3 Calculation of Short-Circuit Currents in Three-Phase Systems

3.1 Terms and definitions

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3.1.1 Terms as per DIN VDE 0102 / IEC 909

Short circuit: the accidental or deliberate connection across a comparatively low resistance or impedance between two or more points of a circuit which usually have differing voltage.

Short-circuit current: the current in an electrical circuit in which a short circuit occurs.

Prospective (available) short-circuit current: the short-circuit current which would arise if the short circuit were replaced by an ideal connection having negligible impedance without alteration of the incoming supply.

Symmetrical short-circuit current: root-mean-square (r.m.s.) value of the symmetrical alternating-current (a.c.) component of a prospective short-circuit current, taking no account of the direct-current (d.c.) component, if any.

Initial symmetrical short-circuit current I_k'': the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant the short circuit occurs if the short-circuit impedance retains its value at time zero.

Initial symmetrical (apparent) short-circuit power S_k'': a fictitious quantity calculated as the product of initial symmetrical short-circuit current I_k'', nominal system voltage U_n and the factor $\sqrt{3}$.

D.C. (aperiodic) component i_{DC} of short-circuit current: the mean value between the upper and lower envelope curve of a short-circuit current decaying from an initial value to zero.

Peak short-circuit current i_p: the maximum possible instantaneous value of a prospective short-circuit current.

Symmetrical short-circuit breaking current I_a: the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current at the instant of contact separation by the first phase to clear of a switching device.

Steady-state short-circuit current I_k: the r.m.s. value of the symmetrical a.c. component of a prospective short-circuit current persisting after all transient phenomena have died away.

(Independent) Voltage source: an active element which can be simulated by an ideal voltage source in series with a passive element independently of currents and other voltages in the network.

Nominal system voltage U_n: the (line-to-line) voltage by which a system is specified and to which certain operating characteristics are referred.

Equivalent voltage source $cU_n / \sqrt{3}$: the voltage of an ideal source applied at the short-circuit location in the positive-sequence system as the network's only effective voltage in order to calculate the short-circuit currents by the equivalent voltage source method.

Voltage factor c: the relationship between the voltage of the equivalent voltage source and $U_n / \sqrt{3}$.

Subtransient voltage E'' of a synchronous machine: the r.m.s. value of the symmetrical interior voltages of a synchronous machine which is effective behind the subtransient reactance X_d'' at the instant the short circuit occurs.

Far-from-generator short circuit: a short circuit whereupon the magnitude of the symmetrical component of the prospective short-circuit current remains essentially constant.

Near-to-generator short circuit: a short circuit whereupon at least one synchronous machine delivers an initial symmetrical short-circuit current greater than twice the synchronous machine's rated current, or a short circuit where synchronous or induction motors contribute more than 5 % of the initial symmetrical short-circuit current I_k'' without motors.

Positive-sequence short-circuit impedance $\underline{Z}_{(1)}$ of a three-phase a.c. system: the impedance in the positive-phase-sequence system as viewed from the fault location.

Negative-sequence short-circuit impedance $\underline{Z}_{(2)}$ of a three-phase a.c. system: the impedance in the negative-phase-sequence system as viewed from the fault location.

Zero-sequence short-circuit impedance $\underline{Z}_{(0)}$ of a three-phase a.c. system: the impedance in the zero-phase-sequence system as viewed from the fault location. It includes the threefold value of the neutral-to-earth impedance.

Subtransient reactance X_d'' of a synchronous machine: the reactance effective at the instant of the short circuit. For calculating short-circuit currents, use the saturated value X_d''.

Minimum time delay t_{min} of a circuit-breaker: the shortest possible time from commencement of the short-circuit current until the first contacts separate in one pole of a switching device.

3.1.2 Symmetrical components of asymmetrical three-phase systems

In three-phase networks a distinction is made between the following kinds of fault:

a) three-phase fault ($I''_{k\,3}$)
b) phase-to-phase fault clear of ground ($I''_{k\,2}$)
c) two-phase-to-earth fault ($I''_{k\,2\,E}$; $I''_{k\,E\,2\,E}$)
d) phase-to-earth fault ($I''_{k\,1}$)
e) double earth fault ($I''_{k\,E\,E}$)

A 3-phase fault affects the three-phase network symmetrically. All three conductors are equally involved and carry the same rms short-circuit current. Calculation need therefore be for only one conductor.

All other short-circuit conditions, on the other hand, incur asymmetrical loadings. A suitable method for investigating such events is to split the asymmetrical system into its symmetrical components.

With a symmetrical voltage system the currents produced by an asymmetrical loading (I_1, I_2 and I_3) can be determined with the aid of the symmetrical components (positive-, negative- and zero-sequence system).

The symmetrical components can be found with the aid of complex calculation or by graphical means.

We have:

Current in pos.-sequence system $\underline{I}_m = \frac{1}{3}(\underline{I}_1 + \underline{a}\ \underline{I}_2 + \underline{a}^2\,\underline{I}_3)$

Current in neg.-sequence system $\underline{I}_g = \frac{1}{3}(\underline{I}_1 + \underline{a}^2\,\underline{I}_2 + \underline{a}\ \underline{I}_3)$

Current in zero-sequence system $\underline{I}_o = \frac{1}{3}(\underline{I}_1 + \underline{I}_2 + \underline{I}_3)$

For the rotational operators of value 1:

$$\underline{a} = e^{j120^\circ};\ \underline{a}^2 = e^{j240^\circ};\ 1 + \underline{a} + \underline{a}^2 = 0$$

The above formulae for the symmetrical components also provide information for a graphical solution.

If the current vector leading the current in the reference conductor is rotated 120° *backwards,* and the lagging current vector 120 ° *forwards,* the resultant is equal to three times the vector $\underline{I}_m$ in the reference conductor. The negative-sequence components are apparent.

If one turns in the other direction, the positive-sequence system is evident and the resultant is three times the vector $\underline{I}_g$ in the reference conductor.

Geometrical addition of all three current vectors ($\underline{I}_1$, $\underline{I}_2$ and $\underline{I}_3$) yields three times the vector $\underline{I}_0$ in the reference conductor.

If the neutral conductor is unaffected, there is no zero-sequence system.

3.2 Fundamentals of calculation according to DIN VDE 0102 / IEC 909

In order to select and determine the characteristics of equipment for electrical networks it is necessary to know the magnitudes of the short-circuit currents and short-circuit powers which may occur.

The short-circuit current at first runs asymmetrically to the zero line, Fig. 3-1. It contains an alternating-current component and a direct-current component.

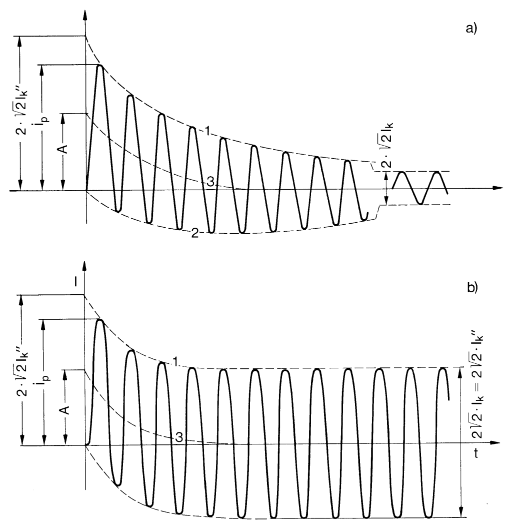


Fig. 3-1

Curve of short-circuit current: a) near-to-generator fault, b) far-from-generator fault I_k'' *initial symmetrical short-circuit current,* i_p *peak short-circuit current,* I_k *steady state short-circuit current, A initial value of direct current, 1 upper envelope, 2 lower envelope, 3 decaying direct current.*

Calculatlon of initial symmetrical short-circuit current I_k''

The calculation of short-circuit currents is always based on the assumption of a dead short circuit. Other influences, especially arc resistances, contact resistances, conductor temperatures, inductances of current transformers and the like, can have the effect of lowering the short-circuit currents. Since they are not amenable to calculation, they are accounted for in Table 3-1 by the factor c.

Initial symmetrical short-circuit currents are calculated with the equations in Table 3-2.

Table 3-1

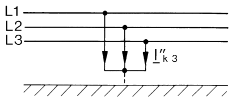
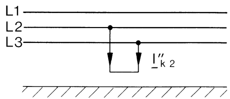
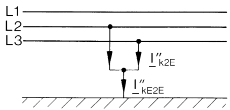
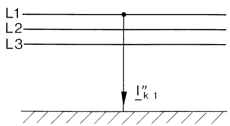
Voltage factor *c*

Nominal voltage	Voltage factor c for calculating the greatest short-circuit current c_{max}	the smallest short-circuit current c_{min}
Low voltage		
100 V to 1000 V		
(see IEC 38, Table I)		
a) 230 V / 400 V	1.00	0.95
b) other voltages	1.05	1.00
Medium voltage		
>1 kV to 35 kV	1.10	1.00
(see IEC 38, Table III)		
High-voltage		
> 35 kV to 230 kV	1.10	1.00
(see IEC 38, Table IV)		
380 kV	1.10	1.00

Note: cU_n should not exceed the highest voltage U_m for power system equipment.

Table 3-2

Formulae for calculating initial short-circuit current and short-circuit powers

Kind of fault		Dimension equations (IEC 909)	Numerical equations of the % / MVA systems
Three-phase fault with or without earth fault		$I''_{k\,3} = \dfrac{1.1 \cdot U_n}{\sqrt{3}\,\lvert \underline{Z}_1 \rvert}$ $S''_k = \sqrt{3}\, U_n\, I''_{k\,3}$	$I''_{k\,3} = \dfrac{1.1 \cdot 100\,\%}{\lvert \sqrt{3}\, \underline{Z}_1 \rvert} \cdot \dfrac{1}{U_n}$ $S''_k = \dfrac{1.1 \cdot 100\,\%}{\underline{Z}_1}$
Phase-to-phase fault clear of ground		$I''_{k\,2} = \dfrac{1.1 \cdot U_n}{\lvert \underline{Z}_1 + \underline{Z}_2 \rvert}$	$I''_{k\,2} = \dfrac{1.1 \cdot 100\,\%}{\lvert \underline{Z}_1 + \underline{Z}_2 \rvert} \cdot \dfrac{1}{U_n}$
Two-phase-to-earth fault		$I''_{kE2E} = \dfrac{\sqrt{3} \cdot 1.1\, U_n}{\left\lvert \underline{Z}_1 + \underline{Z}_0 + \underline{Z}_0 \dfrac{\underline{Z}_1}{\underline{Z}_2} \right\rvert}$	$I''_{kE2E} = \dfrac{\sqrt{3} \cdot 1.1 \cdot 100\,\%}{\left\lvert \underline{Z}_1 + \underline{Z}_0 + \underline{Z}_0 \dfrac{\underline{Z}_1}{\underline{Z}_2} \right\rvert} \cdot \dfrac{1}{U_n}$
Phase-to-earth fault		$I''_{k\,1} = \dfrac{\sqrt{3} \cdot 1.1 \cdot U_n}{\lvert \underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0 \rvert}$	$I''_{k\,1} = \dfrac{\sqrt{3} \cdot 1.1 \cdot 100\,\%}{\lvert \underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0 \rvert} \cdot \dfrac{1}{U_n}$

In the right-hand column of the Table, I''_k is in kA, S''_k in MVA, U_n in kV and Z in % / MVA.
The directions of the arrows shown here are chosen arbitrarily.

Calculation of peak short-circuit current i_p

When calculating the peak short-circuit current i_p, sequential faults are disregarded. Three-phase short circuits are treated as though the short circuit occurs in all three conductors simultaneously. We have:

$$i_p = \kappa \cdot \sqrt{2} \cdot I''_k.$$

The factor κ takes into account the decay of the d. c. component. It can be calculated as

$\kappa = 1.02 + 0.98\ e^{-3\ R/X}$ or taken from Fig. 3-2.

Exact calculation of i_p with factor κ is possible only in networks with branches having the same ratios R/X. If a network includes parallel branches with widely different ratios R/X, the following methods of approximation can be applied:

a) Factor κ is determined uniformly for the smallest ratio R/X. One need only consider the branches which are contained in the faulted network and carry partial short-circuit currents.

b) The factor is found for the ratio R/X from the resulting system impedance $Z_k = R_k + jX_k$ at the fault location, using $1.15 \cdot \kappa_k$ for calculating i_p. In low-voltage networks the product $1.15 \cdot \kappa$ is limited to 1.8, and in high-voltage networks to 2.0.

c) Factor κ can also be calculated by the method of the equivalent frequency as in IEC 909 para. 9.1.3.2.

