circuit location F2 (without the influence of asynchronous motors) is derived from the partial short-circuit currents $\underline{I}''_{kG}$ (see Equation (52)) and I''_{kT} (see Equations (53) and (41)).

$$\underline{I}''_{kG} = \frac{cU_{rG}}{\sqrt{3}\ \underline{Z}_{G,PSU}} = \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3}\ (0.0149 + j\,0.2982)\ \Omega} = (2.23 - j\,44.61)\ \text{kA};\ |\underline{I}''_{kG}| = 44.67\ \text{kA}$$

$$\underline{I}''_{kT} = \frac{cU_{rG}}{\sqrt{3}\left[\ (\underline{Z}_{T,PSU} + \frac{1}{t_f^2}\,\underline{Z}_{Q\,min})\ \right]}$$

$$= \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3}\left[\ 1.1\,(0.00367 + j\,0.2646)\ \Omega + \left(\frac{21\ \text{kV}}{220\ \text{kV}}\right)^2 (0.2649 + j\,2.649)\ \Omega\ \right]}$$

$$\underline{I}''_{kT} = \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3}\ (0.00645 + j\,0.3152)\ \Omega} = (0.8655 - j\,42.29)\ \text{kA}; |\underline{I}''_{kT}| = 42.30\ \text{kA}$$

$$\underline{I}''_{k} = \underline{I}''_{kG} + \underline{I}''_{kT} = (3.10 - j\,86.90)\ \text{kA}; |\underline{I}_{k}| = 86.96\ \text{kA}$$

Using Equation (54) $\underline{Z}_{rsl}$ is calculated from $\underline{Z}_{G,PSU}$ and

$$\left[\underline{Z}_{T,PSU} + \frac{1}{t_f^2} \cdot \underline{Z}_{Q\,min} \right] :$$

$$\underline{Z}_{rsl} = \frac{(0.0149 + j\,0.2982)\ \Omega\ (0.00645 + j\,0.3152)\ \Omega}{(0.02135 + j\,0.6134)\ \Omega} = (0.00546 + j\,0.1533)\ \Omega;$$

$$|\underline{Z}_{rsl}| = 0.1534\ \Omega$$

$$I''_{k} = \frac{cU_{rG}}{\sqrt{3}\ |\underline{Z}_{rsl}|} = \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3} \cdot 0.1534\ \Omega} = 86.94\ \text{kA}$$

Normally it is sufficient to calculate as follows (because $R \ll X$):

$$I''_{kG} = \frac{cU_{rG}}{\sqrt{3}\ Z_{G,PSU}} = \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3} \cdot 0.2986\ \Omega} = 44.66\ \text{kA}$$

$$I''_{kT} = \frac{cU_{rG}}{\sqrt{3} \left[(Z_{T,PSU} + \frac{1}{t_f^2} Z_{Q\,min}) \right]}$$

$$= \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3} \left[1.1 \cdot 0.2646\ \Omega + \left(\frac{21\ \text{kV}}{220\ \text{kV}} \right)^2 \cdot 2.662\ \Omega \right]} = 42.30\ \text{kA}$$

$$I''_{k} = I''_{kG} + I''_{kT} = 86.96\ \text{kA}$$

$$i_p = i_{pG} + i_{pT} \qquad \text{according to Equation (56)}$$

i_{pG} calculated with $R_G / X''_d = 0.05$ (see Sub-clause 11.5.3.6) $\rightarrow \varkappa_G = 1.86$

$$i_{pG} = \varkappa_G \sqrt{2}\ I''_{kG} = 1.86 \cdot \sqrt{2} \cdot 44.67\ \text{kA} = 117.48\ \text{kA}$$

i_{pT} calculated with $R/X = 0.00645\ \Omega / 0.3152\ \Omega = 0.0205 \rightarrow \varkappa_T = 1.94$

$$i_{pT} = \varkappa_T \sqrt{2}\ I''_{kT} = 1.94 \sqrt{2} \cdot 42.30\ \text{kA} = 116.05\ \text{kA}$$

$$i_p = 233.53\ \text{kA}$$

$$I_b = I_{bG} + I_{bT} = I_{bG} + I''_{kT}; \quad I_{bT} = I''_{kT} \text{ (see Equation (57))}$$

$$I_{bG} = \mu I''_{kG}; \; I''_{kG}/I_{rG} = 44.67 \text{ kA}/6.873 \text{ kA} = 6.50 \rightarrow \mu_{0.1\,s} = 0.71$$

$$I_{bG} = 0.71 \cdot 44.67 \text{ kA} = 31.71 \text{ kA}$$

$$I_b = 31.71 \text{ kA} + 42.30 \text{ kA} = 74.01 \text{ kA}$$

Normally, there is no circuit breaker provided to switch off the total breaking current, so that only the current $I_{bT} = I''_{kT}$ is of interest.

