MV network design & devices selection

ANSWER BOOK

Schneider Electric

Exercises

01 - MV substation architectures

02 - MV substation architectures

03 - Industrial C13-200 MV substation

04 - Max. distance between surge arrester and MV equipment (optional)

05 - Calculation of MV cable cross-section

06 - Calculation of Isc

07 - CTs for MV metering

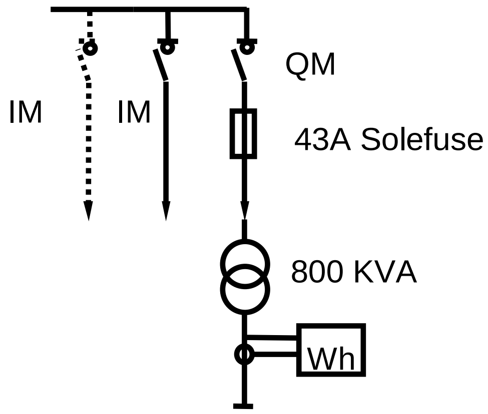
08 - CTs for MV protection

09 - Earth-fault relay settings

10 - Capacitors

Exercise 1: MV substation architectures

Summary of data
Consumer substation on energy supplier loop: 20kV
1 800kVA transformer with 20kV/400V secondary
Short-circuit power 250 MVA



800 kVA < 1250 kVA
800 kVA with 410V =1127A < 2000A
800 kVA with 20 kV = 23A < 45A
OK for LV metering
MV Isc 20 kV = 250 MVA/20 kV /1.732 = 7.2 kA rms
OK for standard equipment 24 KV 12.5 kA

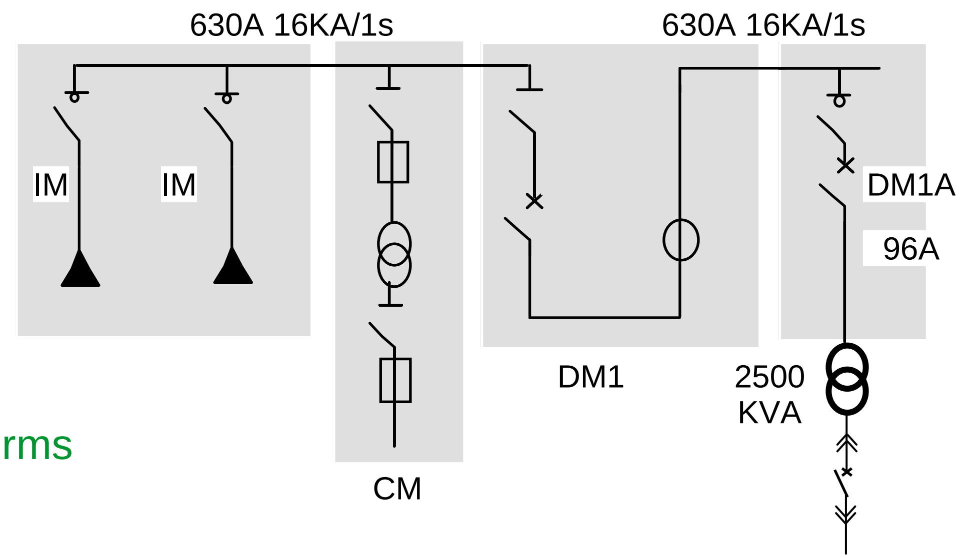
==> 800 kVA 20 kV transformer, UTE standard,
43A Solefuse