The maximum value of $\kappa = 2$ is attained only in the theoretical limiting case with an active resistance of $R = 0$ in the short-circuit path. Experience shows that with a short-circuit at the generator terminals a value of $\kappa = 1.8$ is not exceeded with machines < 100 MVA.

With a unit-connected generator and high-power transformer, however, a value of $\kappa = 1.9$ can be reached in unfavourable circumstances in the event of a short circuit near the transformer on its high-voltage side, owing to the transformer's very small ratio R/X. The same applies to networks with a high fault power if a short circuit occurs after a reactor.

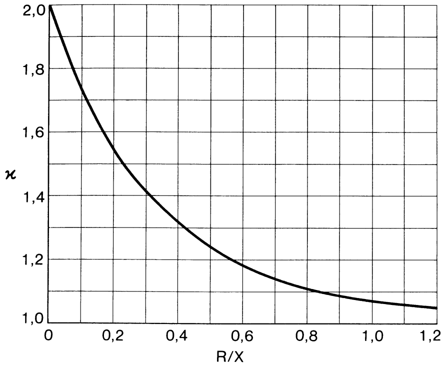


Fig. 3-2

Factor κ

Calculation of steady-state short-circuit current I_k

Three-phase fault with single supply

$I_k = I''_{kQ}$ network

$I_k = \lambda \cdot I_{rG}$ synchronous machine

Three-phase fault with single supply from more than one side

$I_k = I_{bkW} + I''_{kQ}$

I_{bkw} symmetrical short-circuit breaking current of a power plant

I''_{kQ} initial symmetrical short-circuit current of network

Three-phase fault in a meshed network

$I_k = I''_{koM}$

I''_{koM} initial symmetrical short-circuit current without motors

I_k depends on the excitation of the generators, on saturation effects and on changes in switching conditions in the network during the short circuit. An adequate approximation for the upper and lower limit values can be obtained with the factors λ_{max} and λ_{min}, Fig. 3-3 and 3-4. I_{rG} is the rated current of the synchronous machine.

For X_{dsat} one uses the reciprocal of the no-load/short-circuit ratio I_{k0}/I_{rG}(VDE 0530 Part 1).

The 1st series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.3 times the excitation voltage for rated load operation and rated power factor in the case of turbogenerators, or 1.6 times the excitation for rated load operation in the case of salient-pole machines.

The 2nd series of curves of λ_{max} applies when the maximum excitation voltage reaches 1.6 times the excitation for rated load operation in the case of turbogenerators, or 2.0 times the excitation for rated load operation in the case of salient-pole machines.

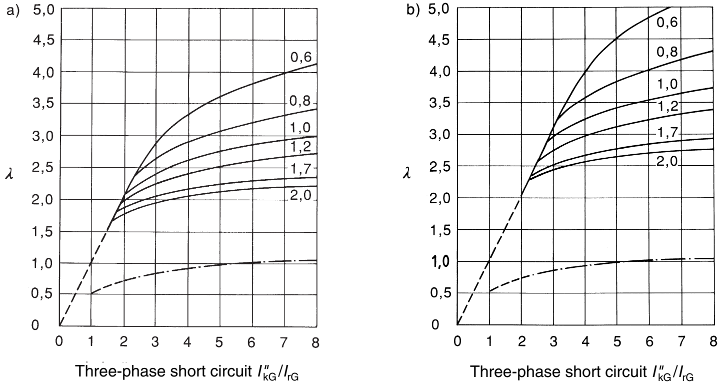


Fig. 3-3

Factors λ for salient-pole machines in relation to ratio I''_{kG}/I_{rG} and saturated synchronous reactance X_d of 0.6 to 2.0, —— λ_{max}, – · – λ_{min};
a) Series 1 U_{fmax} / U_{fr} = 1.6; b) Series 2 U_{fmax} / U_{fr} = 2.0.

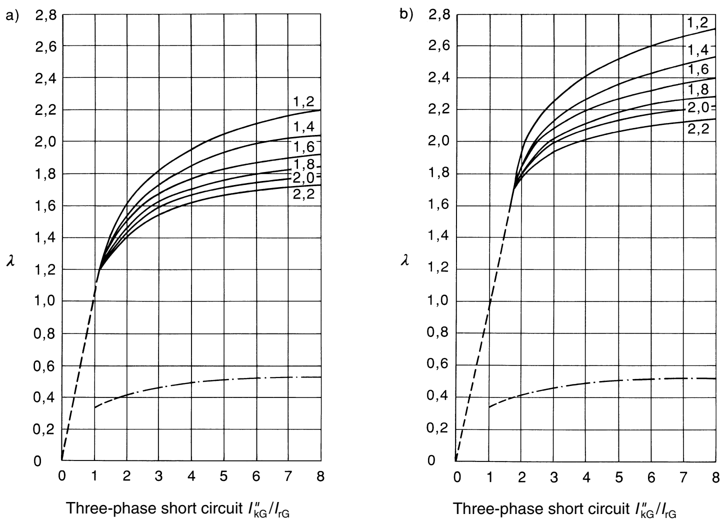


Fig. 3-4

Factors λ for turbogenerators in relation to ratio I''_{kG}/I_{rG} and saturated synchronous reactance X_d of 1.2 to 2.2, —— λ_{max}, – · – λ_{min};
a) Series 1 U_{fmax} / U_{fr} = 1.3; b) Series 2 U_{fmax} / U_{fr} = 1.6.

Calculation of symmetrical breaking current I_a

Three-phase fault with single supply

$I_a = \mu \cdot I''_{kG}$	synchronous machine
$I_a = \mu \cdot q \cdot I''_{kM}$	induction machine
$I_a = I''_{kQ}$	network

Three-phase fault with single supply from more than one side

$I_a = I_{aKW} + I''_{kQ} + I_{aM}$

I_{aKW}	symmetrical short-circuit breaking current of a power plant
I_{kQ}	initial symmetrical short-circuit current of a network
I_{aM}	symmetrical short-circuit breaking current of an induction machine

Three-phase fault in a meshed network

$I_a = I''_k$

A more exact result for the symmetrical short-circuit breaking current is obtained with IEC 909 section 12.2.4.3, equation (60).

The factor μ denotes the decay of the symmetrical short-circuit current during the switching delay time. It can be taken from Fig. 3-5 or the equations.

$\mu = 0.84 + 0.26\ e^{-0.26\ I''_{kG}/\ I_{rG}}$ for $t_{min} = 0.02$ s

$\mu = 0.71 + 0.51\ e^{-0.30\ I''_{kG}/\ I_{rG}}$ for $t_{min} = 0.05$ s

$\mu = 0.62 + 0.72\ e^{-0.32\ I''_{kG}/\ I_{rG}}$ for $t_{min} = 0.10$ s

$\mu = 0.56 + 0.94\ e^{-0.38\ I''_{kG}/\ I_{rG}}$ for $t_{min} = 0.25$ s

$\mu_{max} = 1$

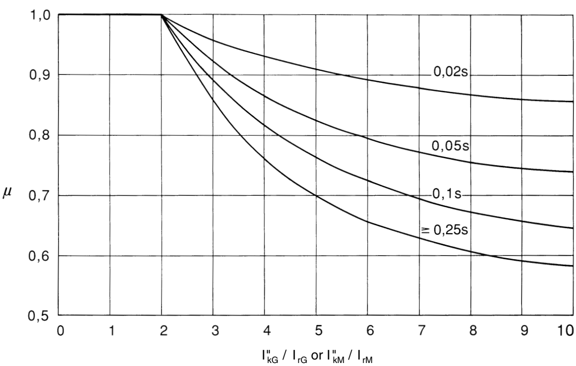


Fig. 3-5

Factor μ for calculating the symmetrical short-circuit breaking current I_a as a function of ratio I''_{kG}/I_{rG} or I''_{kM}/I_{rM}, and of switching delay time t_{min} of 0.02 to 0.25 s.

If the short circuit is fed by a number of independent voltage sources, the symmetrical breaking currents may be added.

With compound excitation or converter excitation one can put $\mu = 1$ if the exact value is not known. With converter excitation Fig. 3-5 applies only if $t_v \leq 0.25$ s and the maximum excitation voltage does not exceed 1.6 times the value at nominal excitation. In all other cases put $\mu = 1$.

The factor q applies to induction motors and takes account of the rapid decay of the motor's short-circuit current owing to the absence of an excitation field. It can be taken from Fig. 3-6 or the equations.

$q = 1.03 + 0.12 \ln m$ for $t_{min} = 0.02$ s

$q = 0.79 + 0.12 \ln m$ for $t_{min} = 0.05$ s

$q = 0.57 + 0.12 \ln m$ for $t_{min} = 0.10$ s

$q = 0.26 + 0.12 \ln m$ for $t_{min} = 0.25$ s

$q_{max} = 1$

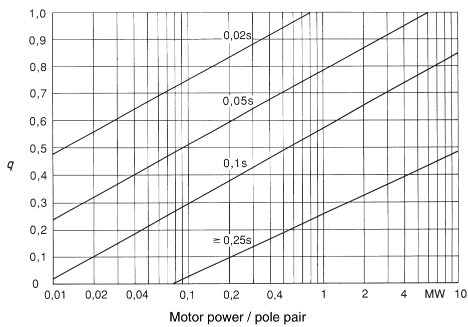


Fig. 3-6

Factor q for calculating the symmetrical short-circuit breaking current of induction motors as a function of the ratio motor power / pole pair and of switching delay time t_{min} of 0.02 to 0.25 s.

Taking account of transformers

The impedances of equipment in the higher- or lower-voltage networks have to be re-calculated with the square of the rated transformer ratio $\ddot{u}_r$ (main tap).

The influence of motors

Synchronous motors and synchronous condensers are treated as synchronous generators.

Induction motors contribute values to I''_k, i_p and I_a and in the case of a two-phase short circuit, to I_k as well.

The heaviest short-circuit currents I''_k, i_p, I_a and I_k in the event of three-phase and two-phase short circuits are calculated as shown in Table 3-3.

For calculating the peak short-circuit current:
κ_m = 1.65 for HV motors, motor power per pole pair < 1MW
κ_m = 1.75 for HV motors, motor power per pole pair ≥ 1MW
κ_m = 1.3 for LV motors

Table 3-3

To calculate short-circuit currents of induction motors with terminal short circuit

	three-phase	two-phase
Initial symmetrical short-circuit current	$I''_{k3M} = \dfrac{c \cdot U_n}{\sqrt{3} \cdot Z_M}$	$I''_{k2M} = \dfrac{\sqrt{3}}{2}\, I''_{k3M}$
Peak short-circuit current	$I''_{p3M} = \kappa_m \sqrt{2}\, I''_{k3M}$	$I''_{p2M} = \dfrac{\sqrt{3}}{2}\, i_{p3M}$
Symmetrical short-circuit breaking current	$I_{a3M} = I''_{k3M}$	$I''_{a2M} \sim \dfrac{\sqrt{3}}{2}\, I''_{k3M}$
Steady-state short-circuit current	$I''_{k3M} = 0$	$I_{k2M} \sim \dfrac{1}{2}\, I''_{k3M}$

The influence of induction motors connected to the faulty network by way of transformers can be disregarded if

$$\frac{\Sigma P_{rM}}{\Sigma S_{rT}} \leqq \frac{0.8}{\dfrac{100\,\Sigma S_{rT}}{S''_k} - 0.3}.$$

Here,

ΣP_{rM} is the sum of the ratings of all high-voltage and such low-voltage motors as need to be considered,

ΣS_{rT} is the sum of the ratings of all transformers feeding these motors and

S''_k is the initial fault power of the network (without the contribution represented by the motors).

To simplify calculation, the rated current I_{rM} of the low-voltage motor group can be taken as the transformer current on the low-voltage side.

%/MVA system

The %/MVA system is particularly useful for calculating short-circuit currents in high-voltage networks. The impedances of individual items of electrical equipment in %/MVA can be determined easily from the characteristics, see Table 3-4.