The additional short-circuit currents fed from the asynchronous motors can be calculated from the results of Table AVI and AVII and from the impedances of the auxiliary transformer (see Sub-clause A3.2.4) related to the HV-side of the transformer AT.

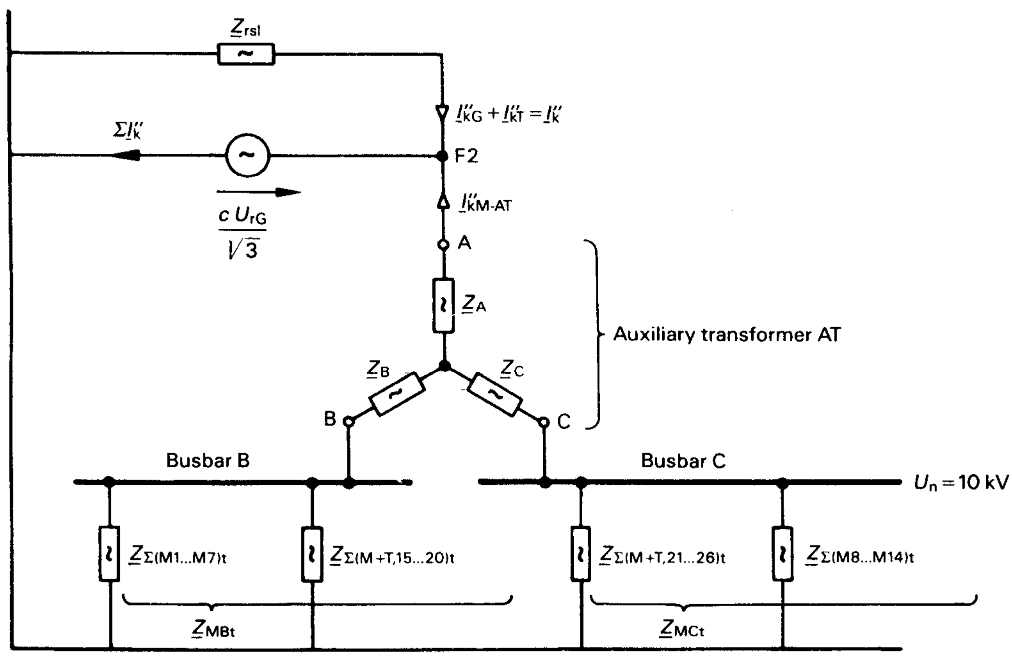


FIG. A7. – Positive-sequence system for the calculation of the partial short-circuit current I''_{kM-AT} from high-voltage and low-voltage motors at the short-circuit location F2. Impedances are transferred to the high-voltage side of the auxiliary transformer AT with $t_r = 21 \text{ kV}/10.5 \text{ kV} = 2$.

