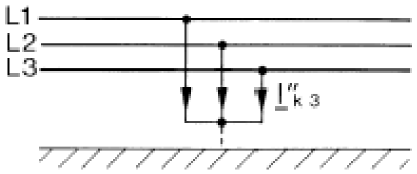
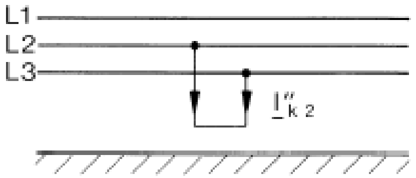
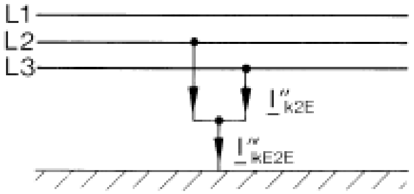
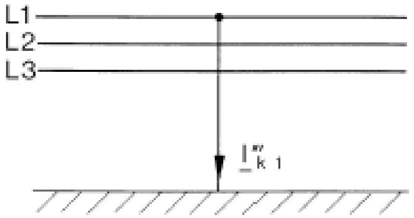
Examples of Short-Circuit Calculations
IEC EN 60909-0

Prepared by; Prof. Dr. İsmail Kaşıkçı

ABB Switchgear Manual, 11th edition
ISBN 10:3-589-24112-8

Table 3-2

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

Kind of fault		Dimension equations (IEC 909)
Three-phase fault with or without earth fault		$I''_{k3} = \frac{1.1 \cdot U_n}{\sqrt{3}\,\lvert\underline{Z}_1\rvert}$ $S''_k = \sqrt{3}\, U_n\, I''_{k3}$
Phase-to-phase fault clear of ground		$I''_{k2} = \frac{1.1 \cdot U_n}{\lvert\underline{Z}_1 + \underline{Z}_2\rvert}$
Two-phase-to-earth fault		$I''_{kE2E} = \frac{\sqrt{3} \cdot 1.1\, U_n}{\left\lvert\underline{Z}_1 + \underline{Z}_0 + \underline{Z}_0 \frac{\underline{Z}_1}{\underline{Z}_2}\right\rvert}$
Phase-to-earth fault		$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot U_n}{\lvert\underline{Z}_1 + \underline{Z}_2 + \underline{Z}_0\rvert}$

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.

Examples of short-circuit calculations

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, the calculation for the biggest short-circuits is on the safe side. Corrections to the
reactances are disregarded.

Example 1: High voltage power systems

Calculation of the single and 3-phase earth fault current.

Find I''_{k3} and I''_{k1} at the 220 kV busbar of the power station represented by Fig. 3-19.
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.