Table 3-4

Formulae for calculating impedances or reactances in %/MVA

Network component		Impedance z or reactance x	
Synchronous machine	$\frac{x''_d}{S_r}$	x''_d = Subtransient reactance S_r = Rated apparent power	in % in MVA
Transformer	$\frac{u_k}{S_r}$	u_k = Impedance voltage drop S_r = Rated apparent power	in % in MVA
Current-limiting reactor	$\frac{u_r}{S_D}$	u_r = Rated voltage drop S_D = Throughput capacity	in % in MVA
Induction motor	$\frac{I_r/I_{start}}{S_r} \cdot 100\,\%$	I_r = Rated current I_{start} = Starting current (with rated voltage and rotor short-circuited) S_r = Rated apparent power	 in MVA
Line	$\frac{Z' \cdot l \cdot 100\,\%}{U_n^2}$	Z' = Impedance per conductor U_n = Nominal system voltage l = Length of line	in Ω/km in kV in km
Series capacitor	$\frac{-X_c \cdot 100\,\%}{U_n^2}$	X_c = Reactance per phase U_n = Nominal system voltage	in Ω in kV
Shunt capacitor	$-\frac{100\,\%}{S_r}$	S_r = Rated apparent power	in MVA
Network	$\frac{1.1 \cdot 100\,\%}{S''_{kQ}}$	S''_{kQ} = Three-phase initial symmetrical short-circuit power at point of connection Q	in MVA

Table 3-5

Reference values for Z_2/Z_1 and Z_2/Z_0

		Z_2/Z_1	Z_2/Z_0
to calculate			
I''_k	near to generator	1	–
	far from generator	1	–
I_k	near to generator	0.05…0.25	–
	far from generator	0.25…1	–
Networks	with isolated neutral	–	0
	with earth compensation	–	0
	with neutral earthed via impedances	–	0…0.25
Networks with effectively earthed neutral		–	> 0.25

Calculating short-circuit currents by the %/MVA system generally yields sufficiently accurate results. This assumes that the ratios of the transformers are the same as the ratios of the rated system voltages, and also that the nominal voltage of the network components is equal to the nominal system voltage at their locations.

The equations for calculating initial short-circuit currents I''_k are given in Table 3-2.

The kind of fault which produces the highest short-circuit currents at the fault site can be determined with Fig. 3-7. The double earth fault is not included in Fig. 3-7; it results in smaller currents than a two-phase short-circuit. For the case of a two-phase-to-earth fault, the short-circuit current flowing via earth and earthed conductors I''_{kE2E} is not considered in Fig. 3-7.

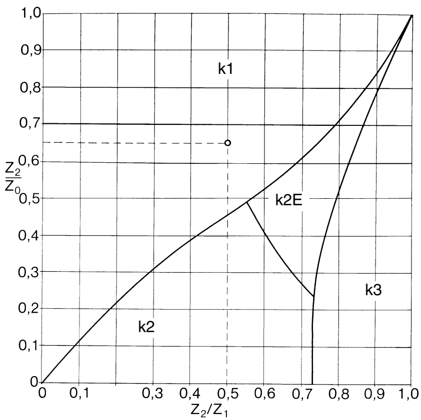


Fig. 3-7

Diagram for determining the fault with the highest short-circuit current

Example: $Z_2/Z_1 = 0.5$; $Z_2/Z_0 = 0.65$, *the greatest short-circuit current occurs with a phase – to-earth fault.*

The data in Fig. 3-7 are true provided that the impedance angles of $\underline{Z}_2/\underline{Z}_1$ and $\underline{Z}_0$ do not differ from each other by more than 15 °. Reference values for Z_2/Z_1 and Z_2/Z_0 are given in Table 3-5.

i_p and I_k are:

for phase-to-phase fault clear of ground: $i_{p2} = \kappa \cdot \sqrt{2} \cdot I''_{k2}$, $I_{k2} = I_{a2} = I''_{k2}$;

for two-phase-to-earth fault: no calculation necessary;

for phase-to-earth fault: $i_{p1} = \kappa \cdot \sqrt{2} \cdot I''_{k1}$, $I_{k1} = I_{a1} = I''_{k1}$.

Fig. 3-8 shows the size of the current with asymmetrical earth faults.

Minimum short-circuit currents

When calculating minimum short-circuit currents one has to make the following changes:

– Reduced voltage factor c
– The network's topology must be chosen so as to yield the minimum short-circuit currents.

– Motors are to be disregarded
– The resistances R_L of the lines must be determined for the conductor temperature t_e at the end of the short circuit (R_{L20} conductor temperature at 20 °C).

$R_L = [1 + 0.004\ (t_e - 20\ °C)/°C] \cdot R_{L20}$

For lines in low-voltage networks it is sufficient to put t_e = 80 °C.

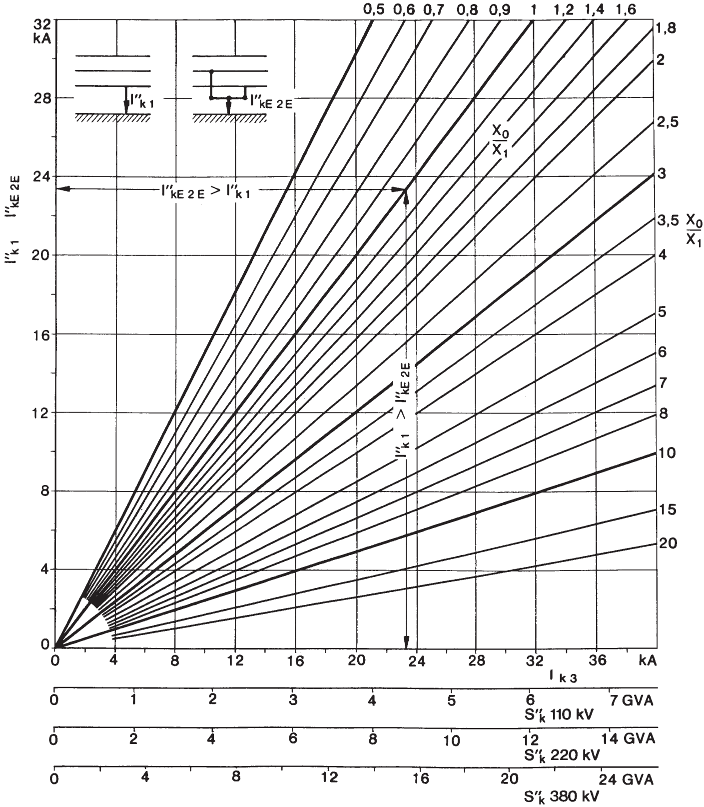


Fig. 3-8

Initial short-circuit current I''_k at the fault location with asymmetrical earth faults in networks with earthed neutral:

S''_k = $\sqrt{3} \cdot UI''_{k3}$ = *Initial symmetrical short-circuit power,*
I''_{kE2E} *Initial short-circuit current via earth for two-phase-to-earth fault,*
I''_{k1} *Initial short-circuit current with phase-to-earth fault,*
X_1, X_0 *Reactances of complete short-circuit path in positive- and zero-phase sequence system ($X_2 = X_1$)*

3.3 Impedances of electrical equipment

The impedances of electrical equipment are generally stated by the manufacturer. The values given here are for guidance only.

3.3.1 System infeed

The effective impedance of the system infeed, of which one knows only the initial symmetrical fault power S''_{kQ} or the initial symmetrical short-circuit current I''_{kQ} at junction point Q, is calculated as:

$$Z_Q = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}}$$

Here U_{nQ} Nominal system voltage

S''_{kQ} Initial symmetrical short-circuit power

I''_{kQ} Initial symmetrical short-circuit current

$\underline{Z}_Q$ $= R_Q + jX_Q$, effective impedance of system infeed for short-circuit current calculation

X_Q $= \sqrt{Z_Q^2 - R_Q^2}$.

If no precise value is known for the equivalent active resistance R_Q of the system infeed, one can put $R_Q = 0.1\ X_Q$ *with* $X_Q = 0.995\ Z_Q$. The effect of temperature can be disregarded.

If the impedance is referred to the low-voltage side of the transformer, we have

$$Z_Q = \frac{c \cdot U_{nQ}^2}{S''_{kQ}} \cdot \frac{1}{\ddot{u}_r^2} = \frac{c \cdot U_{nQ}}{\sqrt{3} \cdot I''_{kQ}} \cdot \frac{1}{\ddot{u}_r^2}.$$

3.3.2 Electrical machines

Synchronous generators with direct system connection

For calculating short-circuit currents the positive- and negative-sequence impedances of the generators are taken as

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

with the correction factor

$$K_G = \frac{U_n}{U_{rg}} \cdot \frac{c_{max}}{1 + X''_d \cdot \sin \varphi_{rg}}$$

Here:

c_{max} Voltage factor

U_n Nominal system voltage

U_{rG} Rated voltage of generator

$\underline{Z}_{GK}$ Corrected impedance of generator

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

X''_d Subtransient reactance of generator referred to impedance

$$x''_d = X''_d / Z_{rG} \qquad \underline{Z}_{rG} = U^2_{rG}/S_{rG}$$

It is sufficiently accurate to put:

$$\left.\begin{aligned} R_G &= 0.05 \cdot X''_d \text{ for rated powers} \geqq 100\text{ MVA} \\ R_G &= 0.07 \cdot X''_d \text{ for rated powers} < 100\text{ MVA} \end{aligned}\right\} \text{with high-voltage generators}$$

$$R_G = 0.15 \cdot X''_d \text{ for low-voltage generators.}$$

The factors 0.05, 0.07 and 0.15 also take account of the decay of the symmetrical short-circuit current during the first half-cycle.
Guide values for reactances are shown in Table 3-6.

Table 3-6

Reactances of synchronous machines

Generator type	Turbogenerators	Salient-pole generators with damper winding[1]	without damper winding
Subtransient reactance (saturated) x''_d in %	9…22[2]	12…30[3]	20…40[3]
Transient reactance (saturated) x''_d in %	14…35[4]	20…45	20…40
Synchronous reactance (unsaturated) [5] x''_d in %	140…300	80…180	80…180
Negative-sequence reactance[6] x_2 in %	9…22	10…25	30…50
Zero-sequence reactance[7] x_0 in %	3…10	5…20	5…25

1) Valid for laminated pole shoes and complete damper winding and also for solid pole shoes with strap connections.

2) Values increase with machine rating. Low values for low-voltage generators.

3) The higher values are for low-speed rotors ($n < 375\text{ min}^{-1}$).

4) For very large machines (above 1000 MVA) as much as 40 to 45 %.

5) Saturated values are 5 to 20 % lower.

6) In general $x_2 = 0.5\,(x''_d + x''_q)$. Also valid for transients.

7) Depending on winding pitch.

Generators and unit-connected transformers of power plant units

For the impedance, use

$$\underline{Z}_{G,\,KW} = K_{G,\,KW}\,\underline{Z}_G$$

with the correction factor

$$K_{G,\,KW} = \frac{c_{max}}{1 + X''_d \cdot \sin\varphi_{rG}}$$

$$\underline{Z}_{T,\,KW} = K_{T,\,KW}\,\underline{Z}_{TUS}$$

with the correction factor

$$K_{T,\,KW} = c_{max}.$$

Here:

$\underline{Z}_{G,\,KW}$ $\underline{Z}_{T,\,KW}$	Corrected impedances of generators (G) and unit-connected transformers (T) of power plant units
$\underline{Z}_G$	Impedance of generator
$\underline{Z}_{TUS}$	Impedance of unit transformer, referred to low-voltage side

If necessary, the impedances are converted to the high-voltage side with the fictitious transformation ratio $\ddot{u}_f = U_n/U_{rG}$

Power plant units

For the impedances, use

$$\underline{Z}_{KW} = K_{KW}\,(\ddot{u}_r^2\,\underline{Z}_G + \underline{Z}_{TOS})$$

with the correction factor

$$K_{KW} = \frac{U_{nQ}^2}{U_{rG}^2} \cdot \frac{U_{rTUS}^2}{U_{rTOS}^2} \cdot \frac{c_{max}}{1 + (X''_d - X''_T)\sin\varphi_{rG}}$$

Here:

$\underline{Z}_{KW}$	Corrected impedance of power plant unit, referred to high-voltage side
$\underline{Z}_G$	Impedance of generator
$\underline{Z}_{TOS}$	Impedance of unit transformer, referred to high-voltage side
U_{nQ}	Nominal system voltage
U_{rG}	Rated voltage of generator
X_T	Referred reactance of unit transformer
U_{rT}	Rated voltage of transformer

Synchronous motors

The values for synchronous generators are also valid for synchronous motors and synchronous condensers.

Induction motors

The short-circuit reactance Z_M of induction motors is calculated from the ratio I_{an}/I_{rM}:

$$Z_M = \frac{1}{I_{start}/I_{rM}} \cdot \frac{U_{rM}}{\sqrt{3} \cdot I_{rM}} = \frac{U^2_{rM}}{I_{start}/I_{rM} \cdot S_{rM}}$$

where I_{start} Motor starting current, the rms value of the highest current the motor draws with the rotor locked at rated voltage and rated frequency after transients have decayed,

U_{rM} Rated voltage of motor

I_{rM} Rated current of motor

S_{rM} Apparent power of motor ($\sqrt{3} \cdot U_{rM} \cdot I_{rM}$).