Exercise 2: MV substation architectures

Consumer substation on energy supplier loop: 15kV

2500kVA transformer with 400V secondary, 3-phase

Short-circuit power 350 MVA



2500 KVA > 1250 KVA
==> MV metering

MV Isc 15 KV = 350MVA/15KV /1.732 = 13.5 kA rms

Not OK for standard equipment 17.5 KV 12.5 kA

required withstand 16 KA/1s ==> busbar 630A 17.5 KA

Exercise 3: MV substation

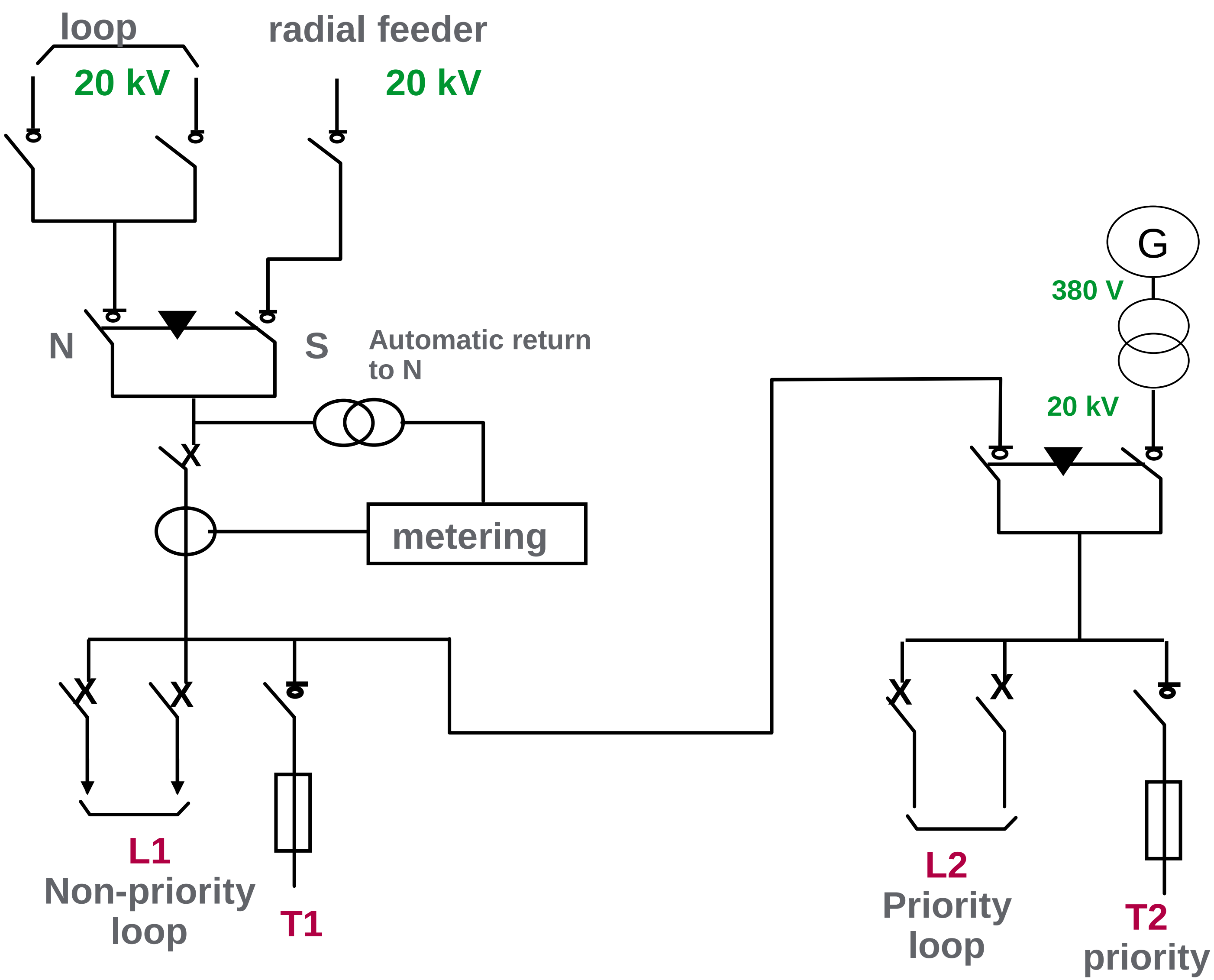
Summary of data

An industrial MV consumer is supplied directly with 20kV (24KV, 125kV impulse; Isc = 12.5kA)
The power distribution system is a loop. In case of interruption, a radial feeder powers the entire installation (the system must automatically switch back to the loop if power is restored to the loop)
The plant includes

- 1 B1 2000kVA non-priority loop supplying different substations
- 1 T1 250kVA non-priority transformer
- 1 B2 2000kVA priority loop
- 1 T2 800kVA priority transformer

The plant also has a 380V/20kV diesel genset to back up priority loads.

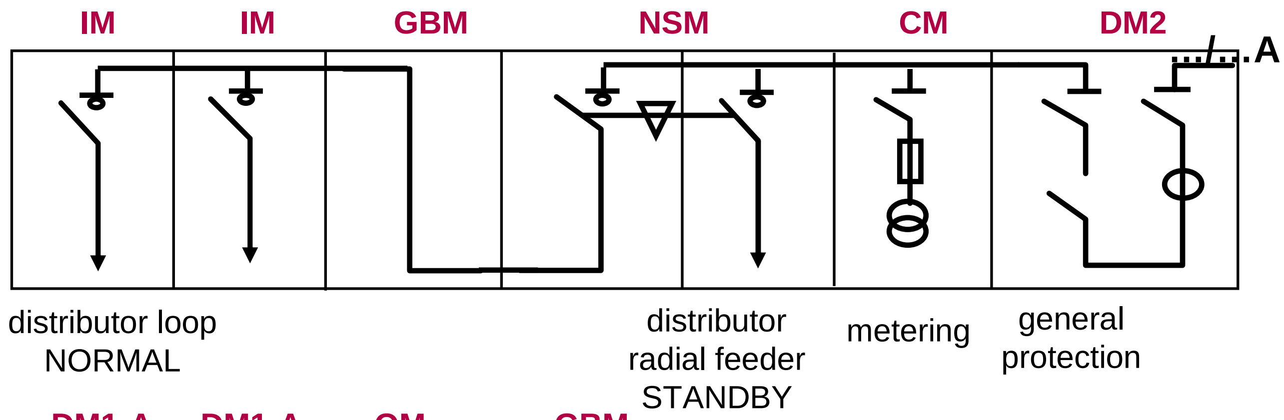
Exercise 3: demand for industrial MV substation with MV metering



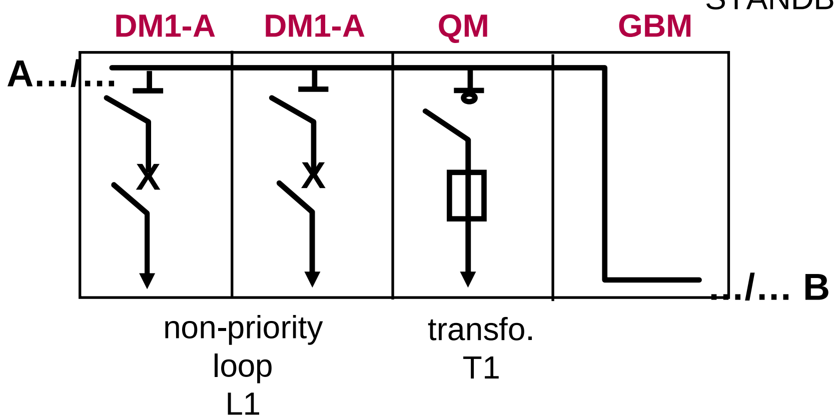
Exercise 3: demand for industrial MV substation with MV metering

Cubicle arrangement of MV substation

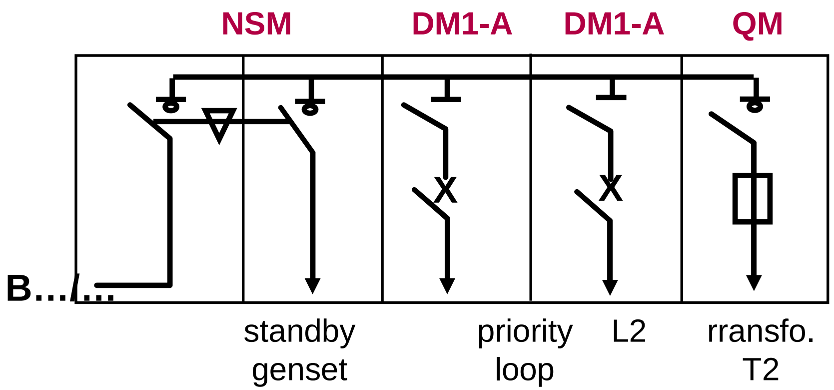
public distribution
consumer substation



subtransmission
substation
with no backup



subtransmission
substation
with backup



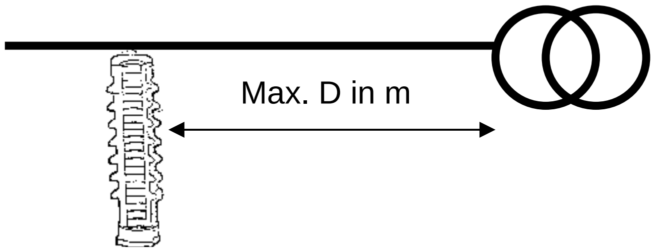
Exercise 4: Max. distance between MV transformer terminals and surge arrester?