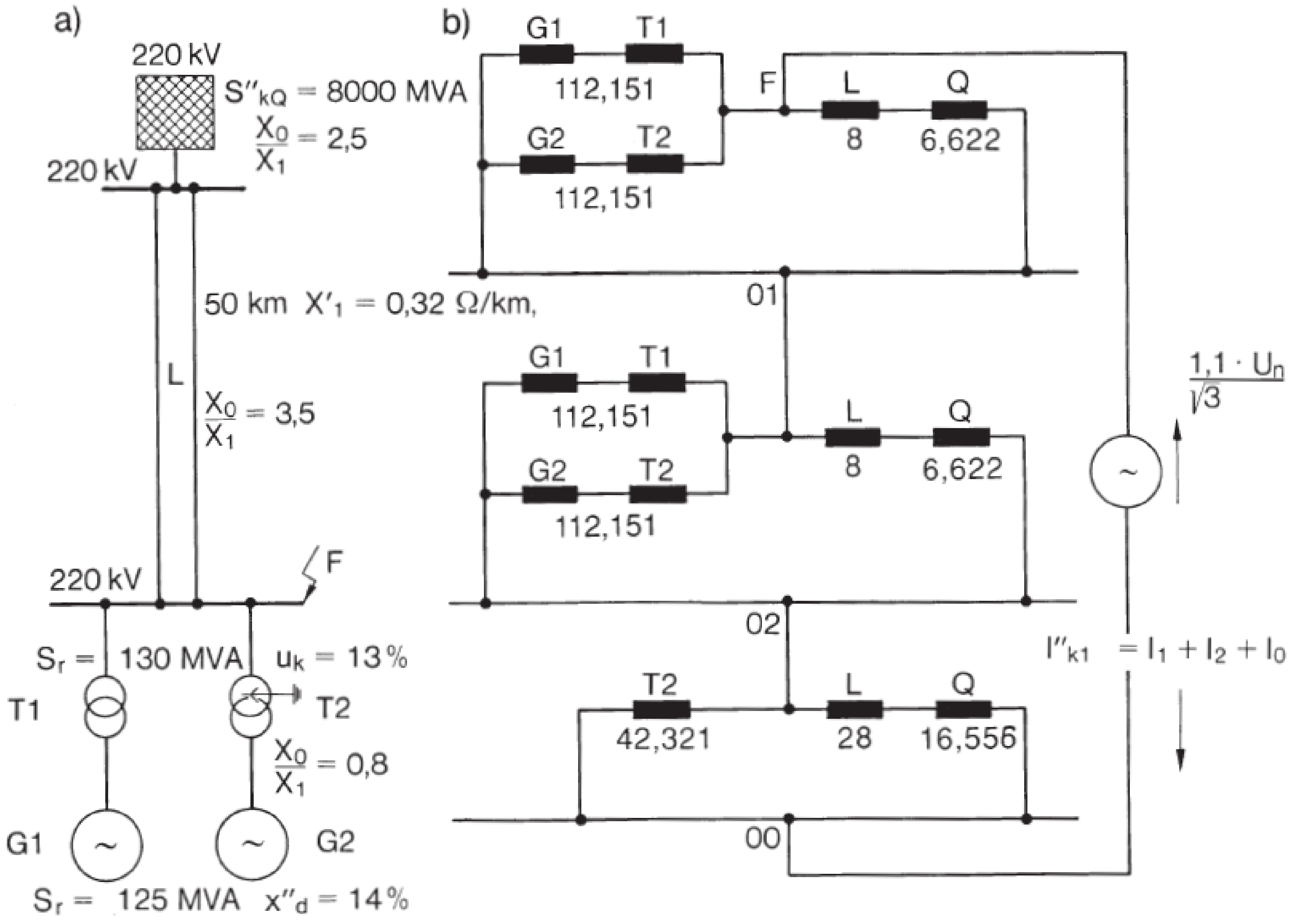


Fig. 3-22

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}.

Positive-sequence reactances (index 1)

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

220 kV network $X_{1Q} = 0.995 \cdot \frac{1.1 \cdot 220\ \text{kV}/\sqrt{3}}{21\ \text{kA}} = 6.620\ \Omega$

Power plant unit $X_{1G} = 0.14 \cdot \frac{(21\ \text{kV})^2}{125\ \text{MVA}} = 0.494\ \Omega$

$$X_{1T} = 0.13 \cdot \frac{(220\ \text{kV})^2}{130\ \text{MVA}} = 48.4\ \Omega$$

$$X_S = K_S\,(t_r^2 \cdot X_{1G} + X_{1T})$$

$$K_S = \left(\frac{220\ \text{kV}}{21\ \text{kV}}\right)^2 \cdot \left(\frac{21\ \text{kV}}{220\ \text{kV}}\right)^2 \cdot \frac{1.1}{1 + |\,0.14 - 0.13\,| \cdot 0.6} = 1.093$$

$$X_S = 1.093\left[\left(\frac{220}{21}\right)^2 \cdot 0.494 + 48.4\right]\Omega = 112.160\ \Omega$$

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.

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	$X_{0Q} = 2.5 \cdot X_{1Q} = 16.55\ \Omega$
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. 3-19b).

