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Course KEE/PDS

Transmission and distribution grids

Short-circuit calculation

Examples

EE2 Seminars no. 8 a 9

Short-circuit calculations

Time behavior of the short circuit current

Figure 1.1 shows the time behavior of the short circuit current for the occurrence of far-from-generator and near-to-generator short circuits.

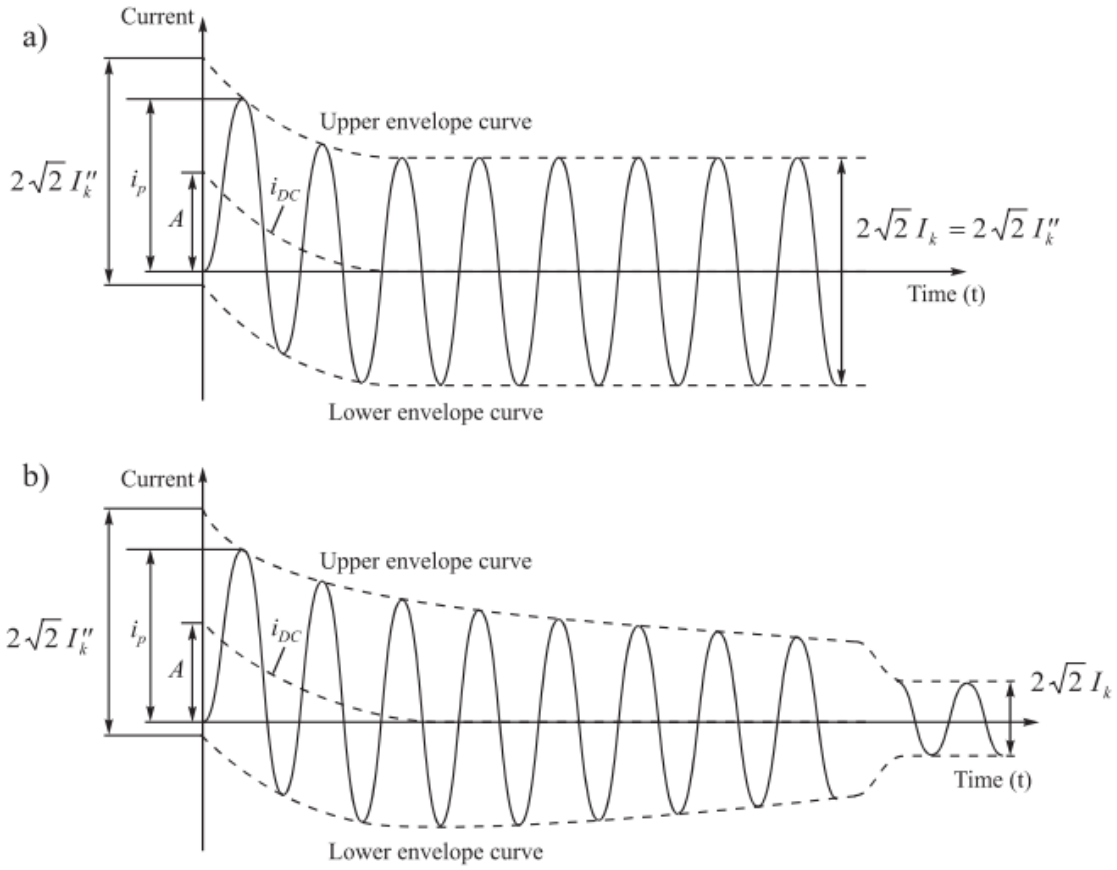


Fig. 1.1: Time behavior of the short circuit current [1], [35]
a) far-from-generator short circuit, b) near-to-generator short circuit

I_k'': Initial symmetrical short circuit current

i_p: Peak short circuit current

i_{DC}: Decaying DC aperiodic component

A: Initial value of DC aperiodic component

The DC aperiodic component depends on the point in time at which the short circuit occurs. For a near-to-generator short circuit, the subtransient and the transient behavior of the synchronous machines is important. Following the decay of all transient phenomena, the steady state sets in.