Summary of data

20 kV transfomer protected by surge arrester

residual voltage of surge arrester 75kV = Ursd

max. distance between MV transformer terminals and surge arrester?



$$D\ (m) = \frac{Ucdf - Ursd}{2\ r} \times \mathbf{300}$$

Propagation speed of impulse wave in m/µs

Steepness of rising front of lightning impulse in kV/µs

20 kV transformer ==> 24 kV family ==> Ucdf withstand 125 kV impulse

r = dV/dT lightning = 300 kV/µS

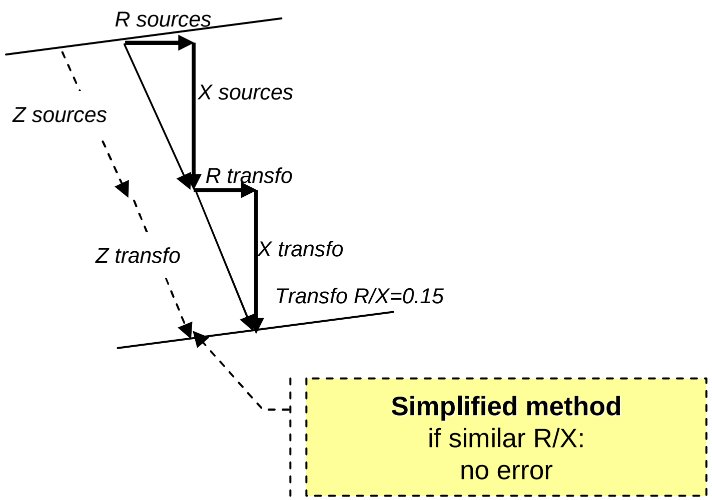
125-75 KV x 300 / 2 x 300 = 25m max.

Exercise 5: Calculation of MV cable cross-section

1	Us rated operating voltage		15 kV	
2	Type of insulating material		PR	
3	Type of conductor		ALU	
4	Type of cable (single or 3-core)		3	
5	Ir rated operating current		210 A	
6	Operating state (discontinuous or continuous)		DISC	
7	Installation method – column 1or2	K1	Buried	1
8	Ambiant temperature on ground	K2	25℃	0.96
9	Type of ground	K3	Damp	1.1
10	Proximity	K4	Alone	1
11	Isc upstream		18 kA	
12	Tripping time		0.4	
Summery: $I_Z\ \frac{I_B}{K_T} \rightarrow \frac{210A}{1 \bullet 0.96 \bullet 1.10 \bullet 1} = 199\ A \rightarrow 70mm^2$				

Verification of cable short-circuit withstand $S = \frac{Isc}{k} \cdot \sqrt{t} = \frac{18000}{87} \bullet \sqrt{0{,}4} = 150mm^2$

Exercise 6: calculation of Isc (Ik3)



Note on method:

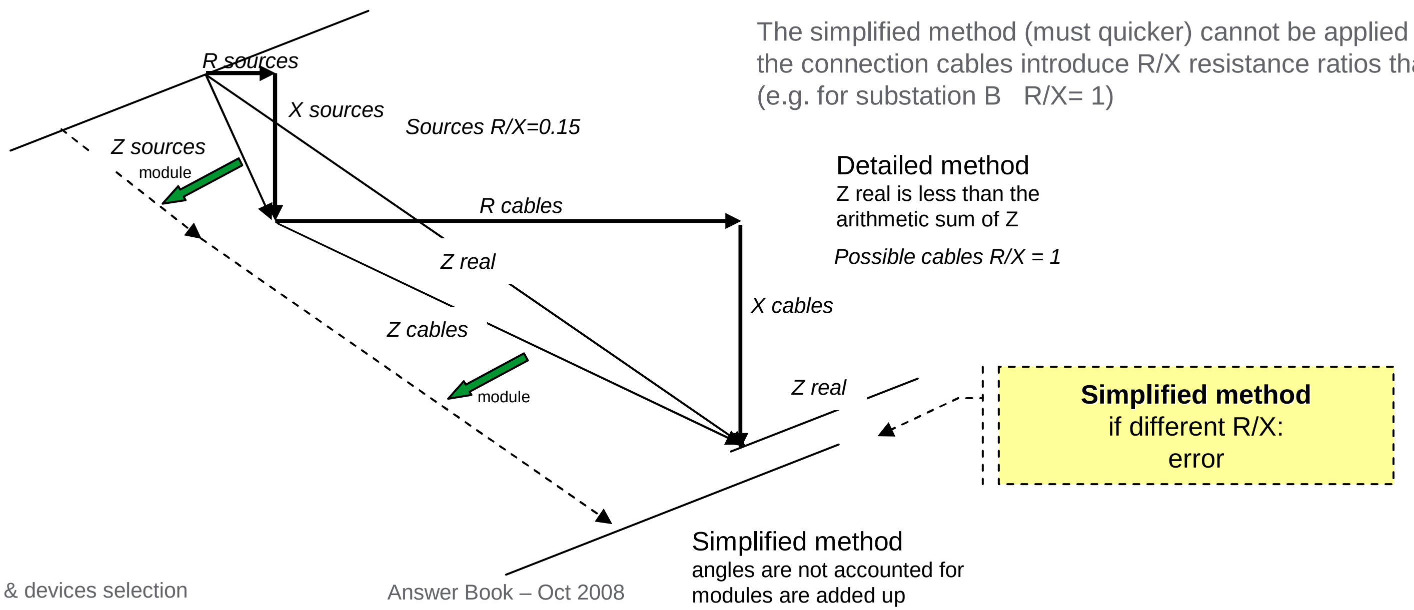
For didactic reasons, the exercise reviews the detailed impedance method whereby reactance values X and resistance values R are added up separately and then the formula $X^2 + R^2$ is used to calculate the impedance values Z at the different levels of the installation.

With this method, Z can be calculated regardless of the R/X ratio in the different portions of the network being studied.