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:

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

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

$$I''_{k3} = \frac{1.1 \cdot U_n \cdot \sqrt{3}}{x_1} = \frac{1.1 \cdot 220\ \text{kV} \cdot \sqrt{3}}{11.597\ \Omega} = 12.05\ \text{kA}.$$

$$I''_{k1} = \frac{1.1 \cdot \sqrt{3} \cdot U_n}{x_1 + x_2 + x_0} = \frac{1.1 \cdot \sqrt{3} \cdot 220\ \text{kV}}{44.897\ \Omega} = 9.34\ \text{kA}.$$

The contributions to I''_{k3} and I''_{k1} represented by the 220 kV network (Q) or power station (S) are obtained on the basis of the relationship

$$I''_{k3} = \underline{I}_1 \text{ with } I_1 = 12{,}05\ \text{kA with}$$

$$I''_{k1} = I_1 + I_2 + I_0 = 3\ \underline{I}_1 \text{ mit } I_0 = I_1 = I_2 = 3.11\ \text{kA}.$$

from the equations:

$$\underline{I}''_{k3Q} = \underline{I}_{1Q} \text{ and } \underline{I}_{k3S} = \underline{I}_{1S}$$

$$\underline{I}''_{k1Q} = \underline{I}_{1Q} + \underline{I}_{2Q} + \underline{I}_{0Q} \text{ und } \underline{I}''_{k1S} = \underline{I}_{1S} + \underline{I}_{2S} + \underline{I}_{0S}.$$

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

3-pole-to-earth-fault:

$$I''_{k3Q} = I_{1Q} = 12.05\ \text{kA} \cdot \frac{56.08}{70.7} = 9.56\ \text{kA}$$

$$I''_{k3S} = I_{1S} = 12.05\ \text{kA} \cdot \frac{14.62}{70.7} = 2.49\ \text{kA}$$

single-pole-to-earth-fault:

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

$$I_{0Q} = 3.11\ \text{kA} \cdot \frac{42.32}{86.87} = 1.52\ \text{kA}$$

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

$$I_{0S} = 1.59\ \text{kA}$$

$$\underline{I}''_{k1Q} = (2.47 + 2.47 + 1.52)\ \text{kA} = 6.46\ \text{kA}$$

$$\underline{I}''_{k1S} = (0.64 + 0.64 + 1.59)\ \text{kA} = 2.87\ \text{kA}.$$

Example 2:
Low voltage power systems

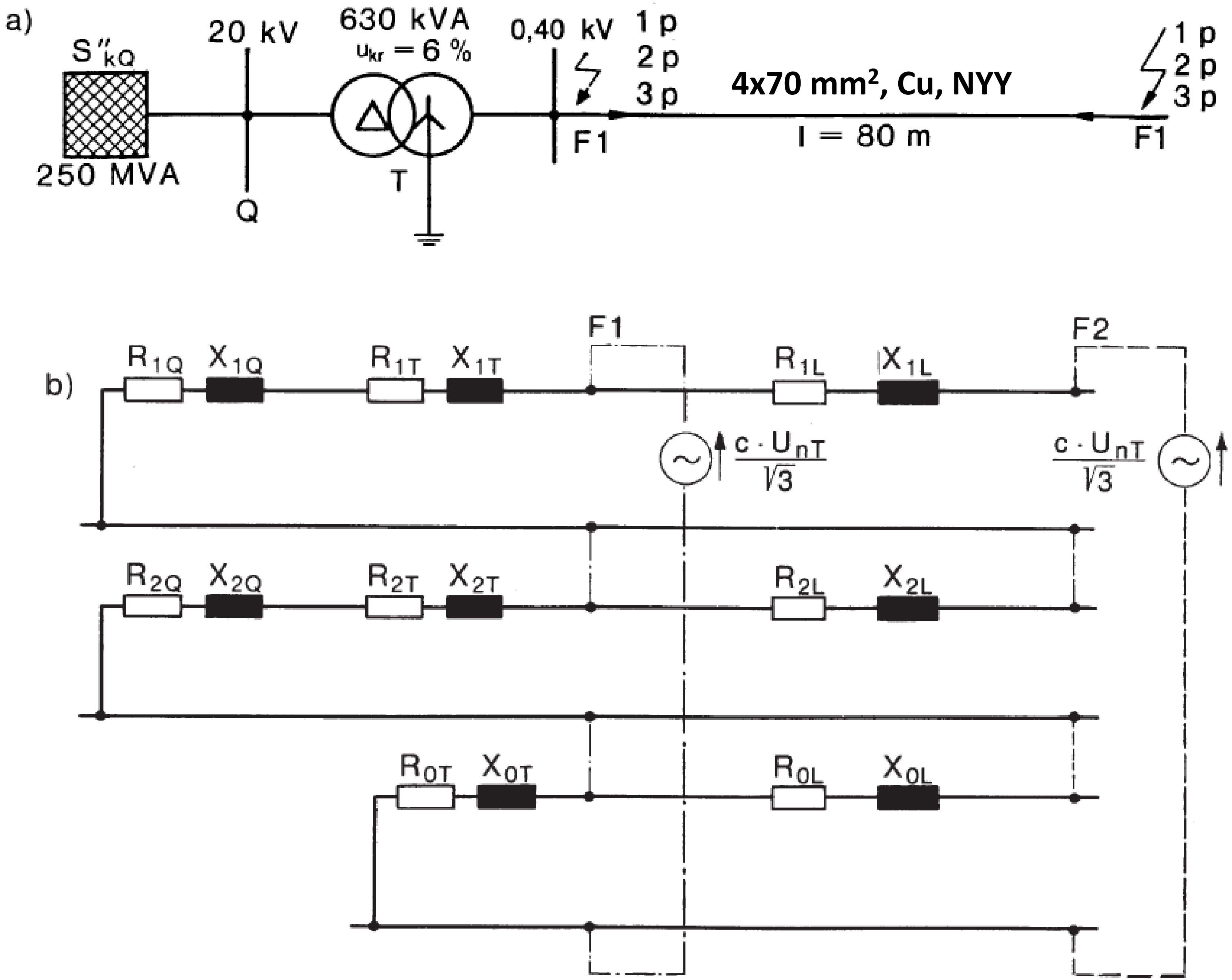


Fig. 3-23

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

The short-circuit currents are calculated with the aid of Table 3-2 (with c_{max} = 1.1 at voltage tolerance ± 10%.

20 kV network:

$$x_{1Q} = 0.995 \frac{1.1 \cdot (0.4)^2}{250} = 0.0007\ \Omega$$

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

Transformer

$$x_{1T} = 0.058 \frac{(0.4)^2}{0.63} \cdot 0.95 \cdot \frac{1.1}{1 + 0.6 \cdot 0.058} = 0.0149\ \Omega$$

$$r_{1T} = 0.015 \frac{(0.4)^2}{0.63} \cdot 0.95 \cdot \frac{1.1}{1 + 0.6 \cdot 0.058} = 0.0039\ \Omega$$

$$x_{0T} = 0.95 \cdot x_{1T} = 0.0142\ \Omega$$

$$r_{0T} \approx r_{1T} = 0.0039\ \Omega$$

Cable:

$$x_{1L} = 0.08 \cdot 0.082 = 0.0066\ \Omega$$

$$r_{1L20} = 0.08 \cdot 0.269 = 0.0215\ \Omega$$

$$r_{1L80} = 1.56 \cdot r_{1L20} = 0.0336\ \Omega$$

$$x_{0L} \approx 5.68 \cdot x_{1L} = 0.0373\ \Omega$$

$$r_{0L20} \approx 3.18 \cdot r_{1L20} = 0.0684\ \Omega$$

$$r_{0L80} = 1.56 \cdot r_{0L20} = 0.1068\ \Omega$$

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

a. Maximum short-circuit currents

$$\underline{Z}_1 = \underline{Z}_2 = (0.0039 + j\,0.0156)\ \Omega; \quad \underline{Z}_0 = (0.0039 + j\,0.0142)\ \Omega$$

$$I''_{k3} = \frac{1.1 \cdot 0.4}{\sqrt{3} \cdot 0.0161}\ \text{kA} = 15.8\ \text{kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 13.7\ \text{kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 0.4}{0.0468}\ \text{kA} = 16.3\ \text{kA}.$$