3.3.3 Transformers and reactors

Transformers

Table 3-7

Typical values of impedance voltage drop u_k of three-phase transformers

Rated primary voltage in kV	5…20	30	60	110	220	400
u_k in %	3.5…8	6…9	7…10	9…12	10…14	10…16

Table 3-8

Typical values for ohmic voltage drop u_R of three-phase transformers

Power rating in MVA	0.25	0.63	2.5	6.3	12.5	31.5
u_R in %	1.4…1.7	1.2…1.5	0.9…1.1	0.7… 0.85	0.6…0.7	0.5…0.6

For transformers with ratings over 31.5 MVA, u_R < 0 5 %.

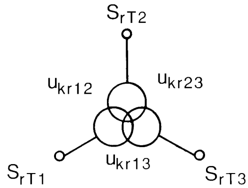
The positive- and negative-sequence transformer impedances are equal. The zero-sequence impedance may differ from this.

The positive-sequence impedances of the transformers $\underline{Z}_1 = \underline{Z}_T = R_T + jX_T$ are calculated as follows:

$$Z_T = \frac{U_{kr}}{100\ \%} \quad \frac{U^2_{rT}}{S_{rT}} \qquad R_T = \frac{u_{Rr}}{100\ \%} \quad \frac{U^2_{rT}}{S_{rT}} \qquad X_T = \sqrt{Z^2_T - R^2_T}$$

With three-winding transformers, the positive-sequence impedances for the corresponding rated throughput capacities referred to voltage U_{rT} are:

a)



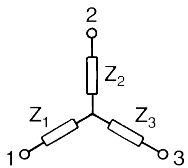
$$|\underline{Z}_{12}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr12}\,\frac{U_{rT}^2}{S_{rT12}}$$

$$|\underline{Z}_{13}| = |\underline{Z}_1| + |\underline{Z}_2| = u_{kr13}\,\frac{U_{rT}^2}{S_{rT13}}$$

$$|\underline{Z}_{23}| = |\underline{Z}_2| + |\underline{Z}_3| = u_{kr23}\,\frac{U_{rT}^2}{S_{rT23}}$$

and the impedances of each winding are

b)



$$\underline{Z}_1 = \frac{1}{2}\,(\underline{Z}_{12} + \underline{Z}_{13} - \underline{Z}_{23})$$

$$\underline{Z}_2 = \frac{1}{2}\,(\underline{Z}_{12} + \underline{Z}_{23} - \underline{Z}_{13})$$

$$\underline{Z}_3 = \frac{1}{2}\,(\underline{Z}_{13} + \underline{Z}_{23} - \underline{Z}_{12})$$

Fig. 3-9

Equivalent diagram a) and winding impedance b) of a three-winding transformer
u_{kr12} short-circuit voltage referred to S_{rT12}
u_{kr13} short-circuit voltage referred to S_{rT13}
$u_{kr2}3$ short-circuit voltage referred to S_{rT23}
S_{rT12}, S_{rT13}, S_{rT23} rated throughput capacities of transformer

Three-winding transformers are mostly high-power transformers in which the reactances are much greater than the ohmic resistances. As an approximation, therefore, the impedances can be put equal to the reactances.

The zero-sequence impedance varies according to the construction of the core, the kind of connection and the other windings.

Fig. 3-10 shows examples for measuring the zero-sequence impedances of transformers.

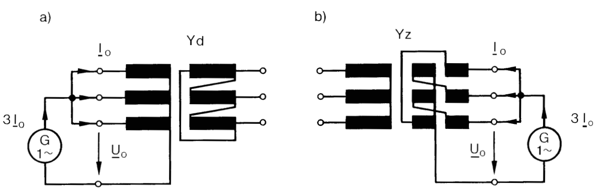
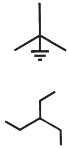
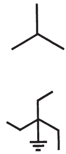


Fig. 3-10

Measurement of the zero-sequence impedances of transformers for purposes of short-circuit current calculation: a) connection Yd, b) connection Yz

Table 3-9

Reference values of X_0/X_1 for three-phase transformers

Connection					
Three-limb core	0.7…1 ∞	3…10 ∞	3…10 ∞	∞ 0.1…0.15	1…2.4 ∞
Five-limb core	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞
3 single-phase transformers	1 ∞	10…100 ∞	10…100 ∞	∞ 0,1…0.15	1…2.4 ∞

Values in the upper line when zero voltage applied to upper winding, values in lower line when zero voltage applied to lower winding (see Fig. 3-10).

For low-voltage transformers one can use:

Connection Dy $R_{0T} \approx R_T \quad X_{0T} \approx 0.95\, X_T$

Connection Dz, Yz $R_{0T} \approx 0.4\, R_T \quad X_{0T} \approx 0.1\, X_T$

Connection Yy[1] $R_{0T} \approx R_T \quad X_{0T} \approx 7…100^{2)}\, X_T$

[1] Transformers in Yy are not suitable for multiple-earthing protection.
[2] HV star point not earthed.

Current-limiting reactors

The reactor reactance X_D is

$$X_D = \frac{\Delta\, u_r \cdot U_n}{100\,\% \cdot \sqrt{3} \cdot I_r} = \frac{\Delta\, u_r \cdot U_n^2}{100\,\% \cdot S_D}$$

where $\Delta\, u_r$ Rated percent voltage drop of reactor

U_n Network voltage

I_r Current rating of reactor

S_D Throughput capacity of reactor.

Standard values for the rated voltage drop

$\Delta\, u_r$ in %: 3, 5, 6, 8, 10.

Further aids to calculation are given in Sections 12.1 and 12.2. The effective resistance is negligibly small. The reactances are of equal value in the positive-, negative- and zero-sequence systems.

3.3.4 Three-phase overhead lines

The usual equivalent circuit of an overhead line for network calculation purposes is the Π circuit, which generally includes resistance, inductance and capacitance, Fig. 3-11.

In the positive phase-sequence system, the effective resistance R_L of high-voltage overhead lines is usually negligible compared with the inductive reactance. Only at the low- and medium-voltage level are the two roughly of the same order.

When calculating short-circuit currents, the positive-sequence capacitance is disregarded. In the zero-sequence system, account normally has to be taken of the conductor-earth capacitance. The leakage resistance R_a need not be considered.

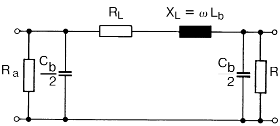


Fig. 3-11

Equivalent circuit of an overhead line

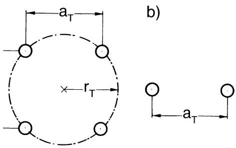


Fig. 3-12

Conductor configurations
a) 4-wire bundle
b) 2-wire bundle

Calculation of positive- and negative-sequence impedance

Symbols used:

a_T Conductor strand spacing,
r Conductor radius,
r_e Equivalent radius for bundle conductors (for single strand $r_e = r$),
n Number of strands in bundle conductor,
r_T Radius of circle passing through midpoints of strands of a bundle (Fig. 3-12),
d Mean geometric distance between the three wires of a three-phase system,
d_{12}, d_{23}, d_{31}, see Fig. 3-13,
r_S Radius of earth wire,
μ_0 Space permeability $4\pi \cdot 10^{-4} \frac{\text{H}}{\text{km}}$,
μ_S Relative permeability of earth wire,
μ_L Relative permeability of conductor (in general $\mu_L = 1$),
ω Angular frequency in s^{-1},
δ Earth current penetration in m,
ρ Specific earth resistance,
R_L Resistance of conductor,
R_S Earth wire resistance (dependent on current for steel wires and wires containing steel),
L_b Inductance per conductor in H/km; $L_b = L_1$.

Calculation

The inductive reactance (X_L) for symmetrically twisted single-circuit and double-circuit lines are:

Single-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi}\left(\ln \frac{d}{r_e} + \frac{1}{4n}\right)$ in Ω/km per conductor,

Double-circuit line: $X_L = \omega \cdot L_b = \omega \cdot \frac{\mu_0}{2\pi}\left(\ln \frac{d\,d'}{r_e d''} + \frac{1}{4n}\right)$ in Ω/km per conductor;

Mean geometric distances between conductors (see Fig. 3-13):

$$d = \sqrt[3]{d_{12} \cdot d_{23} \cdot d_{31}},$$

$$d' = \sqrt[3]{d'_{12} \cdot d'_{23} \cdot d'_{31}},$$

$$d'' = \sqrt[3]{d''_{11} \cdot d''_{22} \cdot d''_{33}}.$$

The equivalent radius r_e is

$$r_e = \sqrt[n]{n \cdot r \cdot r_T^{n-1}}.$$

In general, if the strands are arranged at a uniform angle *n:*

$$r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{n}},$$

e. g. for a 4-wire bundle $r_e = \frac{a_T}{2 \cdot \sin \frac{\pi}{4}} = \frac{a_T}{\sqrt{2}}$

The positive- and negative-sequence impedance is calculated as

$$\underline{Z}_1 = \underline{Z}_2 = \frac{R_1}{n} + X_L.$$

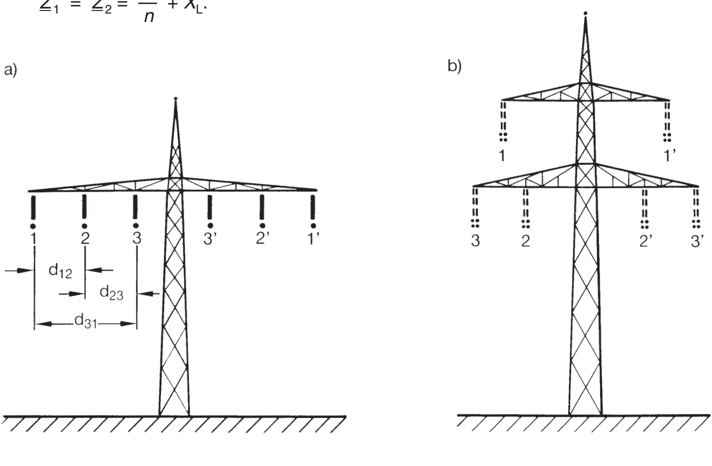


Fig. 3-13

Tower configurations: double-circuit line with one earth wire; a) flat, b) “Donau‘”

Fig. 3-14 and 3-15 show the positive-sequence (and also negative-sequence) reactances of three-phase overhead lines.

Calculation of zero-sequence impedance

The following formulae apply:

Single-circuit line without earth wire	$\underline{Z}_0^{\mathrm{I}} = R_0 + \mathrm{j}X_0,$
Single-circuit line with earth wire	$\underline{Z}_0^{\mathrm{Is}} = \underline{Z}_0^{\mathrm{I}} - 3\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}},$
Double-circuit line without earth wire	$\underline{Z}_0^{\mathrm{II}} = \underline{Z}_0^{\mathrm{I}} + 3\,\underline{Z}_{\mathrm{ab}},$
Double-circuit line with earth wire	$\underline{Z}_0^{\mathrm{IIs}} = \underline{Z}_0^{\mathrm{II}} - 6\,\dfrac{\underline{Z}_{\mathrm{as}}^2}{\underline{Z}_{\mathrm{s}}},$

For the zero-sequence resistance and zero-sequence reactance included in the formulae, we have:

Zero-sequence resistance

$$R_0 = R_{\mathrm{L}} + 3\,\frac{\mu_0}{8}\,\omega, \qquad d = \sqrt[3]{d_{12}\,d_{23}\,d_{31}};$$

Zero-sequence reactance

$$X_0 = \omega\,\frac{\mu_0}{2\,\pi}\left(3\,\ln\frac{\delta}{\sqrt[3]{rd^2}} + \frac{\mu_{\mathrm{L}}}{4\,n}\right) \qquad \delta = \frac{1.85}{\sqrt{\mu_0\,\dfrac{1}{\rho}\,\omega}}.$$

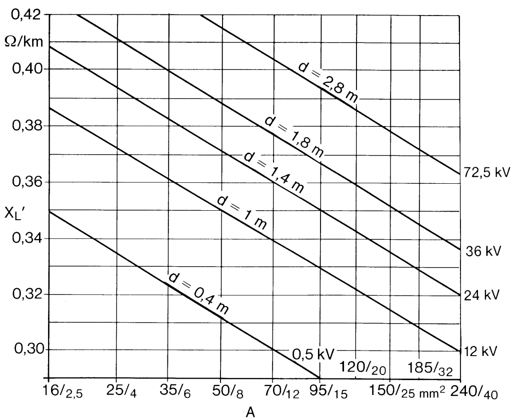


Fig. 3-14

Reactance X_{L}' (positive phase sequence) of three-phase transmission lines up to 72.5 kV, f = 50 Hz, as a function of conductor cross section A, single-circuit lines with aluminium / steel wires, d = mean geometric distance between the 3 wires.