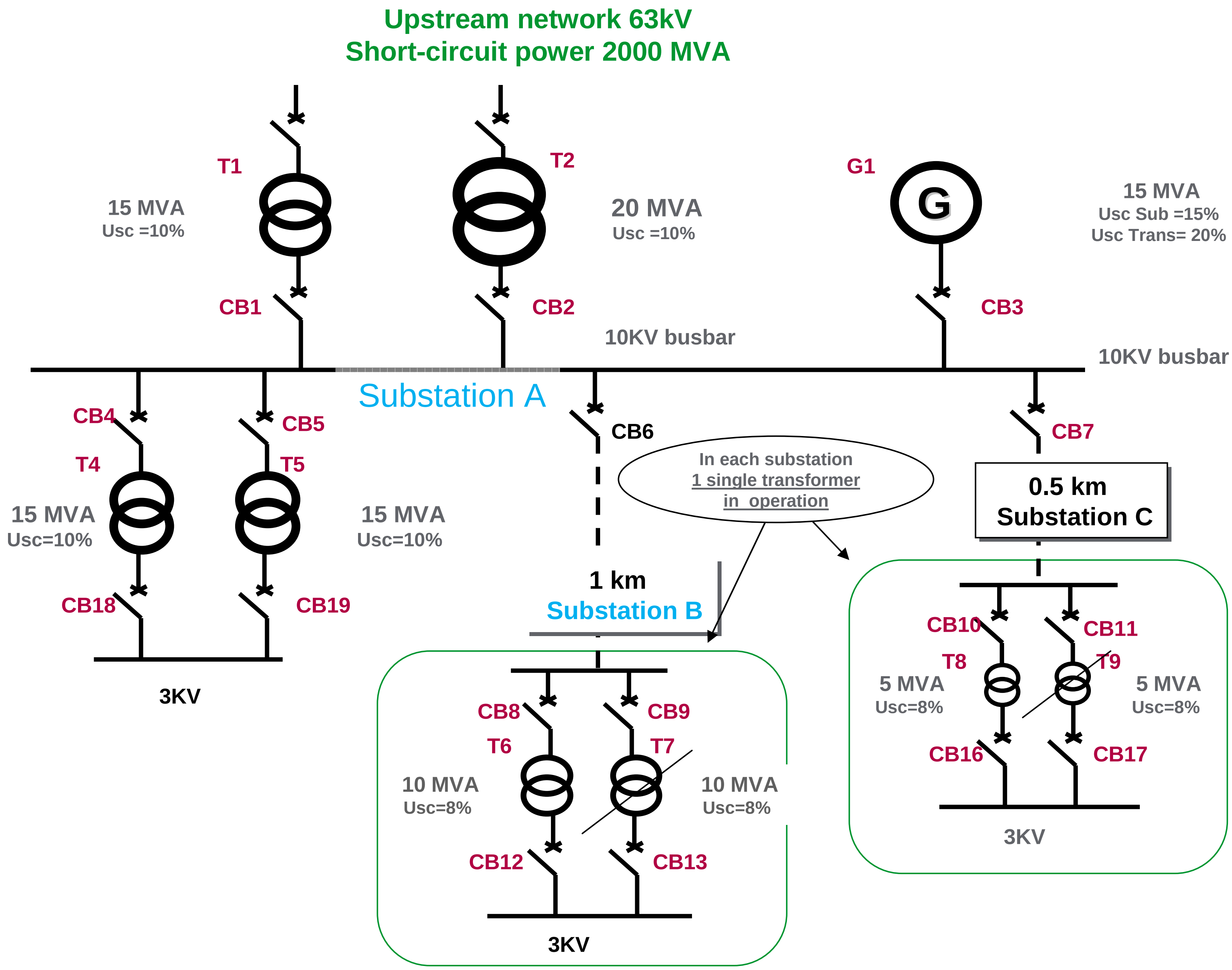
However, at the incoming point of the installation (substation A in this exercise), when precise information is lacking, R/X is often considered constant for the sources (here R/X= 0.15) making it possible to directly add up the Z values and corresponding Isc values, without having to calculate the X and R values which are determined once and for all, for the rest of the calculations, at the level of the main busbar, which the feeders come from.

In the corrections, you will find the solution using the detailed method and also, for substation A only, the same calculations with the simplified method, which may be used in the majority of cases as a first approximation.

The simplified method (must quicker) cannot be applied to substations B and C since the connection cables introduce R/X resistance ratios that are very different from 0.15 (e.g. for substation B   R/X= 1)



Exercise 6



Upstream network 63kV
Short-circuit power 2000 MVA
T1
15 MVA
Usc =10%
T2
20 MVA
Usc =10%
G1
G
15 MVA
Usc Sub =15%
Usc Trans= 20%
CB1
CB2
CB3
10KV busbar
10KV busbar
Substation A
CB4
CB5
CB6
CB7
T4
T5
15 MVA
Usc=10%
15 MVA
Usc=10%
In each substation
1 single transformer
in operation
0.5 km
Substation C
CB18
CB19
1 km
Substation B
3KV
CB8
CB9
T6
T7
10 MVA
Usc=8%
10 MVA
Usc=8%
CB12
CB13
3KV
CB10
CB11
T8
T9
5 MVA
Usc=8%
5 MVA
Usc=8%
CB16
CB17
3KV

Calculation of short-circuit currents

● Upstream network impedance

Impedance viewed downstream of transformers: 10 KV
Z Short-circuit power = 2000 MVA
Application of relative impedance formula:

$$Z_R = \frac{\left(10.10^3\right)^2}{2000\ .10^6} = 0.05\,\Omega$$

$$\frac{R}{X} = 0{,}15 \qquad R = 0.15\,X$$

$$Z_R = \sqrt{R^2 + X^2} = \sqrt{(0.15.X)^2 + (1.X)^2} = 1.0112\ X_R$$

$$X_R = \frac{0.05}{1.0112} = 0.0494\ \Omega \qquad R_R = 0.15\ X = 0.0494\ .0.15 = 0.0074\ \Omega$$

● 15 MVA transformer impedance

$$Z_{T1} = \frac{U^2}{P} \bullet \frac{e}{100} = \frac{10^2}{15} \bullet \frac{10}{100} = \mathbf{0.6667}\,\Omega$$

$$\frac{R}{X} = 0.15 \qquad R_{T1} = 0.15\,X_{T1}$$

$$Z_{T1} = \sqrt{R^2 + X^2} = \sqrt{(0.15X)^2 + (1 \bullet X)^2} = 1.0112\,X_{T1}$$

$$X_{T1} = \frac{0.6667}{1.0112} = \mathbf{0.6593}\,\Omega \qquad R_{T1} = 0.15X = 0.6593 \bullet 0.15 = \mathbf{0.0989}\,\Omega$$

15 MVA

● 20MVA transformer impedance

$$Z_{T2} = \frac{U^2}{P} \bullet \frac{e}{100} = \frac{10^2}{20} \bullet \frac{10}{100} = \mathbf{0.5}\ \Omega$$

$$\frac{R}{X} = 0.15 \qquad R = 0.15\,X$$

$$Z_{T2} = \sqrt{R^2 + X^2} = \sqrt{0.15X)^2 + (1 \bullet X)^2} = 1.0112X_{T2}$$

$$X_{T2} = \frac{0.5}{1.0112} = \mathbf{0.4945}\ \Omega \qquad R_{T2} = 0.15X = 0.4945 \bullet 0.15 = \mathbf{0.0742}\ \Omega$$

20 MVA

• 15 MVA genset impedance

1 - transient (Usc = 20%)

$$Z'_G = \frac{U^2}{Pn} \bullet \frac{e}{100} = \frac{100}{15} \bullet \frac{20}{100} = \mathbf{1.3333} \quad \Omega$$

$$\frac{R}{X} = 0.15$$

$$X'_G = \frac{Z}{1.0112} = \frac{1,3333}{1.0112} = \mathbf{1.3185} \quad \Omega$$

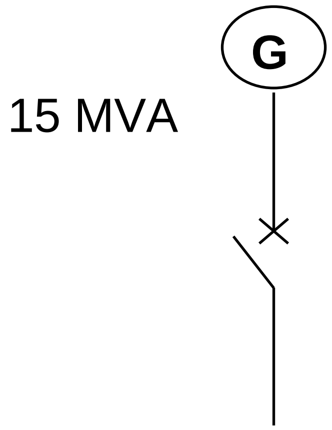
$$R'_G = 0.15X = 1.3185 \bullet 0.15 = \mathbf{0.1978} \quad \Omega$$