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

$$\underline{Z}_1 = \underline{Z}_2 = (0.0254 + j\,0.0222)\ \Omega; \quad \underline{Z}_0 = (0.0723 + j\,0.0514)\ \Omega$$

$$I''_{k3} = \frac{1.1 \cdot 0.4}{\sqrt{3} \cdot 0.0337}\ \text{kA} = 7.5\ \text{kA}$$

$$I''_{k2} = \frac{\sqrt{3}}{2} I''_{k3} = 6.5\ \text{kA}$$

$$I''_{k1} = \frac{\sqrt{3} \cdot 1.1 \cdot 0.4}{0.1560}\ \text{kA} = 4.9\ \text{kA.}$$

Summary of results

Fault location	Max. short-circuit currents			Min. short-circuit currents		
	3p kA	2p kA	1p kA	3p kA	2p kA	1p kA
Fault location F 1	15.8	13.7	16.3	13.6	11.8	14.1
Fault location F 2	7.5	6.5	4.9	5.0	4.4	3.2

The breaking capacity of the circuit-breakers must be at least 16.0 kA or 7.5 kA. Protective devices must be sure to respond at 11.8 kA or 3.2 kA. These figures relate to fault location F1 or F2.

Table 3-4

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 ($n < 375$ 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.

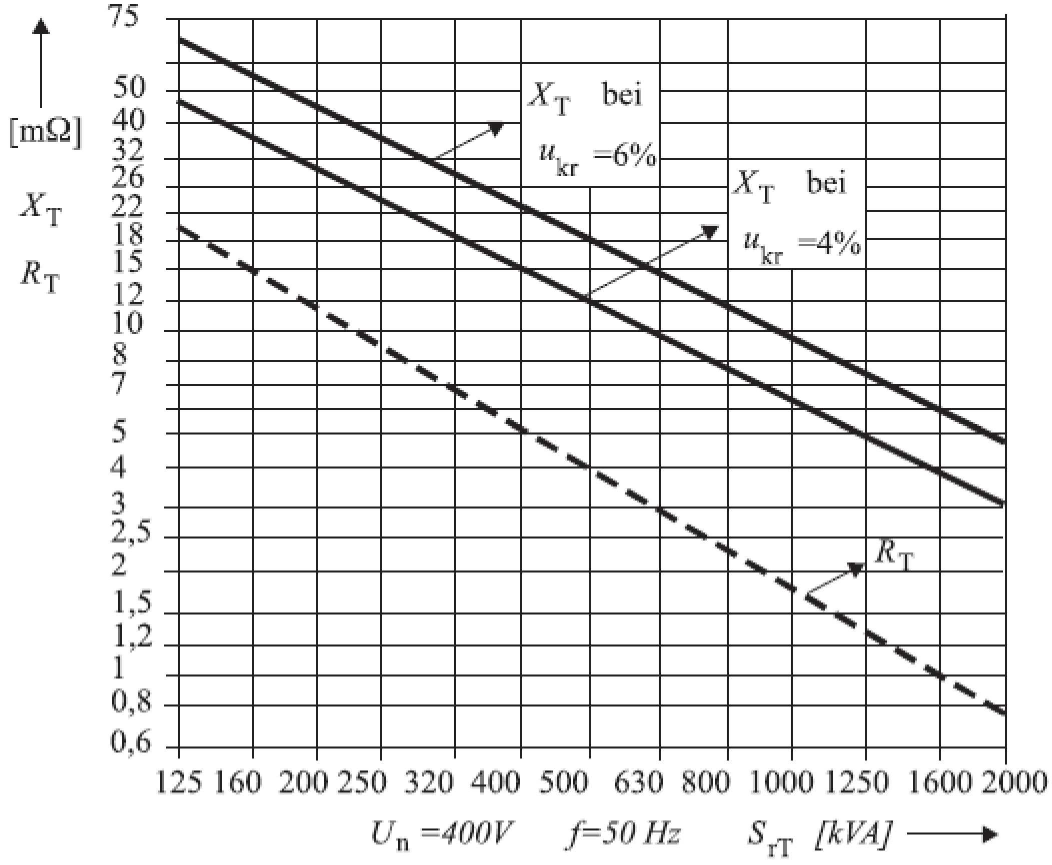


Table 3-6

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 3-7

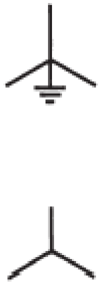
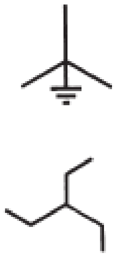
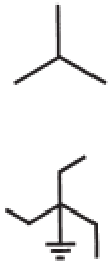
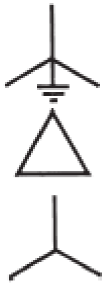
Typical values for ohmic voltage drop u_R of three-phase transformers

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 %.

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] $R_{0T} \approx R_T \quad X_{0T} \approx 7\ldots100^{2)}\, X_T$

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

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[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.

Table 2-8

Effective resistances per unit length of PVC-insulated cables with copper conductors as per DIN VDE 0271 for 0.6/1 kV