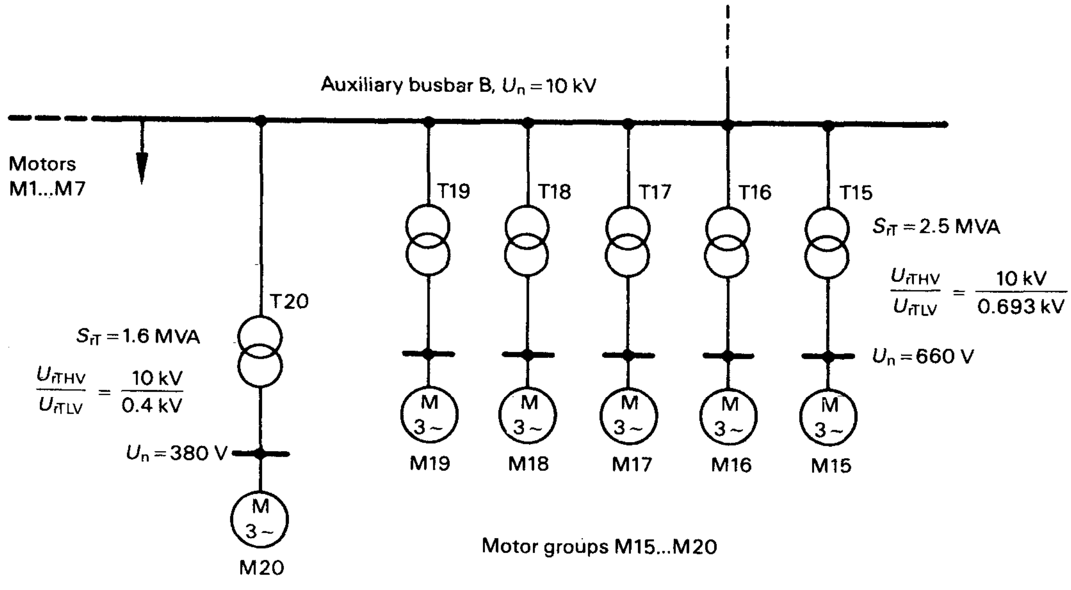


FIG. A8. – Detail of Figure A6, page 149. Transformers and groups of low-voltage asynchronous motors connected to the auxiliary busbar B. Transformers and low-voltage motor groups connected to the busbar C are identical.

$$\underline{Z}_{M,1\ldots7} = (0.086 + j\,0.777)\ \Omega$$

$$\underline{Z}_{M,8\ldots14} = (0.138 + j\,1.165)\ \Omega$$

$$\underline{Z}_{M+T,15\ldots19} = (1.200 + j\,3.152)\ \Omega = \underline{Z}_{M+T,21\ldots25}$$

$$\underline{Z}_{M+T,20} = (5.64 + j\,15.69)\ \Omega = \underline{Z}_{M+T,26}$$

$$\underline{Z}_{MB} = (0.101 + j\,0.606)\ \Omega;\ \underline{Z}_{MBt} = (0.404 + j\,2.424)\ \Omega$$

$$\underline{Z}_{MC} = (0.157 + j\,0.817)\ \Omega;\ \underline{Z}_{MCt} = (0.626 + j\,3.270)\ \Omega$$

$$\underline{Z}_{M-AT} = \underline{Z}_A + \frac{(\underline{Z}_B + \underline{Z}_{MBt})(\underline{Z}_C + \underline{Z}_{MCt})}{\underline{Z}_B + \underline{Z}_C + \underline{Z}_{MBt} + \underline{Z}_{MCt}}$$

$$= (0.00141 + j\,0.0882)\ \Omega + \frac{(0.444 + j\,3.570)\ \Omega\ (0.666 + j\,4.416)\ \Omega}{(1.110 + j\,7.986)\ \Omega}$$

$$\underline{Z}_{M-AT} = (0.00141 + j\,0.0882)\ \Omega + (0.2688 + j\,1.9744)\ \Omega = (0.270 + j\,2.063)\ \Omega$$

$$I''_{kM-AT} = \frac{cU_{rG}}{\sqrt{3}\,|\underline{Z}_{M-AT}|} = \frac{1.1 \cdot 21\ \text{kV}}{\sqrt{3} \cdot 2.08\ \Omega} = 6.41\ \text{kA}$$

TABLE AVII

Data of low-voltage asynchronous motors and data of transformers 10 kV/0.693 kV and 10 kV/0.4 kV respectively connected to the auxiliary busbar B. Partial short-circuit currents of the low-voltage motors at the short-circuit location F3.