Calculation procedure

(Method of equivalent voltage source $-\frac{c \cdot Un}{\sqrt{3}}$ at the fault location)

- Identification of short- circuit sources (upstream networks, generators), fault current path locating

- To draw equivalent circuit, elements are replaced by their reactance X.
  In EHV, HV and MV (networks with overhead power lines): R << X $\Rightarrow$ R of network elements is neglected for simplified calculations of short circuit currents.
  The equivalent voltage source -cUn/√3 is the only active source in the system. It will be applied at the short-circuit location, whereas all other sources in the system are ignored (short-circuited).

- Calculation of elements' reactance.

  Upstream network: $X_S = \frac{c \cdot U_n^{\,2}}{S_K''}$

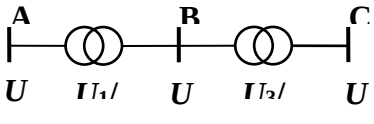
  Generator: $X_G = \frac{x_{d\%}}{100} \cdot \frac{U_n^{\,2}}{S_{nG}}$

  Transformer: $X_T = \frac{u_{k\%}}{100} \cdot \frac{U_n^{\,2}}{S_{nT}}$

  Power line (overhead line - OHL, cable): $X_V = X_{V1} \cdot l$

  Motor: $X_M = \frac{1}{i_k} \cdot \frac{U_n^{\,2}}{S_{nM}}$

If the voltage level is different from voltage level of short-circuit location, the reactance has to be converted to voltage in fault location.



Fault location is in C

$$X_C = \frac{U_C}{I_C} = \frac{U_A \cdot \left(\frac{U_2}{U_1}\right) \cdot \left(\frac{U_4}{U_3}\right)}{I_A \cdot \left(\frac{U_1}{U_2}\right) \cdot \left(\frac{U_3}{U_4}\right)} = \frac{U_A}{I_A} \cdot \left(\frac{U_2}{U_1}\right)^2 \cdot \left(\frac{U_4}{U_3}\right)^2 = X_A \cdot \left(\frac{U_2}{U_1}\right)^2 \cdot \left(\frac{U_4}{U_3}\right)^2$$

Example for an upstream network:

$$X_{S(C)} = X_{S(A)} \cdot \left(\frac{U_2}{U_1}\right)^2 \cdot \left(\frac{U_4}{U_3}\right)^2 = \frac{c \cdot U_{nS(A)}^2}{S_{kS}''} \cdot \left(\frac{U_2}{U_1}\right)^2 \cdot \left(\frac{U_4}{U_3}\right)^2$$

Because $U_{nS(A)} = U_A = U_1 \quad U_2 = U_3 = U_B \quad U_4 = U_C \quad \rightarrow \quad X_{S(C)} = \frac{c \cdot U_C^2}{S''_{kS}}$

Example:
Transformer 110/22 kV, 40 MVA, u_K= 10,5%

Calculate reactance of the transformer on voltage level 110 kV:

$$X_{t110kV} = u_k \cdot \frac{U_n^2}{S_n} = 0{,}105 \cdot \frac{110^2}{40} = 31{,}76\ \Omega$$

Calculate reactance of the transformer on voltage level 22 kV:

$$X_{t22kV} = u_k \cdot \frac{U_n^2}{S_n} = 0{,}105 \cdot \frac{22^2}{40} = 1{,}27\ \Omega$$

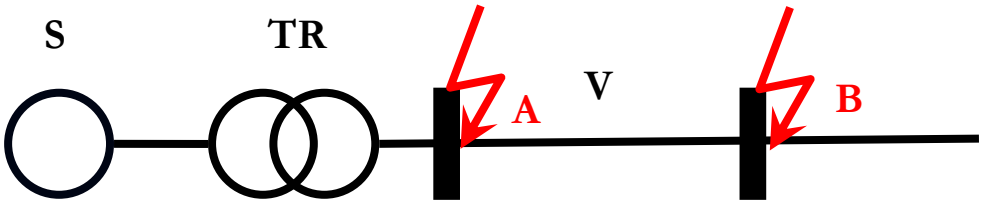
or $X_{t22kV} = X_{t110kV} \cdot \left(\frac{U_{n2}}{U_{n1}}\right)^2 = 31{,}76 \cdot \frac{22^2}{110^2} = 1{,}27\ \Omega$