2 - subtransient (Usc = 15%)

$$\mathbf{Z}''_G = \frac{\mathbf{100}}{\mathbf{15}} \bullet \frac{\mathbf{15}}{\mathbf{100}} = \mathbf{1} \ \Omega$$

$$\mathbf{X}''_G = \frac{\mathbf{1}}{\mathbf{1.0112}} = \mathbf{0.9889} \quad \Omega$$

$$\mathbf{R}''_G = \mathbf{0.9889} \bullet \mathbf{0.15} = \mathbf{0.1483} \quad \Omega$$



• Impedance of 2 transformers in parallel

$$\mathbf{X}_{T1T2//} = \frac{\mathbf{X1} \bullet \mathbf{X2}}{\mathbf{X1} + \mathbf{X2}} = \frac{0.6593 \bullet 0.4945}{0.6593 + 0,4945} = \mathbf{0.2826} \quad \Omega$$

$$R_{T1T2//} = \frac{R1 \bullet R2}{R1 + R2} = \frac{0.0989 \bullet 0.0742}{0.0989 + 0.0742} = \mathbf{0.0421} \quad \Omega$$

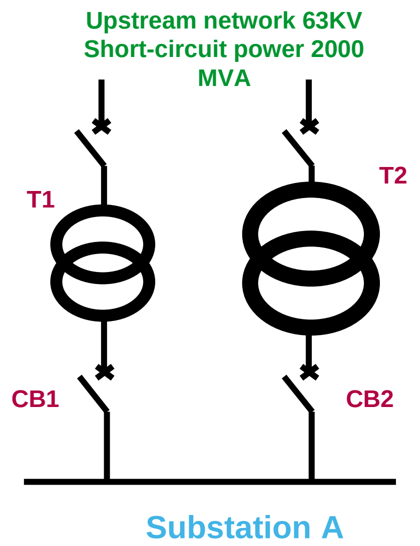
$$Z_{T1T2//} = \sqrt{Xe^2 + Re^2} = \mathbf{0.2857} \quad \Omega$$

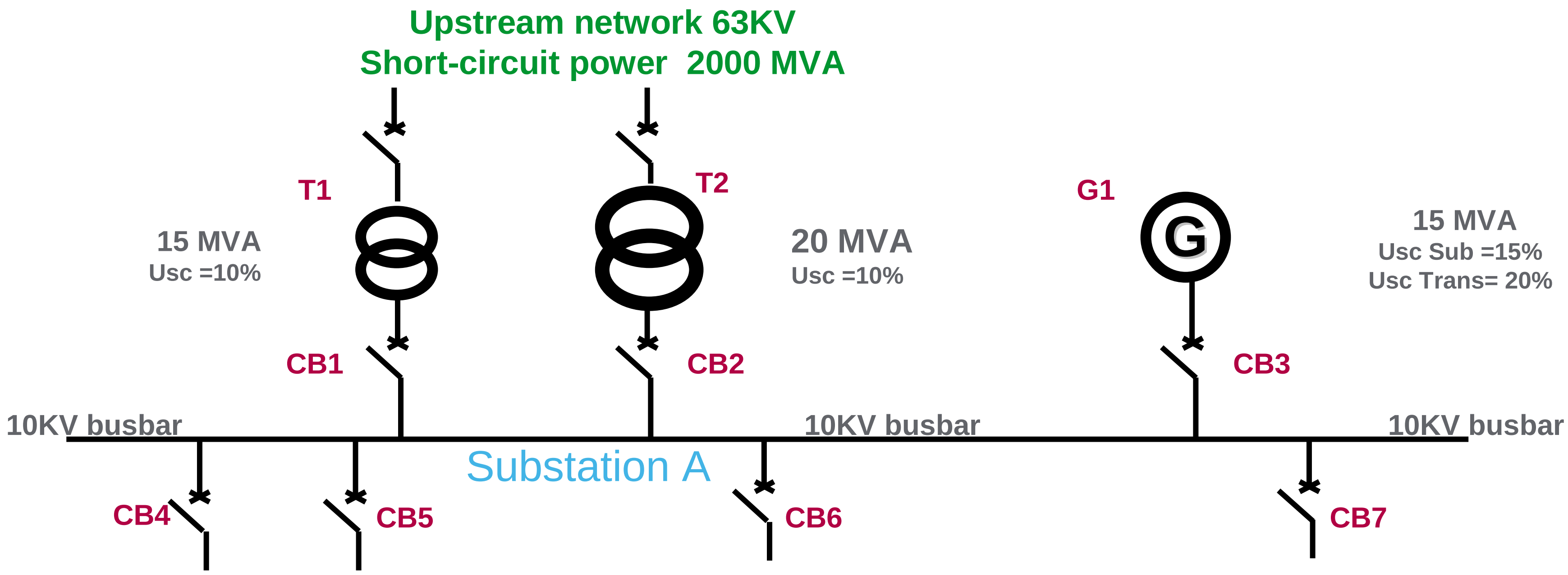
• Impedance of 2 transformers in // + network in series

$$\mathbf{X}_{R+T1T2//} = \mathbf{0.0494} + \mathbf{0.2826} = \mathbf{0.332} \quad \Omega$$

$$\mathbf{R}_{R+T1T2//} = \mathbf{0.0074} + \mathbf{0.0421} = \mathbf{0.0495} \quad \Omega$$

$$Z_{R+T1T2//} = \sqrt{Xer^2 + Rer^2} = \mathbf{0.3357} \quad \Omega$$





- Impedances of 2 transformers in // + network + genset

1 - transient (Usc = 20%)

$$X'_{R + T1T2// + G} = \frac{X1 \bullet X2}{X1 + X2} = \frac{0.332 \bullet 1.3185}{0.332 + 1.3185} = \mathbf{0.2652}\ \Omega$$

$$R'_{R + T1T2// + G} = \frac{R1 \bullet R2}{R1 + R2} = \frac{0.0495 \bullet 0.1978}{0.0495 + 0.1978} = \mathbf{0.03959}\ \Omega$$

$$Z'_{R + T1T2// + G} = \sqrt{X^2 + R^2} = \mathbf{0.2681}\ \Omega$$

2 - subtransient (Usc = 15%)

$$X''_{R + T1T2// + G} = \frac{X1 \bullet X2}{X1 + X2} = \frac{0.332 \bullet 0.9889}{0.332 + 0.9989} = \mathbf{0.2485}\ \Omega$$

$$R''_{R + T1T2// + G} = \frac{R1 \bullet R2}{R1 + R2} = \frac{0.0495 \bullet 0.1483}{0.0495 + 0.1483} = \mathbf{0.0371}\ \Omega$$

$$Z''_{R + T1T2// + G} = \sqrt{X^2 + R^2} = \mathbf{0.2513}\ \Omega$$

Calculation of Ik3, breaking capacity and making capacity

- **Breaking capacity** of circuit breakers CB4 to CB7 (transient)

$$I'k3 = \frac{1,1.U/\sqrt{3}}{Z'_{R+T1T2//+G}} = \frac{10}{0.2681\sqrt{3}} = \mathbf{23.689\ kA\ rms}$$

Breaking capacity = 23.69 KA rms min.