Transformer No. Motor group No.		15 16 17 18 19	Σ (15...19)	20	Σ (15...20)	Remarks
S_{rT}	MVA	2.5	12.5	1.6	14.1	Data given by the manufacturer
U_{rTHV}	kV	10		10		
U_{rTLV}	kV	0.693		0.4		
u_{kr}	%	6		6		
P_{krT}	kW	23.5		16.5		
P_{rM} (motor group)	MW	0.9	4.5	1.0	5.5	Data given by the manufacturer
U_{rM}	kV	0.66		0.38		
$\cos \varphi_r \eta_r$	–	$0.8 \cdot 0.9 = 0.72$		0.72		
I_{LR}/I_{rM}	–	5		5		Sub-clause 13.2.1
R_M/X_M	–	0.42		0.42		Sub-clause 11.5.3.5 and Table II
$\varkappa_M$	–	1.3		1.3		Table II
S_{rM}	MVA	1.25	6.25	1.39	7.67	$S_{rM} = P_{rM}/(\cos \varphi_r \eta_r)$
Z_{THV}	Ω	2.40		3.75		Equations (6) to (8)
R_{THV}	Ω	0.376		0.6445		
X_{THV}	Ω	2.3704		3.694		
Z_M	Ω	0.0697		0.0208		Equation (34)
R_M	Ω	0.0270		0.0081		$R_M = 0.42\, X_M$
X_M	Ω	0.0643		0.0192		$X_M = 0.922\, Z_M$
I''_{k3M}	kA	5.74		11.8		$U_n = 0.66$ kV; 0.38 kV; $c = 1.05$
$Z_{Mt} = Z_M \cdot t_r^2$	Ω	14.51		13.00		Converted to the high-voltage side of the transformer
$R_{Mt} = R_M \cdot t_r^2$	Ω	5.62		5.00		
$X_{Mt} = X_M \cdot t_r^2$	Ω	13.39		12.00		
$R_{THV} + R_{MT}$	Ω	6.00	1.20	5.64	0.991	
$X_{THV} + X_{MT}$	Ω	15.76	3.152	15.69	2.625	
$\lvert Z_{THV} + Z_{Mt} \rvert$	Ω	16.862	3.372	16.693	2.806	
I''_{kT} $(\Sigma I''_{kT})$	kA	0.377	1.883	0.381	2.264	$U_n = 10$ kV; $c = 1.1$

This partial short-circuit current has to be considered because its magnitude reaches approximately 7% of the current $I''_{kG} + I''_{kT} = I''_k = 86.96$ kA as calculated before. The sum of the short-circuit current $\Sigma I''_k$ reaches:

$$\Sigma I''_k = I''_k + I''_{kM-AT} = 86.96 \text{ kA} + 6.41 \text{ kA} = 93.37 \text{ kA}$$

Additionally, partial peak short-circuit currents and breaking currents fed from the asynchronous motors are to be added to the above calculated currents i_p and I_b. These are $i_{pM-AT} = \varkappa \sqrt{2}\ I''_{kM-AT} = 1.7 \sqrt{2} \cdot 6.41$ kA $= 15.41$ kA with $\varkappa = 1.7$ as a first approach (high-voltage motors have $\varkappa = 1.75$ or $\varkappa = 1.65$, see Table AVI, low-voltage motor groups are to be considered with $\varkappa = 1.3$) and $I_{bM-AT} = I''_{kM-AT}$ as a conservative approach. Account has been taken of the fact that $I_{bG} + I_{bM-AT}$ is smaller than $I_{bT} = I''_{kT}$, so that the breaking capacity for a circuit breaker between the unit transformer and the generator may be $I_{bT} = 42.30$ kA. When calculating i_{pM-AT} with Method C of Sub-clause 9.1.3.2 taking the impedances of the motors from Tables AVI and AVII, the factor $\varkappa_c = 1.701$ is found and therefore $i_{pM-AT} = 15.42$ kA; that is equal to the value given above.

A3.3.3 *Short-circuit at the short-circuit location F3*

The initial symmetrical short-circuit current at the short-circuit location F3 can be calculated from the partial short-circuit currents as shown in Figure A9:

$$\underline{I}''_{k} = \underline{I}''_{kAT} + \underline{I}''_{k\Sigma\,(M1\ldots M7)} + \underline{I}''_{k\,(M+T,\,15\ldots 20)}$$