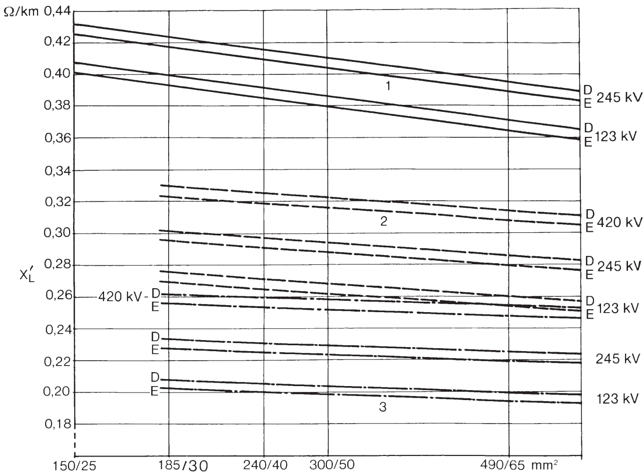


Fig. 3-15

Reactance X_L' (positive-sequence) of three-phase transmission lines with alumimium/ steel wires ("Donau" configuration), f = 50 Hz. Calculated for a mean geometric distance between the three conductors of one system, at 123 kV: d = 4 m, at 245 kV: d = 6 m, at 420 kV: d = 9.4 m;
E denotes operation with one system; D denotes operation with two systems; 1 single wire, 2 two-wire bundle, a = 0.4 m, 3 four-wire bundle, a = 0.4 m.

Table 3-10

Earth current penetration δ in relation to specific resistance ρ at f = 50 Hz

Nature of soil as per:								
DIN VDE 0228 and CCITT		Alluvial	land Clay	Porous	Quartz, impervious Limestone	Limestone	Granite, gneiss	
		Marl		Sandstone, clay schist			Clayey slate	
DIN VDE 0141		Moor- land	—	Loam, clay and soil arable land	Wet sand	Wet gravel	Dry sand or gravel	Stony ground
ρ	Ωm	30	50	100	200	500	1 000	3 000
$\sigma = \frac{1}{\rho}$	μS/cm	333	200	100	50	20	10	3.33
δ	m	510	660	930	1 320	2 080	2 940	5 100

The earth current penetration δ denotes the depth at which the return current diminishes such that its effect is the same as that of the return current distributed over the earth cross section.

Compared with the single-circuit line without earth wire, the double-circuit line without earth wire also includes the additive term $3 \cdot \underline{Z}_{a\,b}$, where $\underline{Z}_{a\,b}$ is the alternating impedance of the loops system a/earth and system b/earth:

$$\underline{Z}_{a\,b} = \frac{\mu_0}{8}\,\omega + j\,\omega\,\frac{\mu_0}{2\,\pi}\ln\frac{\delta}{d_{a\,b}},$$

$$d_{a\,b} = \sqrt{d'd''}$$

$$d' = \sqrt[3]{d'_{12}\cdot d'_{23}\cdot d'_{31}},$$

$$d'' = \sqrt[3]{d''_{11}\cdot d''_{22}\cdot d''_{33}}.$$

For a double-circuit line with earth wires (Fig. 3-16) account must also be taken of:

1. Alternating impedance of the loops conductor/earth and earth wire/earth:

$$\underline{Z}_{as} = \frac{\mu_0}{8}\,\omega + j\,\omega\,\frac{\mu_0}{2\,\pi}\ln\frac{\delta}{d_{as}}, \qquad d_{as} = \sqrt[3]{d_{1s}\,d_{2s}\,d_{3s}};$$

for two earth wires:

$$d_{as} = \sqrt[6]{d_{1s1}\,d_{2s1}\,d_{3s1}\,d_{1s2}\,d_{2s2}\,d_{3s2}}$$

2. Impedance of the loop earth wire/earth:

$$\underline{Z}_s = R + \frac{\mu_0}{8}\,\omega + j\,\omega\,\frac{\mu_0}{2\,\pi}\left(\ln\frac{\delta}{r} + \frac{\mu_s}{4\,n}\right).$$

The values used are for one earth wire $n = 1$; $r = r_s$; $R = R_s$;

for two earth wires $n = 2$; $r = \sqrt{r_s\,d_{s1s2}}$; $R = \frac{R_s}{2}$

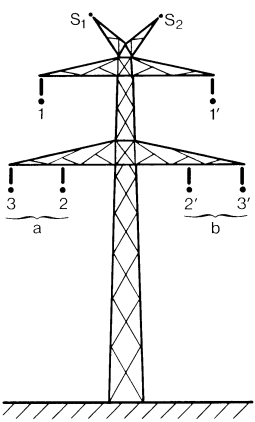


Fig: 3-16

Tower configuration: Double-circuit line with two earth wires, system a and b

Values of the ratio R_s/R_- (effective resistance / d. c. resistance) are roughly between 1.4 and 1.6 for steel earth wires, but from 1.05 to 1.0 for well-conducting earth wires of Al/St, Bz or Cu.

For steel earth wires, one can take an average of $\mu_s \approx 25$, while values of about $\mu_s = 5$ to 10 should be used for Al/St wires with one layer of aluminium. For Al/St earth wires with a cross-section ratio of 6:1 or higher and two layers of aluminium, and also for earth wires or ground connections of Bz or Cu, $\mu_s \approx 1$.

The operating capacitances C_b of high-voltage lines of 110 kV to 380 kV lie within a range of $9 \cdot 10^{-9}$ to $14 \cdot 10^{-9}$ F/km. The values are higher for higher voltages.

The earth wires must be taken into account when calculating the conductor/earth capacitance. The following values are for guidance only:

Flat tower: $C_E = (0.6…0.7) \cdot C_b$.

“Donau” tower: $C_E = (0.5…0.55) \cdot C_b$

The higher values of C_E are for lines with earth wire, the lower values for those without earth wire.

The value of C_E for double-circuit lines is lower than for single-circuit lines.

The relationship between conductor/conductor capacitance C_g, conductor/earth capacitance C_E and operating capacitance C_b is

$$C_b = C_E + 3 \cdot C_g.$$

Technical values for transmission wires are given in Section 13.1.4.

Table 3-11

Reference values for the impedances of three-phase overhead lines: “Donau” tower, one earth wire, conductor Al/St 240/40, specific earth resistance $\rho = 100\ \Omega \cdot \mathrm{m}$, $f = 50$ Hz

Voltage	d	d_{ab}	d_{as}	Earth wire	Impedance $\underline{Z}_1 = R_1 + \mathrm{j}\, X_1$	Operation with one system zero-sequence impedance $\underline{Z}_0^{\mathrm{I}}$	$\frac{X_0'}{X_1}$	Operation with two systems zero-sequence impedance $\underline{Z}_0^{\mathrm{II}}$	$\frac{X_0''}{X_1}$
	m	m	m		Ω/km per cond.	Ω/km per conductor		Ω/km per cond. and system	
123 kV	4	10	11	St 50	0.12 + j 0.39	0.31 + j 1.38	3.5	0.50 + j 2.20	5.6
				Al/St 44/32		0.32 + j 1.26	3.2	0.52 + j 1.86	4.8
				Al/St 240/40		0.22 + j 1.10	2.8	0.33 + j 1.64	4.2
245 kV	6	15.6	16.5	Al/St 44/32	0.12 + j 0.42	0.30 + j 1.19	2.8	0.49 + j 1.78	4.2
				Al/St 240/40		0.22 + j 1.10	2.6	0.32 + j 1.61	3.8
245 kV 2-wire bundle	6	15.6	16.5	Al/St 240/40	0.06 + j 0.30	0.16 + j 0.98	3.3	0.26 + j 1.49	5.0
420 kV 4-wire bundle	9.4	23	24	Al/St 240/40	0.03 + j 0.26	0.13 + j 0.91	3.5	0.24 + j 1.39	5.3

3.3.5 Three-phase cables

The equivalent diagram of cables can also be represented by Π elements, in the same way as overhead lines (Fig. 3-11). Owing to the smaller spacings, the inductances are smaller, but the capacitances are between one and two orders greater than with overhead lines.

When calculating short-circuit currents the positive-sequence operating capacitance is disregarded. The conductor/earth capacitance is used in the zero phase-sequence system.

Calculation of positive and negative phase-sequence impedance

The a.c. resistance of cables is composed of the d.c. resistance *(R_{-})* and the components due to skin effect and proximity effect. The resistance of metal-clad cables (cable sheath, armour) is further increased by the sheath and armour losses.

The d.c. resistance (R_{-}) at 20 °C and A = conductor cross section in mm^2 is

for copper: $R'_{-} = \frac{18.5}{A}$ in $\frac{\Omega}{\text{km}}$,

for aluminium: $R'_{-} = \frac{29.4}{A}$ in $\frac{\Omega}{\text{km}}$,

for aluminium alloy: $R'_{-} = \frac{32.3}{A}$ in $\frac{\Omega}{\text{km}}$.

The supplementary resistance of cables with conductor cross-sections of less than 50 mm^2 can be disregarded (see Section 2, Table 2-8).

The inductance L and inductive reactance X_L at 50 Hz for different types of cable and different voltages are given in Tables 3-13 to 3-17.

For low-voltage cables, the values for positive- and negative-sequence impedances are given in DIN VDE 0102, Part 2 /11.75.

Table 3-12

Reference value for supplementary resistance of different kinds of cable in Ω/km, f = 50 Hz

Type of cable	cross-section mm^2	50	70	95	120	150	185	240	300	400
Plastic-insulated cable										
NYCY[1)] 0.6/1 kV		—	0.003	0.0045	0.0055	0.007	0.0085	0.0115	0.0135	0.018
NYFGbY[2)]	3.5/6 kV to 5.8/10 kV	—	0.008	0.008	0.0085	0.0085	0.009	0.009	0.009	0.009
NYCY[2)]	3.5/6 kV to 5.8/10 kV	—	—-	0.0015	0.002	0.0025	0.003	0.004	0.005	0.0065
Armoured lead-covered cable up to 36 kV		0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015
Non-armoured aluminium-covered cable up to 12 kV		0.0035	0.0045	0.0055	0.006	0.008	0.010	0.012	0.014	0.018
Non-armoured single-core cable (laid on one plane, 7 cm apart) up to 36 kV										
with lead sheath		0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012
with aluminium sheath		0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Non-armoured single-core oil-filled cable with lead sheath										
(bundled) 123 kV		—	—	0.009	0.009	0.009	0.0095	0.0095	0.010	0.0105
(laid on one plane, 18 cm apart) 245 kV		—	—	—	—	0.0345	0.035	0.035	0.035	0.035
Three-core oil-filled cable,										
armoured with lead sheath,	36 to 123 kV	0.010	0.011	0.011	0.012	0.012	0.013	0.013	0.014	0.015
non-armoured with	36 kV	—	0.004	0.006	0.007	0.009	0.0105	0.013	0.015	0.018
aluminium sheath,	123 kV	—	—	0.0145	0.0155	0.0165	0.018	0.0205	0.023	0.027

1) With NYCY 0.6/1 kV effective cross section of C equal to half outer conductor.
2) With NYFGbY for 7.2/12 kV, at least 6 mm^2 copper.

Table 3-13

Armoured three-core belted cables[1], inductive reactance X'_L (positive phase sequence) per conductor at f = 50 HZ

Number of cores and conductor cross-section mm²	U = 3.6 kV X'_L Ω/km	U = 7.2 kV X'_L Ω/km	U = 12 kV X'_L Ω/km	U = 17.5 kV X'_L Ω/km	U = 24 kV X'_L Ω/km
3 × 6	0.120	0.144	—	—	—
3 × 10	0.112	0.133	0.142	—	—
3 × 16	0.105	0.123	0.132	0.152	—
3 × 25	0.096	0.111	0.122	0.141	0.151
3 × 35	0.092	0.106	0.112	0.135	0.142
3 × 50	0.089	0.10	0.106	0.122	0.129
3 × 70	0.085	0.096	0.101	0.115	0.122
3 × 95	0.084	0.093	0.098	0.110	0.117
3 × 120	0.082	0.091	0.095	0.107	0.112
3 × 150	0.081	0.088	0.092	0.104	0.109
3 × 185	0.080	0.087	0.09	0.10	0.105
3 × 240	0.079	0.085	0.089	0.097	0.102
3 × 300	0.077	0.083	0.086	—	—
3 × 400	0.076	0.082	—	—	—

1) Non-armoured three-core cables: –15 % of values stated.
Armoured four-core cables: + 10 % of values stated.