- To calculate equivalent short-circuit reactance Xk of the upstream grid (essentially its Thevenin impedance) at the short-circuit location.
- Calculation of the initial symmetrical current and short-circuit power (level)

$$I_K'' = \frac{c \cdot U_n}{\sqrt{3} \cdot X_k} \qquad S_K'' = \sqrt{3} \cdot U_n \cdot I_K''$$

Examples

Example 1:



U_N = 22 kV	22/6 kV	Overhead line 6 kV
S_K" = 200 MVA	S_N = 1000 kVA	l = 2 km
	u_k = 6%	X_{Vk} = 0,3 Ω/km

Upstream network 22 kV (the reactance has to be transferred to voltage level in fault location):

$$X_S = \frac{c \cdot U_{NS}^{\ 2}}{S_{KS}"} \cdot \frac{1}{p^2} = \frac{1{,}1 \cdot 22^2}{200} \cdot \left(\frac{6}{22}\right)^2 = \frac{c \cdot U_n^{\ 2}}{S_{KS}"} = 0{,}2\,\Omega$$

Transformer 22/6 kV (secondary side has the same voltage like voltage in fault location, 6 kV is substituted into formula):

$$X_T = \frac{u_{k\%}}{100} \cdot \frac{U_{NT}^{\ 2}}{S_{NT}} = \frac{u_{k\%}}{100} \cdot \frac{U_n^{\ 2}}{S_{NT}} = \frac{6}{100} \cdot \frac{6^2}{1} = 2{,}2\,\Omega$$

Overhead power line 6 kV:

$$X_V = X_{Vk} \cdot l = 0{,}3 \cdot 2 = 0{,}6\,\Omega$$

Fault position at the beginning of the cable (short circuit at location A):

Total short-circuit reactance:

$$X_{CA} = X_S + X_T = 2{,}4\,\Omega$$

Short-circuit current and short-circuit power:

$$I_{KA}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CA}} = \frac{1{,}1 \cdot 6}{\sqrt{3} \cdot 2{,}4} = 1{,}59\ kA \qquad c = 1{,}1$$

$$S_{KA}" = \sqrt{3} \cdot U_n \cdot I_{KA}" = \sqrt{3} \cdot 6 \cdot 1{,}59 = 16{,}5\ MVA$$

Fault position at the end of the cable (short circuit at location B):

Total short-circuit reactance:

$$X_{CB} = X_S + X_T + X_V = 3\,\Omega$$

or upstream network at node A (22kV network + transformer) is replaced by the reactance

$$X_{SA} = \frac{c \cdot U_n^{\,2}}{S_{KA}''} = \frac{1{,}1 \cdot 6^2}{16{,}5} = 2{,}4\,\Omega = X_{CA}$$

then

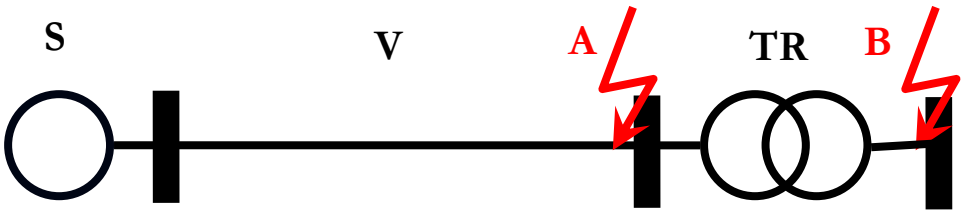
$$X_{CB} = X_{SA} + X_V = 3\,\Omega$$

Short-circuit current and short-circuit power:

$$I_{KB}'' = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CB}} = \frac{1{,}1 \cdot 6}{\sqrt{3} \cdot 3} = 1{,}27\ kA \qquad c = 1{,}1$$

$$S_{KB}'' = \sqrt{3} \cdot U_n \cdot I_{KB}'' = \sqrt{3} \cdot 6 \cdot 1{,}27 = 13{,}2\ MVA$$

Example 2:



U_N = 110 kV	**Overhead line 110 kV**	**110/6 kV**
S_K'' = 1200 MVA	**l = 50 km**	**S_N = 40 MVA**
	X_{Vk} = 0,4 Ω/km	**u_k = 10%**

Fault position in A (Un = 110 kV):

110 kV upstream network:

$$X_S = \frac{c \cdot U_{NS}^{\,2}}{S_{KS}''} = \frac{1{,}1 \cdot 110^2}{1200} = 11{,}1\,\Omega$$

110 kV overhead power line:

$$X_V = X_{Vk} \cdot l = 0{,}4 \cdot 50 = 20\,\Omega$$

Total short-circuit reactance:

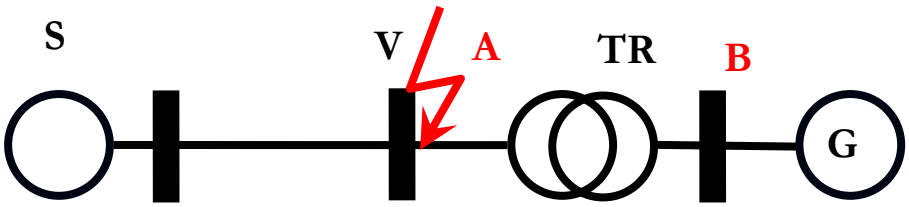
$$X_{CA} = X_S + X_V = 31{,}1\,\Omega$$

Short-circuit current and short-circuit power:

$$I_{KA}'' = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CA}} = \frac{1{,}1 \cdot 110}{\sqrt{3} \cdot 31{,}1} = 2{,}25\ kA \qquad c = 1{,}1$$

$$S_{KA}'' = \sqrt{3} \cdot U_n \cdot I_{KA}'' = \sqrt{3} \cdot 110 \cdot 2{,}25 = 429\ MVA$$

Subtask:
Calculate the short-circuit ratios at fault position A (Un = 110 kV) if a local generator is located behind the transformer (at point B).
G: U_{NG} = 6 kV, S_{NG} = 10 MVA, $x_{d\%}^{"}$ = 12%



Transformer 110/6 kV (primary side has the same voltage like in fault position):

$$X_T = \frac{u_{k\%}}{100} \cdot \frac{U_{NT}^{\ 2}}{S_{NT}} = \frac{u_{k\%}}{100} \cdot \frac{U_n^{\ 2}}{S_{NT}} = \frac{10}{100} \cdot \frac{110^2}{40} = 30,25\,\Omega$$

Generator 6kV (reactance has to be converted into fault position):

$$X_G = \frac{x_{d\%}^{"}}{100} \cdot \frac{U_{NG}^{\ 2}}{S_{NG}} \cdot \frac{1}{p^2} = \frac{12}{100} \cdot \frac{6^2}{10} \cdot \left(\frac{110}{6}\right)^2 = 145,2\,\Omega$$

Short-circuit reactance from 110 kV side:

$$X_1 = X_S + X_V = 31,1\,\Omega$$

Short-circuit reactance from the side of 6 kV generator:

$$X_2 = X_G + X_T = 175,45\,\Omega$$

Sources of the short-circuit currents are radially connected to fault position A.

Total short-circuit reactance (X_1 and X_2 in parallel):

$$X_{CA} = \frac{X_1 \cdot X_2}{X_1 + X_2} = 26,42\,\Omega$$

Short-circuit current and short-circuit power:

$$I_{KA}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CA}} = \frac{1,1 \cdot 110}{\sqrt{3} \cdot 26,42} = 2,64\,kA \qquad c = 1,1$$

$$S_{KA}" = \sqrt{3} \cdot U_n \cdot I_{KA}" = \sqrt{3} \cdot 110 \cdot 2,64 = 503\,MVA$$

Other way:
Sources of the short-circuit currents are radially connected to fault position A →
Total short-circuit current at fault position A = the sum of the contributions of both sources

Short-circuit current from the 110 kV network:

$$I_{K1}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_1} = \frac{1,1 \cdot 110}{\sqrt{3} \cdot 31,1} = 2,24\,kA$$