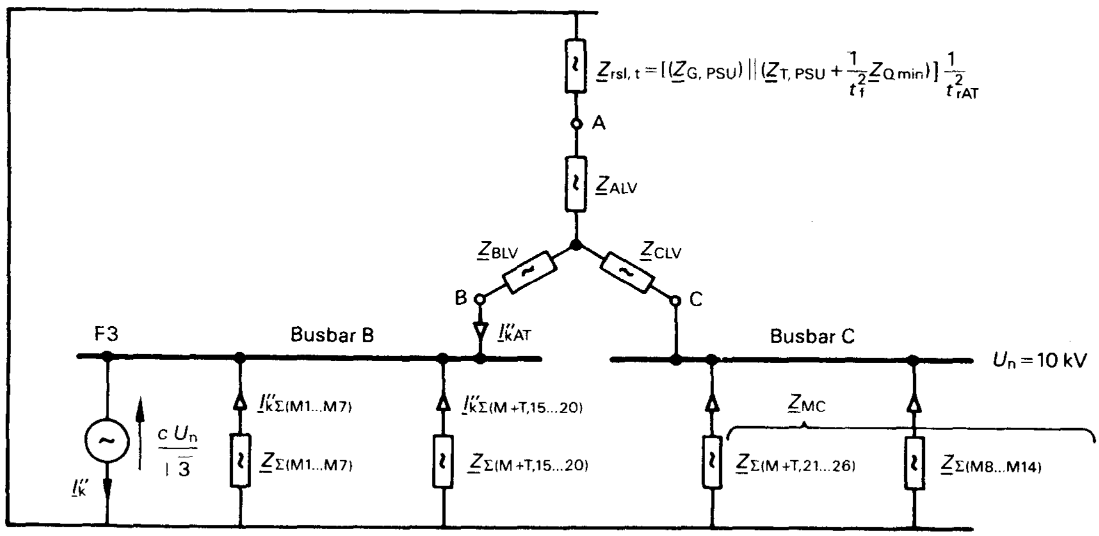


FIG. A9. – Positive-sequence system for the calculation of $\underline{I}''_k$ at the short-circuit location F3.

Calculation of $\underline{I}''_{kAT}$:

$$\underline{Z}_{kAT} = \underline{Z}_{BLV} + \frac{(\underline{Z}_{ALV} + \underline{Z}_{rsl,t})(\underline{Z}_{CLV} + \underline{Z}_{MC})}{\underline{Z}_{ALV} + \underline{Z}_{CLV} + \underline{Z}_{rsl,t} + \underline{Z}_{MC}} = (0.0101 + j\,0.2865)\ \Omega + (0.0020 + j\,0.0573)\ \Omega$$

$$\underline{Z}_{kAT} = (0.0121 + j\,0.3438)\ \Omega;\ Z_{kAT} = 0.3440\ \Omega$$

where:

$$\underline{Z}_{BLV} = (0.0101 + j\,0.2865)\ \Omega = \underline{Z}_{CLV}$$

$$\underline{Z}_{ALV} = (0.000353 + j\,0.02205)\ \Omega$$

$$\underline{Z}_{rsl,t} = (0.00546 + j\,0.1533)\ \Omega \left(\frac{10.5\ \text{kV}}{21\ \text{kV}}\right)^2 = (0.00137 + j\,0.0383)\ \Omega$$

$$\underline{Z}_{MC} = \underline{Z}_{\Sigma\,(M8\ldots M14)} \| \underline{Z}_{\Sigma\,(M+T,\,21\ldots 26)} = (0.157 + j\,0.817)\ \Omega$$

$$\underline{I}''_{kAT} = \frac{cU_n}{\sqrt{3}\ \underline{Z}_{kAT}} = \frac{1.1 \cdot 10\ \text{kV}}{\sqrt{3}\ (0.0121 + j\,0.3438)\ \Omega} = (0.649 - j\,18.45)\ \text{kA}$$

$$|\underline{I}''_{kAT}| = 18.46\ \text{kA}$$

Together with $\underline{I}''_{k\Sigma(M1...M7)} = (0.894 - j\,8.075)$ kA; ($|\underline{I}''_{k\Sigma(M1...7)}| = 8.124$ kA) and $\underline{I}''_{k\Sigma(M+T,15...20)} = (0.799 - j\,2.118)$ kA; ($|\underline{I}''_{k\Sigma(M+T,15...20)}| = 2.264$ kA)

the current $\underline{I}''_k$ can be calculated:

$$\underline{I}''_k = (0.649 - j\,18.45)\text{ kA} + (0.894 - j\,8.075)\text{ kA} + (0.799 - j\,2.118)\text{ kA} = (2.342 - j\,28.64)\text{ kA}$$

$$|\underline{I}''_k| = 28.74\text{ kA}$$

It follows for the short-circuit power (see Sub-clause 3.6):

$$S''_k = \sqrt{3}\,U_n I''_k = \sqrt{3}\;10\text{ kV} \cdot 28.74\text{ kA} = 497.8\text{ MVA}$$