Table 3-14

Hochstädter cable (H cable) with metallized paper protection layer, inductive reactance X'_L (positive phase sequence) per conductor at f = 50 Hz

Number of cores and conductor cross-section mm²	U = 7.2 kV X'_L Ω/km	U = 12 kV X'_L Ω/km	U = 17.5 kV X'_L Ω/km	U = 24 kV X'_L Ω/km	U = 36 kV X'_L Ω/km
3 × 10 re	0.134	0.143	—	—	—
3 × 16 re or se	0.124	0.132	0.148	—	—
3 × 25 re or se	0.116	0.123	0.138	0.148	—
3 × 35 re or se	0.110	0.118	0.13	0.14	0.154
3 × 25 rm or sm	0.111	0.118	—	—	—
3 × 35 rm or sm	0.106	0.113	—	—	—
3 × 50 rm or sm	0.10	0.107	0.118	0.126	0.138
3 × 70 rm or sm	0.096	0.102	0.111	0.119	0.13
3 × 95 rm or sm	0.093	0.098	0.107	0.113	0.126
3 × 120 rm or sm	0.090	0.094	0.104	0.11	0.121
3 × 150 rm or sm	0.088	0.093	0.10	0.107	0.116
3 × 185 rm or sm	0.086	0.090	0.097	0.104	0.113
3 × 240 rm or sm	0.085	0.088	0.094	0.10	0.108
3 × 300 rm or sm	0.083	0.086	0.093	0.097	0.105

Table 3-15

Armoured SL-type cables[1)], inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ HZ

Number of cores and conductor cross-section mm²	$U = 7.2$ kV X'_L Ω/km	$U = 12$ kV X'_L Ω/km	$U = 17.5$ kV X'_L Ω/km	$U = 24$ kV X'_L Ω/km	$U = 36$ kV X'_L Ω/km
3 x 6 re	0.171	—	—	—	—
3 x 10 re	0.157	0.165	—	—	—
3 x 16 re	0.146	0.152	0.165	—	—
3 x 25 re	0.136	0.142	0.152	0.16	—
3 x 35 re	0.129	0.134	0.144	0.152	0.165
3 x 35 rm	0.123	0.129	—	—	—
3 x 50 rm	0.116	0.121	0.132	0.138	0.149
3 x 70 rm	0.11	0.115	0.124	0.13	0.141
3 x 95 rm	0.107	0.111	0.119	0.126	0.135
3 x 120 rm	0.103	0.107	0.115	0.121	0.13
3 x 150 rm	0.10	0.104	0.111	0.116	0.126
3 x 185 rm	0.098	0.101	0.108	0.113	0.122
3 x 240 rm	0.096	0.099	0.104	0.108	0.118
3 x 300 rm	0.093	0.096	0.102	0.105	0.113

1) These values also apply to SL-type cables with H-foil over the insulation and for conductors with a high space factor (rm/v and r se/3 f). Non-armoured SL-type cables: –15 % of values stated.

Table 3-16

Cables with XLPE insulation, inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ Hz, triangular arrangement

Number of cores and conductor cross-section mm²	$U = 12$ kV X'_L Ω/km	$U = 24$ kV X'_L Ω/km	$U = 36$ kV X'_L Ω/km	$U = 72.5$ kV X'_L Ω/km	$U = 123$ kV X'_L Ω/km
3 x 1 x 35 rm	0.135	—	—	—	—
3 x 1 x 50 rm	0.129	0.138	0.148	—	—
3 x 1 x 70 rm	0.123	0.129	0.138	—	—
3 x 1 x 95 rm	0.116	0.123	0.132	—	—
3 x 1 x 120 rm	0.110	0.119	0.126	0.151	0.163
3 x 1 x 150 rm	0.107	0.116	0.123	0.148	0.160
3 x 1 x 185 rm	0.104	0.110	0.119	0.141	0.154
3 x 1 x 240 rm	0.101	0.107	0.113	0.138	0.148
3 x 1 x 300 rm	0.098	0.104	0.110	0.132	0.145
3 x 1 x 400 rm	0.094	0.101	0.107	0.129	0.138
3 x 1 x 500 rm	0.091	0.097	0.104	0.126	0.132
3 x 1 x 630 rm	—	—	—	0.119	0.129

Table 3-17

Cables with XLPE insulation, inductive reactance X'_L (positive phase sequence) per conductor at $f = 50$ Hz

Number of cores and conductor cross-section mm²	$U = 12$ kV X'_L Ω/km
3 x 50 se	0.104
3 x 70 se	0.101
3 x 95 se	0.094
3 x 120 se	0.091
3 x 150 se	0.088
3 x 185 se	0.085
3 x 240 se	0.082

Zero-sequence impedance

It is not possible to give a single formula for calculating the zero-sequence impedance of cables. Sheaths, armour, the soil, pipes and metal structures absorb the neutral currents. The construction of the cable and the nature of the outer sheath and of the armour are important. The influence of these on the zero-sequence impedance is best established by asking the cable manufacturer. Dependable values of the zero-sequence impedance can be obtained only by measurement on cables already installed.

The influence of the return line for the neutral currents on the zero-sequence impedance is particularly strong with small cable cross-sections (less than 70 mm²). If the neutral currents return *exclusively* by way of the neutral (4th) conductor, then

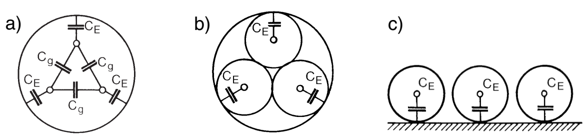
$$R_{0L} = R_L + 3 \cdot R_{neutral}, \qquad X_{0L} \approx (3{,}5 \ldots 4.0) x_L$$

The zero-sequence impedances of low-voltage cables are given in DIN VDE 0102, Part 2 / 11.75.

Capacitances

The capacitances in cables depend on the type of construction (Fig. 3-17).

With belted cables, the operating capacitance C_b is $C_b = C_E + 3\ C_g$, as for overhead transmission lines. In SL and Hochstädter cables, and with all single-core cables, there is no capacitive coupling between the three conductors; the operating capacitance C_b is thus equal to the conductor/earth capacitance C_E. Fig. 3-18 shows the conductor/earth capacitance C_E of belted three-core cables for service voltages of 1 to 20 kV, as a function of conductor cross-section A. Values of C_E for single-core, SL and H cables are given in Fig. 3-19 for service voltages from 12 to 72.5 kV.



$C_b = C_E = 3\ C_g$ $\quad$ $C_g = 0 \longrightarrow C_b = C_E$ $\quad$ $C_g = 0 \longrightarrow C_b = C_E$

Fig. 3-17 $\quad C_E \approx 0{,}6\ C_b$

Partial capacitances for different types of cable:
a) Belted cable, b) SL and H type cables, c) Single-core cable

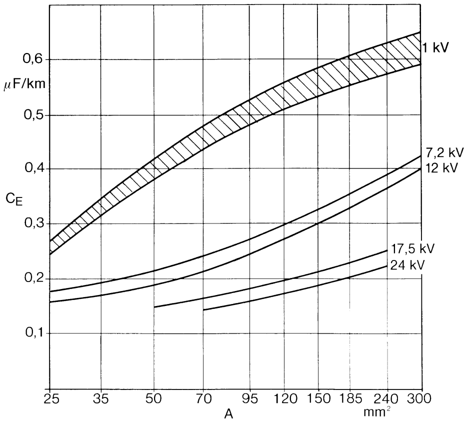


Fig. 3-18

Conductor/earth capacitance C_E of *belted three-core cables as a function of conductor cross-section A. The capacitances of 1 kV cables must be expected to differ considerably.*

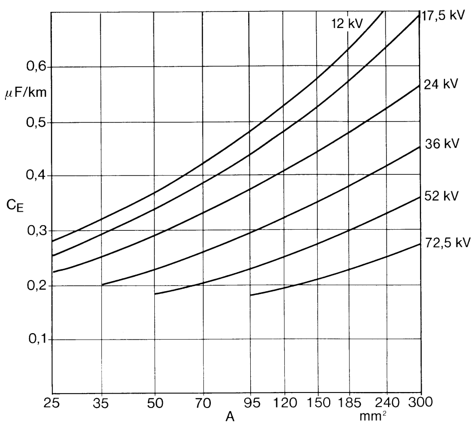


Fig. 3-19

Conductor/earth capacitance C_E of *single-core, SL- and H-type cables as a function of conductor cross-section A.*

The conductor/earth capacitances of XLPE-insulated cables are shown in Tables 3-18 and 3-19.

Table 3-18

Cables with XLPE insulation, conductor/earth capacitance C'_E per conductor

Number of cores and conductor cross-section mm²	U = 12 kV C'_E µF/km	U = 24 kV C'_E µF/km	U = 36 kV C'_E µF/km	U = 72.5 kV C'_E µF/km	U = 123 kV C'_E µF/km
3 x 1 x 35 rm	0.239	—	—	—	—
3 x 1 x 50 rm	0.257	0.184	0.141	—	—
3 x 1 x 70 rm	0.294	0.202	0.159	—	—
3 x 1 x 95 rm	0.331	0.221	0.172	—	—
3 x 1 x 120 rm	0.349	0.239	0.184	0.138	0.110
3 x 1 x 150 rm	0.386	0.257	0.196	0.147	0.115
3 x 1 x 185 rm	0.423	0.285	0.208	0.156	0.125
3 x 1 x 240 rm	0.459	0.312	0.233	0.165	0.135
3 x 1 x 300 rm	0.515	0.340	0.251	0.175	0.145
3 x 1 x 400 rm	0.570	0.377	0.276	0.193	0.155
3 x 1 x 500 rm	0.625	0.413	0.300	0.211	0.165
3 x 1 x 630 rm	—	—	—	0.230	0.185

Table 3-19

Cables with XLPE insulation, conductor/earth capacitance C'_E per conductor

Number of cores and conductor cross-section mm²	U = 12 kV C'_E µF/km
3 x 50 se	0.276
3 x 70 se	0.312
3 x 95 se	0.349
3 x 120 se	0.368
3 x 150 se	0.404
3 x 185 se	0.441
3 x 240 se	0.496

3.3.6 Busbars in switchgear installations

In the case of large cross-sections the resistance can be disregarded.

Average values for the inductance per metre of bus of rectangular section and arranged as shown in Fig. 3-20 can be calculated from

$$L' = 2 \cdot \left[\ln \left(2 \frac{\pi \cdot D + b}{\pi \cdot B + 2\,b} \right) + 0.33 \right] \cdot 10^{-7} \text{ in H/m.}$$

Here:

D Distance between centres of outer main conductor,
b Height of conductor,
B Width of bars of one phase,
L' Inductance of one conductor in H/m.

To simplify calculation, the value for L' for common busbar cross sections and conductor spacings has been calculated per 1 metre of line length and is shown by the curves of Fig. 3-20. Thus,

$$X = 2\,\pi \cdot f \cdot L' \cdot l$$

Example:

Three-phase busbars 40 m long, each conductor comprising three copper bars 80 mm × 10 mm ($A = 2400\ \text{mm}^2$), distance $D = 30$ cm, $f = 50$ Hz. According to the curve, $L' = 3.7 \cdot 10^{-7}$ H/m; and so

$$X = 3.7 \cdot 10^{-7}\ \text{H/m} \cdot 314\ \text{s}^{-1} \cdot 40\ \text{m} = 4.65\ \text{m}\,\Omega.$$

The busbar arrangement has a considerable influence on the inductive resistance.

The inductance per unit length of a three-phase line with its conductors mounted on edge and grouped in phases (Fig. 3-20 and Fig. 13-2a) is relatively high and can be usefully included in calculating the short-circuit current.

Small inductances can be achieved by connecting two or more three-phase systems in parallel. But also conductors in a split phase arrangement (as in Fig. 13-2b) yield very small inductances per unit length of less than 20 % of the values obtained with the method described. With the conductors laid flat side by side (as in the MNS system) the inductances per unit length are about 50 % of the values according to the method of calculation described.