Short-circuit current from the 6 kV generator:

$$I_{K2}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_2} = \frac{1{,}1 \cdot 110}{\sqrt{3} \cdot 175{,}45} = 0{,}4\ kA$$

Short-circuit current and short-circuit power:

$$I_{KA}" = I_{K1}" + I_{K2}" = 2{,}24 + 0{,}4 = 2{,}64\ kA \qquad c = 1{,}1$$

$$S_{KA}" = \sqrt{3} \cdot U_n \cdot I_{KA}" = \sqrt{3} \cdot 110 \cdot 2{,}64 = 503\ MVA$$

Fault position in B (Un = 6 kV) – generator G is switched-off:

110 kV upstream network (reactance has to be transferred into the fault position B):

$$X_S = \frac{c \cdot U_{NS}{}^2}{S_{KS}"} \cdot \frac{1}{p^2} = \frac{1{,}1 \cdot 110^2}{1200} \cdot \left(\frac{6}{110}\right)^2 = \frac{c \cdot U_n{}^2}{S_{KS}"} = 0{,}033\ \Omega$$

110 kV power line (reactance has to be transferred into the fault position B):

$$X_V = X_{Vk} \cdot l \cdot \frac{1}{p^2} = 0{,}4 \cdot 50 \cdot \left(\frac{6}{110}\right)^2 = 0{,}06\ \Omega$$

Transformer 110/6 kV (secondary side has the same voltage like the fault position B):

$$X_T = \frac{u_{k\%}}{100} \cdot \frac{U_{NT}{}^2}{S_{NT}} = \frac{u_{k\%}}{100} \cdot \frac{U_n{}^2}{S_{NT}} = \frac{10}{100} \cdot \frac{6^2}{40} = 0{,}09\ \Omega$$

Total short-circuit reactance:

$$X_{CB} = X_S + X_T + X_V = 0{,}183\ \Omega$$

or the 110 kV system at the point A (network + power line) is replaced by upstream network reactance, but it has to be transferred via transformer to voltage of the fault position (6 kV):

$$X_{SA} = \frac{c \cdot U_{NS}{}^2}{S_{KA}"} \cdot \frac{1}{p^2} = \frac{1{,}1 \cdot 110^2}{429} \cdot \left(\frac{6}{110}\right)^2 = 0{,}093\ \Omega$$

then

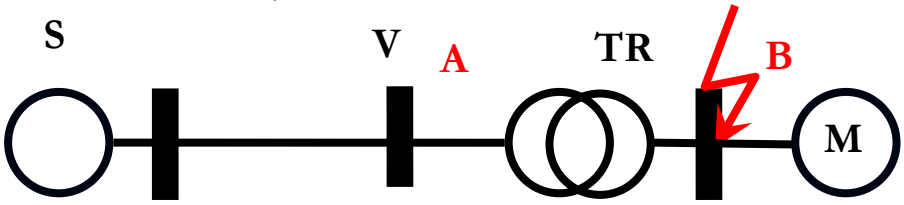
$$X_{CB} = X_{SA} + X_T = 0{,}183\ \Omega$$

Short-circuit current and short-circuit power:

$$I_{KB}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CB}} = \frac{1{,}1 \cdot 6}{\sqrt{3} \cdot 0{,}183} = 20{,}8\ kA \qquad c = 1{,}1$$

$$S_{KB}" = \sqrt{3} \cdot U_n \cdot I_{KB}" = \sqrt{3} \cdot 6 \cdot 20{,}8 = 216{,}2\ MVA$$

Subtask:
Calculate the fault current in node B (Un = 6 kV) if the group of motors is connected in node B.
M: U_{MG} = 6 kV, P_{NM} = 5 MW, cos φn = 0,8, η = 0,9, i_k=5 (the ratio of locked-rotor to rated current of the motors).