The peak short-circuit current i_p can be derived with the following $\varkappa$-factors:

$$\varkappa_{AT} = 1.02 + 0.98\,e^{-3\,(0.0121\,\Omega/0.3438\,\Omega)} = 1.90$$

(see Sub-clause 9.1.3.2, Method B: $1.15 \cdot 1.9 > 2.0$)

$$\varkappa_{\Sigma(M1...M7)} = \frac{i_{p3M}}{\sqrt{2}\,I''_{k3M}} = \frac{19.8\text{ kA}}{\sqrt{2} \cdot 8.124\text{ kA}} = 1.723 \quad (i_{p3M}\text{ according to Table AVI})$$

$$\varkappa_{\Sigma(M+T,15...20)} = 1.02 + 0.98\,e^{-3\,(0.991\,\Omega/2.625\,\Omega)} = 1.34$$

$$i_p = 1.15\,\varkappa_{AT}\sqrt{2}\,I''_{kAT} + \varkappa_{\Sigma(M1...M7)}\sqrt{2}\,I''_{k\Sigma(M1...M7)} + \varkappa_{\Sigma(M+T,15...20)}\sqrt{2}\,I''_{k\Sigma(M+T,15...20)}$$

$$i_p = 2 \cdot \sqrt{2} \cdot 18.46\text{ kA} + 1.723 \cdot \sqrt{2} \cdot 8.124\text{ kA} + 1.34\sqrt{2} \cdot 2.264\text{ kA} = 76.30\text{ kA}$$

with $1.15 \cdot \varkappa_{AT} = 2$ (see Sub-clause 9.1.3.2, Method B) and the ratio R/X of the low-voltage motors including the transformers 15 to 20 according to Table AVII.

As a medium effective value $\bar{\varkappa}$ is found:

$$\bar{\varkappa} = \frac{i_p}{\sqrt{2}\,I''_k} = \frac{76.30\text{ kA}}{\sqrt{2} \cdot 28.74\text{ kA}} = 1.88$$

If the short-circuit current I''_{kAT} is transformed to the side A of the auxiliary transformer AT it becomes obvious, that I''_{kATt} is already smaller than twice I_{rG}, so that $I_{bAT} = I''_{kAT}$ is valid (see Equation (18), far-from generator short circuit).

$$I_b = I_{bAT} + I_{b\Sigma(M1...M7)} + I_{b\Sigma(M+T,15...20)}$$

$$I_{b\Sigma(M1...M7)} = \sum_{i=1}^{7} \mu_i\,q_i\,I''_{kMi} = 4.04\text{ kA (see Table AVI)}$$

$$I_{b\Sigma(M+T,15...20} = \mu\,q\,I''_{k\Sigma(M+T,15...20)} = 0.77 \cdot 0.342 \cdot 2.264\text{ kA} = 0.60\text{ kA}$$

with $\mu = 0.77$ ($t_{min} = 0.1$ s) according to $I''_{kM}/I_{rM} \approx 5$ (see Sub-clause 13.2.1) and $q \approx 0.342$ derived from the conservative estimation that the low-voltage asynchronous motors of the motor group have rated powers ≤ 0.3 MW and $p = 2$ (pair of poles).

$$I_b = 18.46\text{ kA} + 4.04\text{ kA} + 0.60\text{ kA} = 23.10\text{ kA} \quad (I_b/I''_k \approx 0.8;\ t_{min} = 0.1\text{ s})$$

A3.3.4 *Short-circuit at the short-circuit location F4*

$\underline{I}''_k$ is calculated with the help of Figure A10.