Number of conductors and cross-section	D. C. resistance at 70 °C	Ohmic resistance at 70 °C	Inductive reactance	Effective resistance per unit length $R'_L \cdot \cos\varphi + X'_L \cdot \sin\varphi$ at $\cos\varphi$ 0.95	0.9	0.8	0.7	0.6
	R'_{L-}	$R'_{L\sim}$	X'_L					
mm²	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km	Ω/km
4 × 1.5	14.47	14.47	0.115	13.8	13.1	11.65	10.2	8.77
4 × 2.5	8.71	8.71	0.110	8.31	7.89	7.03	6.18	5.31
4 × 4	5.45	5.45	0.107	5.21	4.95	4.42	3.89	3.36
4 × 6	3.62	3.62	0.100	3.47	3.30	2.96	2.61	2.25
4 × 10	2.16	2.16	0.094	2.08	1.99	1.78	1.58	1.37
4 × 16	1.36	1.36	0.090	1.32	1.26	1.14	1.020	0.888
4 × 25	0.863	0.863	0.086	0.847	0.814	0.742	0.666	0.587
4 × 35	0.627	0.627	0.083	0.622	0.60	0.55	0.498	0.443
4 × 50	0.463	0.463	0.083	0.466	0.453	0.42	0.38	0.344
4 × 70	0.321	0.321	0.082	0.331	0.326	0.306	0.283	0.258
4 × 95	0.231	0.232	0.082	0.246	0.245	0.235	0.221	0.205
4 × 120	0.183	0.184	0.080	0.2	0.2	0.195	0.186	0.174
4 × 150	0.149	0.150	0.080	0.168	0.17	0.168	0.162	0.154
4 × 185	0.118	0.1202	0.080	0.139	0.143	0.144	0.141	0.136
4 × 240	0.0901	0.0922	0.079	0.112	0.117	0.121	0.121	0.119
4 × 300	0.0718	0.0745	0.079	0.0954	0.101	0.107	0.109	0.108

Table 3-14

XLPE-cabel [N2XSEY; NA2XS2Y]: a.c. resistance $R'_{\sim}$ and inductive operation reactance X' at positive-sequence system at $f = 50$ Hz, 12 kV

cores and cross-section	N2XSEY		NA2XS2Y	
	$R'_{\sim}$ Ω / km	X' Ω / km	$R'_{\sim}$ Ω / km	X' Ω / km
3 × 35	0.525	0.118	–	–
3 × 50	0.388	0.112	0.642	0.106
3 × 70	0.269	0.106	0.444	0.100
3 × 95	0.194	0.101	0.321	0.095
3 × 120	0.155	0.097	0.254	0.092
3 × 150	0.126	0.095	0.208	0.090
3 × 185	0.102	0.091	0.166	0.087
3 × 240	0.078	0.088	0.127	0.084