Group of motors:

$$X_M = \frac{1}{i_k} \cdot \frac{U_{NM}{}^2}{S_{NM}} = \frac{1}{5} \cdot \frac{6^2}{6,94} = 1,034\,\Omega$$

$$S_{NM} = \frac{\sum P_{NM}}{\cos\varphi_n \cdot \eta} = \frac{5}{0,8 \cdot 0,9} = 6,94\ MVA$$

Short-circuit current from the 110 kV upstream network:

$$X_1 = X_S + X_T + X_V = 0,183\,\Omega$$

Sources of short-circuit current (110 kV network and motors) are connected to fault position B radially (in parallel) →

Short-circuit reactance (reactances in parallel):

$$X_{CBM} = X_1 // X_M = \frac{X_1 \cdot X_M}{X_1 + X_M} = 0,155\,\Omega$$

Reactance X_{CB} has a lower value than in the case without motors (0,183 Ω), i.e. the fault current will be higher than for case without motors.

Short-circuit current and short-circuit power:

$$I_{KBM}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CB}} = \frac{1,1 \cdot 6}{\sqrt{3} \cdot 0,155} = 24,58\ kA \qquad c = 1,1$$

$$S_{KBM}" = \sqrt{3} \cdot U_n \cdot I_{KBM}" = \sqrt{3} \cdot 6 \cdot 24,58 = 255,5\ MVA$$

Sources of short-circuit current are connected to fault position B radially (in parallel) →
The total short-circuit current in node B = sum of contributions from both sources.

Short-circuit current from the 110 kV upstream network:

$$I_{K1}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_1} = \frac{1,1 \cdot 6}{\sqrt{3} \cdot 0,183} = 20,8\ kA$$

Short-circuit current from the group of motors:

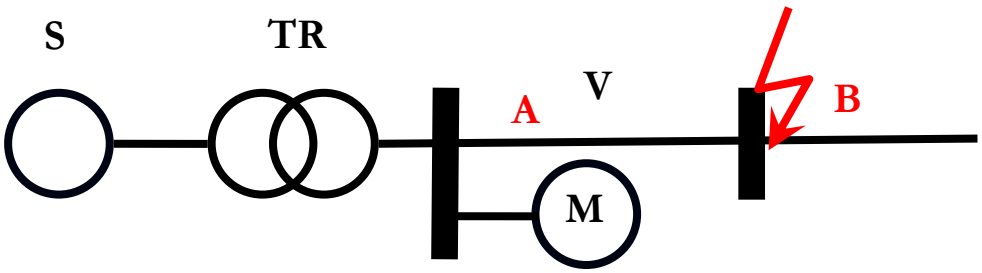
$$I_{K2}" = \frac{c \cdot U_n}{\sqrt{3} \cdot X_M} = \frac{c \cdot U_n}{\sqrt{3} \cdot \frac{1}{i_k} \cdot \frac{U_{NM}^{\ 2}}{S_{NM}}} = c \cdot i_k \cdot \frac{S_{NM}}{\sqrt{3} \cdot U_{NM}} = c \cdot i_k \cdot I_{NM} = c \cdot I_{rozb} = 3,7\ kA$$

Short-circuit current and short-circuit power:

$$I_{KBM}" = I_{K1}" + I_{K2}" = 20,8 + 3,7 = 24,5\ kA \qquad c = 1,1$$

$$S_{KBM}" = \sqrt{3} \cdot U_n \cdot I_{KBM}" = \sqrt{3} \cdot 6 \cdot 24,5 = 254,6\ MVA$$

Example 3:



U_N = 22 kV	**22/6 kV**	**Power line 6 kV**
S_K" = 200 MVA	**S_N = 1000 kVA**	**l = 2 km**
	u_k = 6%	**X_{Vk} = 0,3 Ω/km**

M: U_{MG} = 6 kV, P_{NM} = 5 MW, cos φn = 0,8, η = 0,9, i_k=5

Upstream network 22 kV (reactance has to be transferred to 6 kV):

$$X_S = \frac{c \cdot U_{NS}^{\ 2}}{S_{KS}"} \cdot \frac{1}{p^2} = \frac{1,1 \cdot 22^2}{200} \cdot \left(\frac{6}{22}\right)^2 = \frac{c \cdot U_n^{\ 2}}{S_{KS}"} = 0,2\ \Omega$$