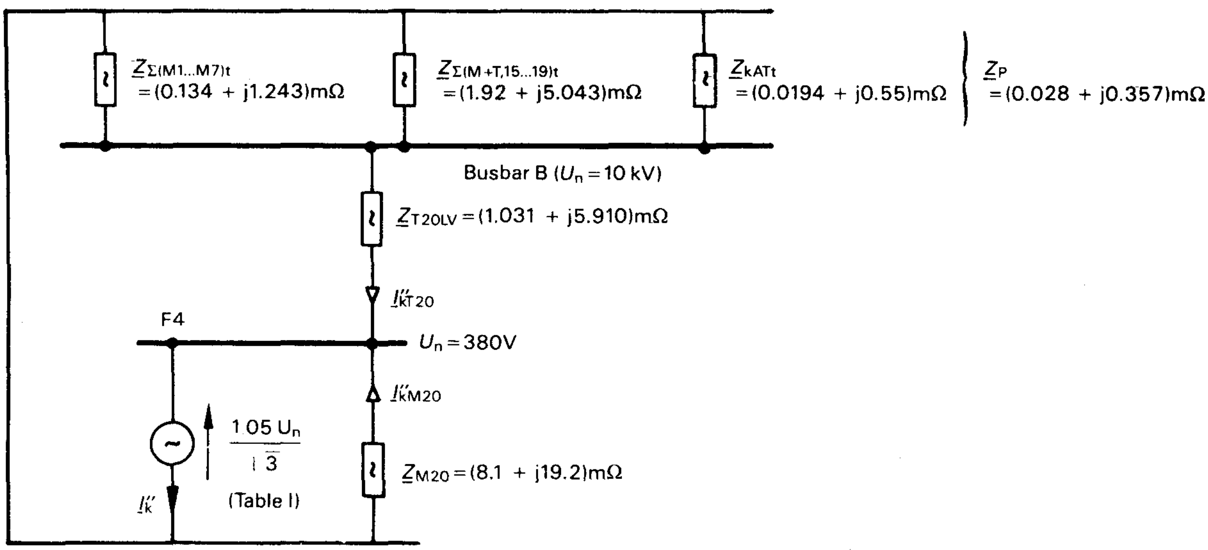


FIG. A10. – Positive-sequence system for the calculation of $\underline{I}''_k$ at the short-circuit location F4.

$$\underline{I}''_{kT20} = \frac{cU_n}{\sqrt{3}\ (\underline{Z}_P + \underline{Z}_{T20LV})} = \frac{1.05 \cdot 380\ \text{V}}{\sqrt{3}\ (1.059 + \text{j}\ 6.267)\ \text{m}\Omega} = (6.04 - \text{j}\ 35.74)\ \text{kA}$$

$$\underline{I}''_{kM20} = \frac{cU_n}{\sqrt{3}\ \underline{Z}_{M20}} = \frac{1.05 \cdot 380\ \text{V}}{\sqrt{3}\ (8.1 + \text{j}\ 19.2)\ \text{m}\Omega} = (4.30 - \text{j}\ 10.19)\ \text{kA}$$

$$\underline{I}''_k = \underline{I}''_{kT20} + \underline{I}''_{kM20} = (10.34 - \text{j}\ 45.93)\ \text{kA};\ |\underline{I}''_k| = 47.08\ \text{kA}$$

The peak short-circuit current is calculated from:

$$i_p = i_{pT20} + i_{pM20}$$

$$i_{pT20} = 1.15\ \varkappa_b \sqrt{2}\ I''_{kT20}\ \text{with}\ \varkappa_b = 1.02 + 0.98\ e^{-3\,(1.052\ \text{m}\Omega/6.261\ \text{m}\Omega)} = 1.61$$

According to Method B of Sub-clause 9.1.3.2, it is necessary to take $1.15 \cdot \varkappa_b = 1.15 \cdot 1.61 = 1.85$. In this case for a low-voltage short circuit the maximum for $1.15\ \varkappa_b$ is limited to 1.8.

$$i_{pM20} = \varkappa_M \sqrt{2}\ I''_{kM20}\ \text{with}\ \varkappa_m = 1.3\ \text{according to Table AVII}$$

$$i_p = 1.8 \cdot \sqrt{2} \cdot 36.25\ \text{kA} + 1.3 \sqrt{2} \cdot 11.06\ \text{kA} = 112.61\ \text{kA}$$

(When considering the calculation of i_{pT20} it can be recognized that the impedance of the low-voltage transformer T20 gives the main part of the impedance $\underline{Z}_P + \underline{Z}_{T20LV}$, so that the ratio R_{T20}/X_{T20} of the transformer will determine $\varkappa$ for the calculation of i_{pT20}. From the ratio $R_{T20}/X_{T20} = 1.031\ m\Omega/5.910\ m\Omega = 0.174$ the factor $\varkappa = 1.60$ can be determined and therefore for the whole peak short-circuit current at the short-circuit location F4:

$$i_p = 1.60\sqrt{2} \cdot 36.25\ kA + 1.3\sqrt{2} \cdot 11.06\ kA = 102.4\ kA)$$