Making capacity of CB4 to CB7 as asymmetrical peak kÂ (2.5) and subtransient

$$I'k3 = \frac{1.1.U/\sqrt{3}}{Z'_{R+T1T2//+G}} = \frac{10}{\mathbf{0.2681 \cdot \sqrt{3}}} = \mathbf{23.689kArms}$$

- **Breaking capacity** of CB3 (genset circuit breaker)

$$Ik\,3 = \frac{1.1 \cdot U\ /\sqrt{3}}{Z'_{R+T1T2//+G}} \bullet 2.5 = \mathbf{63.18\ k\hat{A}}$$

Making capacity = 63.18 kÂ min.

Making capacity of CB3 as peak kÂ (genset circuit breaker)

$$Ik3 = \frac{1.1.U/\sqrt{3}}{Z'_{R+T1T2//}} = \frac{1.1.10}{0.3357\sqrt{\mathbf{3}}} = \mathbf{18.92\ kA\ rms}$$

Breaking capacity = 18.92 kA rms min.

(N.B. for sector i’k3 =I ‘’k3)

$$I''k3 = 18.92 \bullet 2.5 = \mathbf{47.3\ k\hat{A}}$$

Making capacity = 47.3 kÂ min.

Breaking capacity of CB1 (15 MVA transformer) (Ik3 to be considered = Ik3 20 MVA TR + Ik3 genset TR)

Impedance of upstream network + 20 MVA transformer

X = 0.0494 + 0.4945 = 0.5439
R = 0.0074 + 0.0742 = 0.0816

$$Z = \sqrt{X^2 + R^2} = \mathbf{0.55}\Omega$$

Parallel connection network + transformer and genset in transient

$$X'e = \frac{0.5439 \bullet 1.3185}{0.5439 + 1.3185} = \mathbf{0.3850}\ \Omega$$

$$R'e = \frac{0.0816 \bullet 0.1978}{0.0816 + 0.1978} = \mathbf{0.05776}\ \Omega$$

$$Z'e = \sqrt{Xe^2 + \mathrm{Re}^2} = \mathbf{0.3894}\ \Omega$$

$$I'k3 = \frac{1.1.10/\sqrt{3}}{0.3894} = \mathbf{16.31\ kA\ rms}$$

Breaking capacity CB1 = 16.31 kA rms min.

•Making capacity of CB1 (15 MVA transfomer)

Parallel connection network + transformer and genset in subtransient

$$X''e = \frac{0.5439 \ .0.0889}{0,5439 + 0,0889} = 0.3509\ \Omega$$

$$R''e = \frac{0.0816 \ .0.1483}{0.0816 + 0.1483} = 0.05264\ \Omega$$

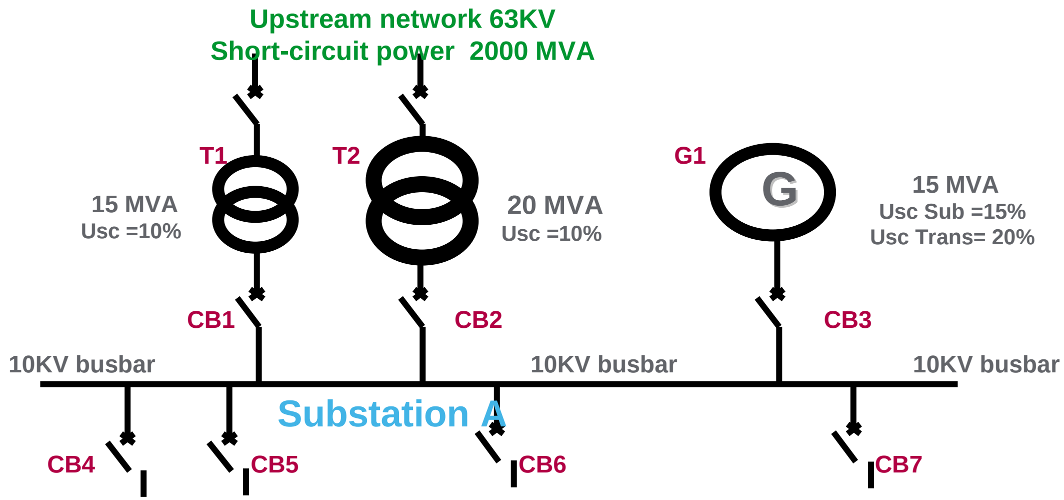
$$Z''e = \sqrt{X''e^2 + R''e^2} = 0.3548\ \Omega$$

$$I''k3 = \frac{1.1.10 / \sqrt{3}}{0.3548} = \mathbf{17.90\ \ kA\ \ rms}$$

•Making capacity of CB1 as peak kÂ (15 MVA transformer circuit breaker)

Making capacity = 17.90 • 2.5 = **44.75 kÂ minimum**

Example for comparison



Breaking capacity of CB2 (20 MVA transformer)

For this calculation, we use the simplified method, considering that the R/X ratios are identical, the Z values are similar, directly, without having to add up the X values and R values.

Impedance of network + 15 MVA transformer T1

$$Z = 0.05 + 0.6667 = \mathbf{0.7167\ \Omega}$$

Parallel connection network + transformer and genset in transient

$$Ze = \frac{0.7167 \bullet 1.3333}{0.7167 + 1.3333} = \mathbf{0.4661\ \Omega}$$

$$Ik3 = \frac{1.1 \cdot 10 / \sqrt{3}}{0.4661} = \mathbf{13.63\ kA\ rms}$$

Breaking capacity = 13.63 kA rms min.

Making capacity of CB2 (20 mVA transformer)

Parallel connection network + transformer and genset in subtransient

$$Ze = \frac{0.7167 \bullet 1}{0.7167 + 1} = \mathbf{0.4175\ \Omega}$$

$$Ik3 = \frac{1.1 \cdot 10 / \sqrt{3}}{0.4175} = \mathbf{15.21\ kA\ rms}$$

Making capacity of CB2 as peak kÂ (d20 MVA transformer circuit breaker)

Making capacity = 15.21 • 2.5 = **38 kÂ minimum**

Simplified version of calculations for substation A

Direct calculation of impedance Z and cumulative total of resulting Ik3

Impedance of upstream network

$$\frac{U^2}{Psc} = \frac{102}{2000} = \mathbf{0.05}\ \Omega$$

Impedance of 15 and 20 MVA transformers in //

$$Z = \frac{U^2}{Ptr1 + Ptr2}\ Usc = \frac{10^2}{15+20}\ 10\% = \mathbf{0.285}\ \Omega$$

Impedance of network + 2 TR in //

$$Z = Znetwork + Z\ 2\ transfos = 0.3357\ \Omega$$

Ik3 of network + TR in //

$$IK3 = \frac{1<.1.U/\sqrt{3}}{Z} = \frac{1.1.10}{0.3357.1.732} = \mathbf{18.92\ kA}\ rms$$