Transformer 110/6 kV (secondary side has voltage 6 kV):

$$X_T = \frac{u_{k\%}}{100} \cdot \frac{U_{NT}^{\ 2}}{S_{NT}} = \frac{u_{k\%}}{100} \cdot \frac{U_n^{\ 2}}{S_{NT}} = \frac{6}{100} \cdot \frac{6^2}{1} = 2,2\ \Omega$$

Power line 6 kV:

$$X_V = X_{Vk} \cdot l = 0,3 \cdot 2 = 0,6\ \Omega$$

Group of motors:

$$X_M = \frac{1}{i_k} \cdot \frac{U_{NM}^{\ 2}}{S_{NM}} = \frac{1}{5} \cdot \frac{6^2}{6,94} = 1,034\ \Omega \qquad S_{NM} = \frac{\sum P_{NM}}{\cos\varphi_n \cdot \eta} = \frac{5}{0,8 \cdot 0,9} = 6,94\ MVA$$

Sources of short-circuit current (network and motors) are NOT connected to fault position B radially (they are connected via reactance Xv) → total fault current IS NOT SUM of contributions from both sources.

The total short-circuit reactance has to be calculated as a series-parallel combination of reactances:

$$X_1 = X_S + X_T = 2{,}4\,\Omega$$

$$X_2 = X_1 // X_M = \frac{X_1 \cdot X_M}{X_1 + X_M} = 0{,}723\,\Omega$$

$$X_{CB} = X_2 + X_V = 1{,}323\,\Omega$$

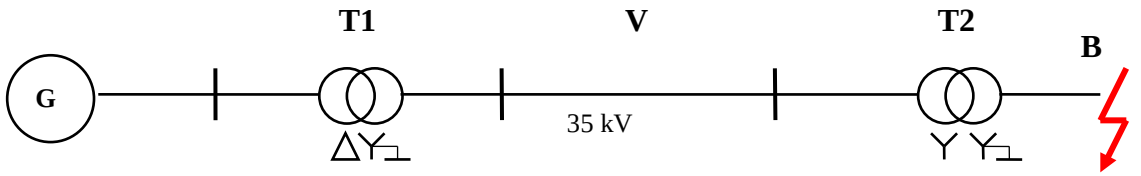
Short-circuit current and short-circuit power:

$$I_{KB}'' = \frac{c \cdot U_n}{\sqrt{3} \cdot X_{CB}} = \frac{1{,}1 \cdot 6}{\sqrt{3} \cdot 3} = 2{,}88\,kA \qquad \text{c = 1,1}$$

$$S_{KB}'' = \sqrt{3} \cdot U_n \cdot I_{KB}'' = \sqrt{3} \cdot 6 \cdot 2{,}88 = 29{,}9\,MVA$$

Example 4:

Calculate the initial symmetrical current and the short-circuit power (level) at fault location B.



S_{ng}= 20 MVA
U_{ng}= 6 kV
x''_d = 0,12

S_{nT1}= 30 MVA
6/35 kV
u_k = 0,11

X_k= 0,37 Ω/km
l = 4,5 km

S_{nT2}= 40 MVA
35/110 kV
u_k = 0,11

$$X_g = x''_d \cdot \frac{U_{ng}^2}{S_g} = 0{,}12 \cdot \frac{6^2}{20} = 0{,}22\ \Omega$$

$$X_{gB} = 0{,}22 \cdot \left(\frac{35}{6}\right)^2 \cdot \left(\frac{110}{35}\right)^2 = 72{,}6\ \Omega$$

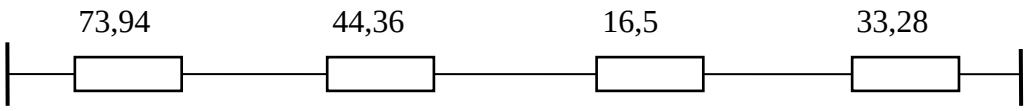
$$X_{T1B} = u_k \cdot \frac{U_{nT}^2}{S_{T1}} \cdot \left(\frac{110}{35}\right)^2 = 0{,}11 \cdot \frac{35^2}{30} \cdot \left(\frac{110}{35}\right)^2 = 44{,}36\ \Omega$$

$$X_V = X_K \cdot \ell = 0{,}37 \cdot 4{,}5 = 1{,}67\ \Omega$$

$$X_{VB} = X_V \cdot \left(\frac{110}{35}\right)^2 = 1{,}67 \cdot \left(\frac{110}{35}\right)^2 = 16{,}5\ \Omega$$

$$X_{T2B} = u_k \cdot \frac{U_{nT}^2}{S_{T2}} = 0{,}11 \cdot \frac{110^2}{40} = 33{,}28\ \Omega$$