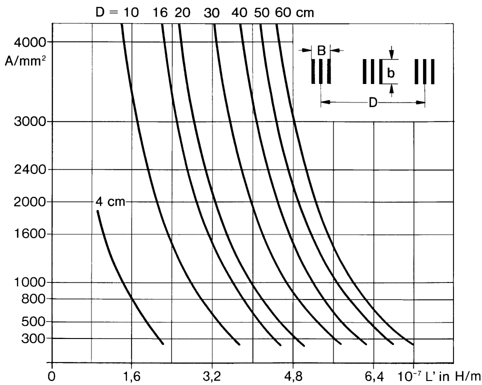


Fig. 3-20

Inductance L´ of busbars of rectangular cross section

3.4 Examples of calculation

More complex phase fault calculations are made with computer programs (Calpos®). See Section 6.1.5 for examples.

When calculating short-circuit currents in high-voltage installations, it is often sufficient to work with reactances because the reactances are generally much greater in magnitude than the effective resistances. Also, if one works only with reactances in the following examples, the calculation is on the safe side. Corrections to the reactances are disregarded.

The ratios of the nominal system voltages are taken as the transformer ratios. Instead of the operating voltages of the faulty network one works with the nominal system voltage. It is assumed that the nominal voltages of the various network components are the same as the nominal system voltage at their respective locations. Calculation is done with the aid of the %/MVA system.

Example 1

To calculate the short-circuit power S''_k, the peak short-circuit current i_p and the symmetrical short-circuit breaking current I_a in a branch of a power plant station service busbar. This example concerns a fault with more than one infeed and partly common current paths. Fig. 3-21 shows the equivalent circuit diagram.

For the reactances of the equivalent circuit the formulae of Table 3-4 give:

Network reactance $$x_Q = \frac{1.1 \cdot 100}{S''_{kQ}} = \frac{110}{8000} = 0.0138\ \%/\text{MVA},$$

Transformer *1* $$x_{T1} = \frac{u_K}{S_{rT1}} = \frac{13}{100} = 0.1300\ \%/\text{MVA},$$

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

Transformer *2* $$x_{T2} = \frac{u_K}{S_{rT2}} = \frac{7}{8} = 0.8750\ \%/\text{MVA},$$

Induction motor $$x_{M1} = \frac{I_{rM}/I_{start}}{S_{rM}} \cdot 100 = \frac{1}{5 \cdot 2.69} \cdot 100 = 7.4349\ \%/\text{MVA},$$

Induction-motor group $$x_{M2} = \frac{I_{rM}/I_{start}}{S_{rM}} \cdot 100 = \frac{1}{5 \cdot 8 \cdot 0.46} \cdot 100 = 5.4348\ \%/\text{MVA}.$$

For the location of the fault, one must determine the total reactance of the network. This is done by step-by-step system transformation until there is only one reactance at the terminals of the equivalent voltage source: this is then the short-circuit reactance.

Calculation can be made easier by using Table 3-20, which is particularly suitable for calculating short circuits in unmeshed networks. The Table has 9 columns, the first of which shows the numbers of the lines. The second column is for identifying the parts and components of the network. Columns 3 and 4 are for entering the calculated values.

The reactances entered in column 3 are added in the case of series circuits, while the susceptances in column 4 are added for parallel configurations.

Columns 6 to 9 are for calculating the maximum short-circuit current and the symmetrical breaking current.

To determine the total reactance of the network at the fault location, one first adds the reactances of the 220 kV network and of transformer *1*. The sum 0.1438 %/MVA is in column 3, line 3.

The reactance of the generator is then connected in parallel to this total. This is done by forming the susceptance relating to each reactance and adding the susceptances (column 4, lines 3 and 4).

The sum of the susceptances 15.1041 %/MVA is in column 4, line 5. Taking the reciprocal gives the corresponding reactance 0.0662 %/MVA, entered in column 3, line 5. To this is added the reactance of transformer 2. The sum of 0.9412 %/MVA is in column 3, line 7.

The reactances of the induction motor and of the induction motor group must then be connected in parallel to this total reactance. Again this is done by finding the susceptances and adding them together.

The resultant reactance of the whole network at the site of the fault, 0.7225%/MVA, is shown in column 3, line 10. This value gives

$$S_k'' = \frac{1.1 \cdot 100\ \%}{x_k} \qquad \frac{1.1 \cdot 100\ \%}{0.7225\ \%/\mathrm{MVA}} = 152\ \mathrm{MVA}, \text{(column 5, line 10).}$$

3

To calculate the *breaking capacity* one must determine the contributions of the individual infeeds to the short-circuit power S_k''.

The proportions of the short-circuit power supplied via transformer *2* and by the motor group and the single motor are related to the total short-circuit power in the same way as the susceptances of these branches are related to their total susceptance.

Contributions of individual infeeds to the short-circuit power:

Contribution of single motor $S_{kM1}'' = \dfrac{0.1345}{1.381} \cdot 152 = 14.8\ \mathrm{MVA},$

Contribution of motor group $S_{kM2}'' = \dfrac{0.184}{1.381} \cdot 152 = 20.3\ \mathrm{MVA},$

Contribution via transformer *2* $S_{kT2}'' = \dfrac{1.0625}{1.381} \cdot 152 = 116.9\ \mathrm{MVA}.$

The proportions contributed by the 220 kV network and the generator are found accordingly.

Contribution of generator $S_{kG}'' = \dfrac{8.150}{15.104} \cdot 116.9 = 63.1\ \mathrm{MVA},$

Contribution of 220 kV network $S_{kQ}'' = \dfrac{6.954}{15.104} \cdot 116.9 = 53.8\ \mathrm{MVA}.$

The calculated values are entered in column 5. They are also shown in Fig. 3-21b.

To find the factors μ and q

When the contributions made to the short-circuit power S_k'' by the 220 kV network, the generator and the motors are known, the ratios of S_k''/S_r are found (column 6). The corresponding values of μ for $t_v = 0.1$ s (column 7) are taken from Fig. 3-5.

Values of q (column 8) are obtained from the ratio motor rating / number of pole pairs (Fig. 3-6), again for $t_v = 0.1$ s.

Single motor

$$\frac{S_{kM1}''}{S_{rM1}} = \frac{14.8}{2.69} = 5.50 \rightarrow \mu = 0.74 \qquad \frac{\text{motor rating}}{\text{no. pole pairs}} = \frac{2.3}{2} = 1.15 \rightarrow q = 0.59$$

Motor group

$$\frac{S_{kM2}''}{S_{rM2}} = \frac{20.3}{8 \cdot 0.46} = 5.52 \rightarrow \mu = 0.74 \qquad \frac{\text{motor rating}}{\text{no. pole pairs}} = \frac{0.36}{3} = 1.12 \rightarrow q = 0.32$$

Generator

$$\frac{S_{kG}''}{S_{rG}} = \frac{63.1}{93.7} = 0.67 \rightarrow \mu = 1$$

For the contribution to the short-circuit power provided by the 220 kV network, $\mu = 1$, see Fig. 3-5, since in relation to generator G 3 it is a far-from-generator fault.

Contributions of individual infeeds to the "breaking capacity"

The proportions of the short-circuit power represented by the 220 kV network, the generator and the motors, when multiplied by their respective factors μ and *q,* yield the contribution of each to the breaking capacity, column 9 of Table 3-20.

Single motor	$S_{aM1} = \mu\, q\, S''_{kM1}$	$= 0.74 \cdot 0.59 \cdot 14.8$ MVA	$= 6.5$ MVA
Motor group	$S_{aM2} = \mu\, q\, S''_{kM2}$	$= 0.74 \cdot 0.32 \cdot 20.3$ MVA	$= 4.8$ MVA
Generator	$S_{aG} = \mu\, S''_{kG}$	$= 1 \cdot 63.1$ MVA	$= 63.1$ MVA
220 kV network	$S_{aQ} = \mu\, S''_{kQ}$	$= 1 \cdot 53.8$ MVA	$= 53.8$ MVA

The total breaking capacity is obtained as an approximation by adding the individual breaking capacities. The result $S_a = 128.2$ MVA is shown in column 9, line 10.

Table 3-20

Example 1, calculation of short-circuit current

1	2 Component	3 x %/MVA	4 $\frac{1}{x}$ MVA/%	5 S''_k MVA	6 S''_k/S_r	7 μ (0.1 s)	8 q (0.1 s)	9 S_a MVA
1	220 kV network	0.0138	—	53.8	—	1	—	53.8
2	transformer *1*	0.1300	—	—	—	—	—	—
3	1 and 2 in series	0.1438 →	6.9541	—	—	—	—	—
4	93.7 MVA generator	0.1227 →	8.1500	63.1	0.67	1	—	63.1
5	3 and 4 in parallel	0.0662 ←	15.1041	—	—	—	—	—
6	transformer *2*	0.8750	—	—	—	—	—	—
7	5 and 6 in series	0.9412 →	1.0625	116.9	—	—	—	—
8	induction motor 2.3 MW/2.69 MVA	7.4349 →	0.1345	14.8	5.50	0.74	0.59	6.5
9	motor group $\Sigma = 3.68$ MVA	5.4348 →	0.1840	20.3	5.52	0.74	0.32	4.8
10	fault location 7, 8 and 9 in parallel	0.7225 ←	1.3810	152.0	—	—	—	128.2

At the fault location:

$$I''_k = \frac{S''_k}{\sqrt{3} \cdot U_n} = \frac{152.0 \text{ MVA}}{\sqrt{3} \cdot 6.0 \text{ kV}} = 14.63 \text{ kA},$$

$$I_p = \kappa \cdot \sqrt{2} \cdot I''_k = 2.0 \cdot \sqrt{2} \cdot 14.63 \text{ kA} = 41.4 \text{ kA (for } \kappa = 2.0),$$

$$I_a = \frac{S_a}{\sqrt{3} \cdot U_n} = \frac{128.2 \text{ MVA}}{\sqrt{3} \cdot 6.0 \text{ kV}} = 12.3 \text{ kA}.$$

Example 2

Calculation of the phase-to-earth fault current I''_{k1}.

Find I''_{k1} at the 220 kV busbar of the power station represented by Fig. 3-22.

Calculation is made using the method of symmetrical components. First find the positive-, negative- and zero-sequence reactances X_1, X_2 and X_0 from the network data given in the figure.

Positive-sequence reactances (index 1)

Overhead line $X_{1L} = 50 \cdot 0.32\ \Omega \cdot \dfrac{1}{2} = 8\ \Omega$

220 kV network $X = 0.995 \cdot \dfrac{1.1 \cdot (220\ \text{kV})^2}{8000\ \text{MVA}} = 6.622\ \Omega$

Power plant unit $X_G = 0.14 \cdot \dfrac{(21\ \text{kV})^2}{125\ \text{MVA}} = 0.494\ \Omega$

$$X_T = 0.13 \cdot \frac{(220\ \text{kV})^2}{130\ \text{MVA}} = 48.4\ \Omega$$

$$X_{KW} = K_{KW}\,(\ddot{u}_r^2 \cdot X_G + X_T)$$

$$K_{KW} = \frac{1.1}{1 + (0.14 - 0.13) \cdot 0.6}$$

$$X_{KW} = 1.093 \left[\left(\frac{220}{21}\right)^2 \cdot 0.494 + 48.4\right] \Omega = 112.151\ \Omega$$

At the first instant of the short circuit, $x_1 = x_2$. The negative-sequence reactances are thus the same as the positive-sequence values. For the generator voltage: $U_{rG} = 21$ kV with sin $\varphi_{rG} = 0.6$, the rated voltages of the transformers are the same as the system nominal voltages.

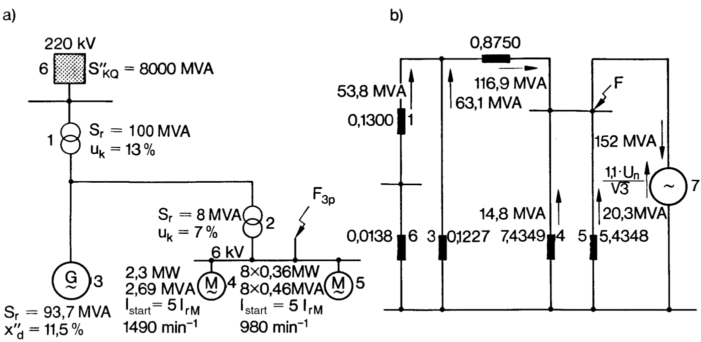


Fig. 3-21

a) Circuit diagram, b) Equivalent circuit diagram in positive phase sequence with equivalent voltage source at fault location, reactances in %/MVA: 1 transformer 1, 2 transformer 2, 3 generator, 4 motor, 5 motor group, 6 220 kV network, 7 equivalent voltage at the point of fault.