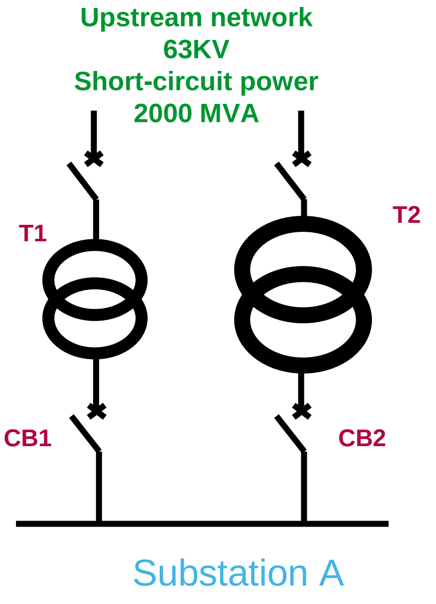
0.3357 = Series-connection of network with equivalence of transformer

Impedance of network + T1

$$Z = 0.05 + \frac{U\ 2}{PT\ 1} \bullet 10\ \% = 0.7167\ \Omega$$

Impedance of network + T2

$$Z = 0.05 + \frac{U^2}{PT\ 2} \bullet 10\ \% = 0.55\ \Omega$$



Ik3 supplied by (network + T1)

$$Ik3 = \frac{1.1.10 / \sqrt{3}}{0.7167} = 8.861\ kA$$

Ik3 supplied by network (network + T2)

$$Ik3 = \frac{1.1.10 / \sqrt{3}}{0.55} = 11.55\ \text{kA}$$

GE current

$$I = \frac{P}{U\sqrt{3}} = \frac{15000}{10 \cdot 1.732} = \mathbf{866A}$$

I'k3 GE transient

$$I'k3 = \frac{1.1.In}{Usc} = \frac{866.100}{20} = \mathbf{4.763kA\ rms}$$

Reminder: $\frac{1.1.10\ \text{kV}}{\sqrt{3}.1.333\Omega} = \mathbf{4.764\ kA\ rms}$

I''k3 GE substransient

$$I''k3 = \frac{1.1.In}{USc} = \frac{866.100}{15} = \mathbf{6.350\ kA\ rms}$$

Breaking capacity of CB1 (15 MVA transformer circuit breaker):

11.55 (res + T2)+4.763 = **16.31 kA rms min.**

Breaking capacity of CB2 (20 MVA transformer circuit breaker):

8.86 (res + T1) + 4.763 (G1 trans)= **13.62 kA rms min.**

Making capacity of CB1 (15 MVA transformer circuit breaker):

(11.55 (res + T2) + 6.35 (G1 sub)) • 2.5 = **44.75 kÂ min.**

Making capacity of CB2 (20 MVA transformer circuit breaker):

(8.86 (res + T1) + 6.35 (G1 sub)) • 2.5 = **38 kÂ min.**

Breaking capacity CB4 to CB7 (global Ik3): (network + 2 TR + GE)

18.92 (res + T1T2//) + 4.763 (G1 trans) = **23.68 kA min.**

Making capacity CB4 to CB7: (network + 2 TR + GE)

18.92 (res + T1T2//) + 6.35 (G1 sub) . 2.5 = **63.18 kÂ min.**

Choice of cables for substations B and C (detailed method cont'd.)

Single-pole Al – PR cables, buried directly in dry, calcareous ground, temperature 20°C, continuous operation,

Substation B :

Operational current Ir: **577 A** $\frac{10 \quad MVA}{10 \quad kV \quad \sqrt{3}}$

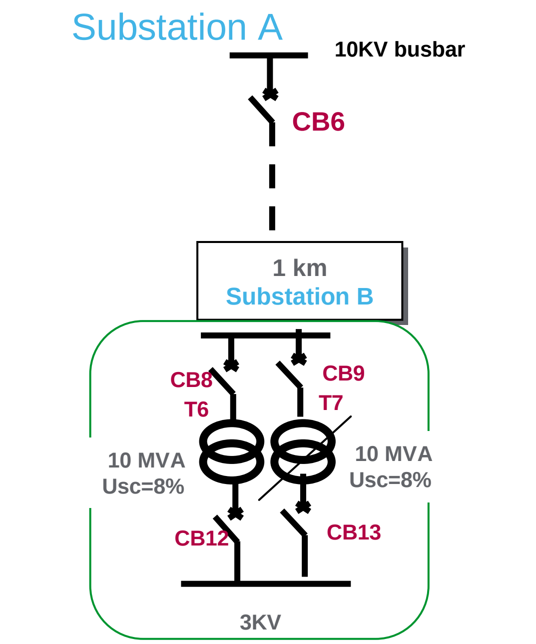
2 cables in // imposed

Installation mode factor	=	1 column 1
Temperature factor	=	1
Proximity factor	=	0.75
Ground factor	=	1

Chosen theoretical currents:

577 : 0.75 = 770 A i.e. 385 A per cable
column 1: 185^2 = 380A 240^2 = 440A

cables to substation B: **2 x 240 mm²** per phase
(14% remaining for possible extension)



Substation C

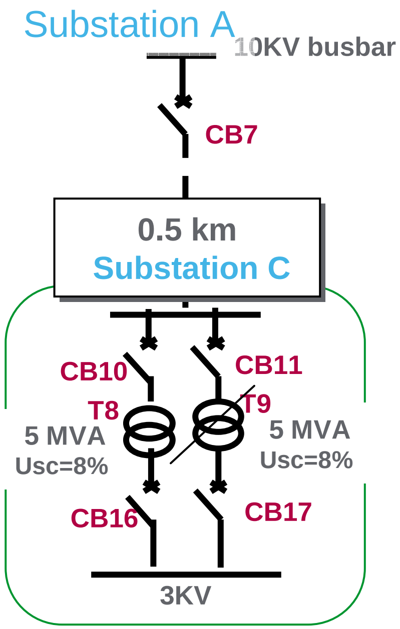
Operational current Ir: **288 A** $\frac{5 \quad MVA}{10 \quad kV \quad \sqrt{3}}$

Installation mode factor	=	1
Temperature factor	=	1
Proximity factor	=	1
Ground factor	=	1

Chosen theoretical currents:

288 : 1 = 288 A

column 1 952 = 260 A 1202 = 300 A
cables to substation C: **1 x 120 mm2** per phase



Verification of short-circuit current withstand of cables

Upstream protection circuit breaker tripping time: 0.4 sec.
Permissible temperature rise in cables: 160°(+90°=25 0°)

$$S > \frac{Isc}{k}\sqrt{t} \quad \text{with } k = 94$$

$$S > \frac{23689\sqrt{0.4}}{94} = 159.45 \text{ mm2}$$

The cable planned for Substation C (120 mm^2) would not withstand the short-circuit currents. It should have a cross-section of 185 mm^2