Equivalent circuit:

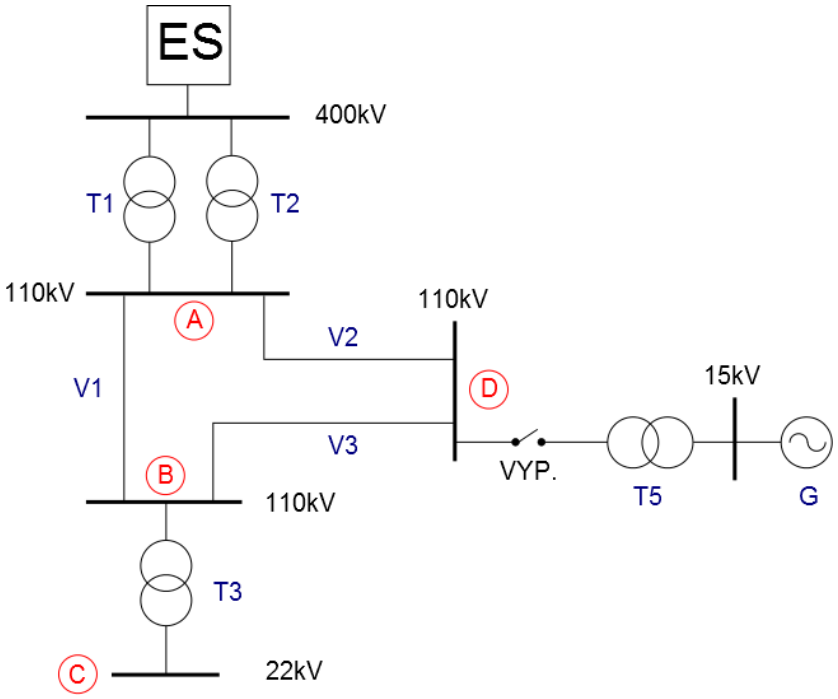


$$X_K = 72{,}6 + 44{,}37 + 16{,}5 + 33{,}28 = 166{,}8\ \Omega$$

$$I''_K = \frac{U_{výp}}{X_K} = \frac{c \cdot U_{nf}}{X_K} = \frac{1{,}1 \cdot \frac{110}{\sqrt{3}}}{166{,}8} = 0{,}42\ \text{kA}$$

$$S''_K = \sqrt{3} \cdot U_n \cdot I'' = \sqrt{3} \cdot 110 \cdot 0{,}42 = 80\ \text{MVA}$$

Example



Parameters of network elements:

ES:	S_K''= 10 GVA		
G:	S_N= 55 MVA	$x_{d\%}$ = 12%	U_N = 15kV
T1 + T2:	S_N= 200 MVA	$u_{k\%}$ = 11%	
T3:	S_N= 40 MVA	$u_{k\%}$ = 10%	
T5:	S_N= 63 MVA	$u_{k\%}$ = 10%	
V1:	X_K= 0,4 Ω/km	l = 60 km	
V2:	X_K= 0,4 Ω/km	l = 30 km	
V3:	X_K= 0,4 Ω/km	l = 40 km	

Variants of calculation:

a. fault in node A, only T1 in operation (respectively parallel operation T1+T2), G disconnected

b. fault in node B, only T1 in operation, G disconnected, V3 disconnected (radial network)

c. fault in node B, only T1 in operation, G disconnected, V3 in operation (ring network)

d. fault in node C, only T1 in operation, G disconnected, V3 disconnected

e. fault in node D, only T1 in operation, G disconnected, V3 disconnected

f. fault in node D, only T1 in operation, G in operation, V3 disconnected (respectively in operation)

g. fault in node B, only T1 in operation, G in operation, V3 in operation