Zero-sequence reactances (index 0)

A zero-sequence system exists only between earthed points of the network and the fault location. Generators G1 and G 2 and also transformer T1 do not therefore contribute to the reactances of the zero-sequence system.

Overhead line 2 circuits in parallel	X_{0L}	$= 3.5 \cdot X_{1L} = 28\ \Omega$
220 kV network	X_{0Q}	$= 2.5 \cdot X_{1Q} = 16.555\ \Omega$
Transformer T 2	X_{0T_2}	$= 0.8 \cdot X_{1T} \cdot 1.093 = 42.321\ \Omega$

With the reactances obtained in this way, we can draw the single-phase equivalent diagram to calculate I''_{k1} (Fig. 3-22b).

Since the total positive-sequence reactance at the first instant of the short circuit is the same as the negative-sequence value, it is sufficient to find the total positive and zero sequence reactance.

Calculation of positive-sequence reactance:

$$\frac{1}{x_1} = \frac{1}{56.076\ \Omega} + \frac{1}{14.622\ \Omega} \rightarrow x_1 = 11.598\ \Omega$$

Calculation of zero-sequence reactance:

$$\frac{1}{x_0} = \frac{1}{42.321\ \Omega} + \frac{1}{44.556\ \Omega} \rightarrow x_0 = 21.705\ \Omega$$

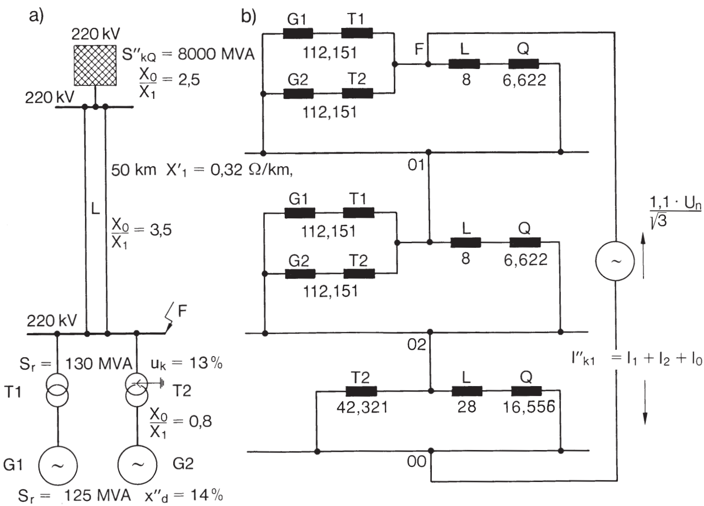


Fig. 3-22

a) Circuit diagram, b) Equivalent circuit diagram in positive phase sequence, negative phase sequence and zero phase sequence with connections and equivalent voltage source at fault location F for I''_{k1}.

With the total positive-, negative- and zero-sequence reactances, we have

$$I''_{k1} = \frac{1.1 \cdot \sqrt{3} \cdot U_n}{x_1 + x_2 + x_0} = \frac{1.1 \cdot \sqrt{3} \cdot 220}{44.901} = 9.34\ \text{kA}.$$

The contributions to I''_{k1} represented by the 220 kV network (Q) or power station (KW) are obtained on the basis of the relationship

$$\underline{I}''_{k1} = \underline{I}_1 + \underline{I}_2 + \underline{I}_0 = 3 \cdot \underline{I}_1 \text{ with } \underline{I}_0 = \underline{I}_1 = \underline{I}_2 = 3.11 \text{ kA}$$

to right and left of the fault location from the equations:

$$\underline{I}''_{k1Q} = \underline{I}_{1Q} + \underline{I}_{2Q} + \underline{I}_{0Q}, \text{ and } \underline{I}''_{k1KW} = \underline{I}_{1KW} + \underline{I}_{2KW} + \underline{I}_{0KW}.$$

3

The partial component currents are obtained from the ratios of the respective impedances.

$$I_{1Q} = I''_{2Q} = 3.11 \text{ kA} \cdot \frac{56.08}{70.70} = 2.47 \text{ kA}$$

$$I_{0Q} = 3.11 \text{ kA} \cdot \frac{42.32}{86.88} = 1.51 \text{ kA}$$

$$I_{1KW} = 0.64 \text{ kA}$$

$$I_{0KW} = 1.60 \text{ kA}$$

$$\underline{I}''_{k1Q} = (2.47 + 2.47 + 1.51) \text{ kA} = 6.45 \text{ kA}$$

$$\underline{I}''_{k1KW} = (0.641 + 0.64 + 1.60) \text{ kA} = 2.88 \text{ kA}$$

Example 3

The short-circuit currents are calculated with the aid of Table 3-2.

20 kV network: $x_{1Q} = 0.995 \dfrac{1.1 \cdot (0.4)^2}{250} = 0.0007\ \Omega$

$r_{1Q} \approx 0.1\ x_{1Q} = 0.00007\ \Omega$

Transformer: $x_{1T} = 0.058 \dfrac{(0.4)^2}{0.63} = 0.0147\ \Omega$

$r_{1T} = 0.015 \dfrac{(0.4)^2}{0.63} = 0.0038\ \Omega$

$x_{0T} = 0.95 \cdot x_{1T} = 0.014\ \Omega$

$r_{0T} \approx r_{1T} = 0.0038\ \Omega$

Cable: $x_{1L} = 0.08 \cdot 0.074 = 0.0059\ \Omega$

$r_{1L20} = 0.08 \cdot 0.271 = 0.0217\ \Omega$

$r_{1L80} = 1.24 \cdot r_{1L20} = 0.0269\ \Omega$

$x_{0L} \approx 7.36 \cdot x_{1L} = 0.0434\ \Omega$

$r_{0L20} \approx 3.97 \cdot r_{1L20} = 0.0861\ \Omega$

$r_{0L80} = 1.24 \cdot r_{0L20} = 0.1068\ \Omega$

Maximum and minimum short-circuit currents at fault location F 1

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0039 + \text{j}\ 0.0154)\ \Omega; \quad \underline{Z}_0 = (0.0038 + \text{j}\ 0.0140)\ \Omega$$

$$I''_{k3} = \frac{1.0 \cdot 0.4}{\sqrt{3} \cdot 0.0159} \text{ kA} = 14.5 \text{ kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 12.6 \text{ kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.0 \cdot 0.4}{0.0463} \text{ kA} = 15.0 \text{ kA}.$$

b. Minimum short-circuit currents

The miminum short-circuit currents are calculated with $c = 0.95$.

Maximum and minimum short-circuit currents at fault location F 2

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0265 + \mathrm{j}\,0.0213)\ \Omega; \quad \underline{Z}_0 = (0.0899 + \mathrm{j}\,0.0574)\ \Omega$$

$$I''_{k3} = \frac{1.0 \cdot 0.4}{\sqrt{3} \cdot 0.0333}\ \mathrm{kA} = 6.9\ \mathrm{kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 6.0\ \mathrm{kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.0 \cdot 0.4}{0.1729}\ \mathrm{kA} = 4.0\ \mathrm{kA}.$$

b. Minimum short-circuit currents

The minimum short-circuit currents are calculated with $c = 0.95$ and a temperature of 80 °C.

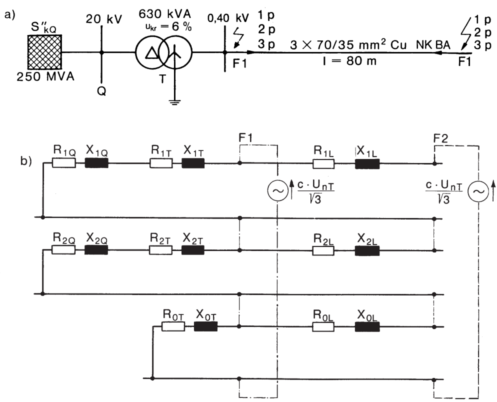


Fig. 3-23

a) Circuit diagram of low-voltage network,
b) Equivalent diagram in component systems and connection for single-phase fault

Table 3-21

Summary of results

Fault location	Max. short-circuit currents 3p kA	2p kA	1p kA	Min. short-circuit currents 3p kA	2p kA	1p kA
Fault location F 1	14.5	12.6	15.0	13.8	12.0	14.3
Fault location F 2	6.9	6.0	4.0	6.4	5.5	3.4

The breaking capacity of the circuit-breakers must be at least 15.0 kA or 6.9 kA. Protective devices must be sure to respond at 12 kA or 3.4 kA. These figures relate to fault location F1 or F2.

3.5 Effect of neutral point arrangement on fault behaviour in three-phase high-voltage networks above 1 kV

Table 3-22

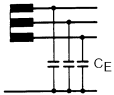
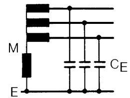
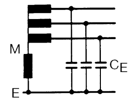
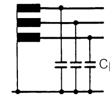
Arrangement of neutral point	isolated	with arc suppression coil	current-limiting *R* or *X*	low-resistance earth
		 $\omega L \approx \frac{1}{3\omega C_E}$	 $\omega L < \frac{1}{3\omega C_E}$	
Examples of use	Networks of limited extent, power plant auxiliaries	Overhead-line networks 10…123 kV	Cable networks 10…230 kV system e. g. in towns	High-voltage networks (123 kV) to 400 kV (protective multiple earthing in l. v. network)
Between system and earth are:	Capacitances, (inst. transformer inductances)	Capacitances, Suppression coils	Capacitances, Neutral reactor	(Capacitances), Earth conductor
$\lvert \underline{Z}_0 / \underline{Z}_1 \rvert$	$\left\lvert \frac{1/\mathrm{j}\omega C_E}{\underline{Z}_1} \right\rvert$	very high resistance	inductive: 4 to 60 resistive: 30 to 60	2 to 4
Current at fault site with single-phase fault Calculation (approximate) $E_1 = \frac{c \cdot U_n}{\sqrt{3}} = E''$	Ground-fault current $\underline{I}_E$ (capacitive) $\underline{I}_E \approx \mathrm{j}\, 3\, \omega C_E \cdot E_1$	Residual ground-fault current $\underline{I}_R$ $\underline{I}_R \approx 3\, \omega C_E (\delta + \mathrm{j}\nu)\, E_1$ δ = loss angle ν = interference	Ground-fault current $\underline{I}_{k1}$ $\underline{I}''_{k1} = \underline{I}_R \approx \frac{3\, E_1}{\mathrm{j}\,(X_1 + X_2 + X_0)}$ $\frac{\underline{I}''_{k1}}{\underline{I}''_{k3}} = \frac{3\, X_1}{2\, X_1 + X_0} = \frac{3}{2 + X_0/X_1}$	(continued)

Table 3-22 (continued)

Arrangement of neutral point	isolated	with arc suppression coil	current-limiting *R* or *X*	low-resistance earth
I''_{k2} / I''_{k3}	I_{CE} / I''_{k3}	I_R / I''_{k3}	*inductive*: 0.05 to 0.5 *resistive*: 0.1 to 0.05	0.5 to 0.75
U_{LEmax} / U_n	≈ 1	1 to (1.1)	inductive: 0.8 to 0.95 resistive: 0.1 to 0.05	0.75 to ≦ 0.80
U_{0max} / U_n	≈ 0.6	0.6 to 0.66	inductive: 0.42 to 0.56 resistive: 0.58 to 0.60	0.3 to 0.42
Voltage rise in whole network	yes	yes	no	no
Duration of fault	10 to 60 min Possible short-time earthing with subsequent selective disconnection by neutral current (< 1 s)	10 to 60 min	< 1 s	< 1 s
Ground-fault arc	Self-quenching up to several A	Self-quenching	Partly self-quenching usually sustained	Sustained
Detection	Location by disconnection, ground-fault wiping-contact relay, wattmeter relay. (With short-time earthing: disconnection by neutral current)		Selective disconnection by neutral current (or short-circuit protection)	Short-circuit protection
Risk of double earth fault	yes	yes	slight	no
Means of earthing DIN VDE 0141	Earth electrode voltage $U_E \leq$ 125 V Touch voltage ≦ 65 V		Earth electrode voltage U_E > 125 V permissible Touch voltages ≦ 65V	
Measures against interference with communication circuits DIN VDE 0228	Generally not necessary needed only with railway block lines	Not necessary	Overhead lines: possibly required if approaching over a considerable distance Cables: generally not necessary	