● Calculation of short-circuit currents in substations B and C

● Impedance of the 2 cables of substation B

1000 m of 2 x 240 mm^2

$$R = \rho\frac{L}{S} = 36.10^{-3} \bullet \frac{1000}{240} = \mathbf{0..15}\Omega$$

i.e. for the two cables in parallel R = 0.075 Ω

- Calculation of reactance

x = **0.15** Ω /km

i.e. for the two cables in parallel X = 0.075 Ω

- Calculation of impedance:

$$Z = \sqrt{0.075^2 + 0.075^2} = \mathbf{0.1060}\ \Omega$$

● Impedance of the cable of substation C

500 m of 1 x 185 mm^2

$$R = \rho\frac{L}{S} = 36 \cdot 10^{-3} \cdot \frac{500}{185} = 0.0973\ \Omega \quad \text{A single cable}$$

Calculsations to be done according to verification of results.

$$X = 0.15\,\Omega / \text{km} = \frac{0.15}{2} = 0.075\ \Omega$$

Short-circuit currents with 10 kV in substation B

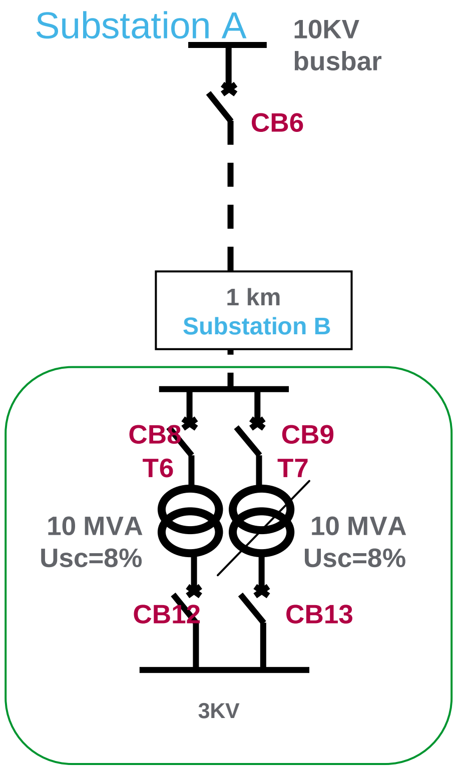
- Calculation of impedance in substation B, transient.

$$\sum R = 0.03959 + 0.075 = \mathbf{0.1146}\ \Omega$$
$$\sum X = 0.2652 + 0.075 = \mathbf{0.3402}\ \Omega$$
$$\sum Z = \sqrt{R^2 + X^2} = \mathbf{0.3590}\ \Omega$$

short-circuit current and breaking capacity CB8 and CB9:

$$I'k3 = \frac{1.1.10/\sqrt{3}}{0.3590} = \mathbf{17.69\ kA\ rms}$$

Breaking capacity = 17.69 kA rms min.



- Calculation of impedance in substation B, subtransient.

$$\sum R = 0.0371 + 0.075 = 0.1121\ \Omega$$
$$\sum X = 0.2485 + 0\ 075 = 0.3235\ \Omega$$
$$\sum Z = \sqrt{R^2 + X^2} = 0.3424\ \Omega$$

short-circuit current and making capacity CB8 and CB9:

$$I''k3 = \frac{11.10/\sqrt{3}}{0.3424} = 18.55\,\text{kA rms}$$

$$\text{Making capacity} = 18.55 \bullet 2.5 = 46.37\,\text{k}\hat{\text{A}}\ \text{min.}$$

Short-circuit currents with 10 kV in substation C

- Calculation of impedance in substation C, transient,185mm² cable

$$\sum R = 0.03959 + 0.0973 = 0.136887\ \Omega$$
$$\sum X = 0.2652 + 0.075 = 0.3402\ \Omega$$
$$\sum Z = \sqrt{R^2 + X^2} = 0.36670\ \Omega$$

short-circuit current and breaking capacity CB10 and CB11:

$$I'k3 = \frac{11.10/\sqrt{3}}{0.36670} = 17.32 kA\ rms$$

Breaking capacity = 17.32 kA rms min.

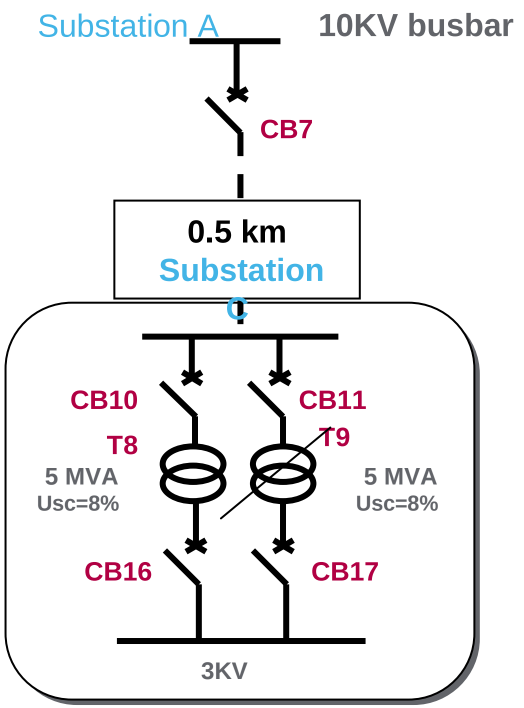
- Calculation of impedance in substation C, subtransient.

$$\sum R = 0.0371 + 0.0973 = 0.13439\ \Omega$$
$$\sum X = 0.2485 + 0.075 = 0.3235\ \Omega$$
$$\sum Z = \sqrt{R^2 + X^2} = 0.35036\ \Omega$$

short-circuit current and making capacity CB10 and CB11:

$$I''k3 = \frac{1..\ .10\ /\sqrt{3}}{0.35036} = \mathbf{18.13\ kA\ rms}$$

Making capacity = 18.13 • 2.5 = **45.32 kÂ min.**

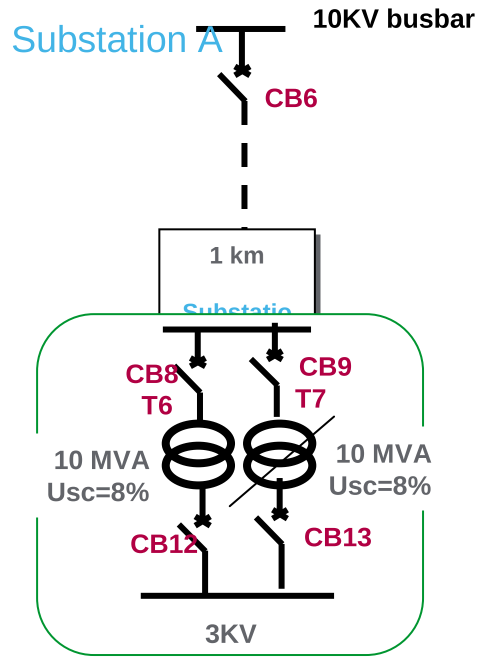


Calculation of short-circuit currents with 3 kV in substation B

Reminder of values with 10 kV in substation B:

Transient: $X = \mathbf{0.3402}\ \Omega$, $R = \mathbf{0.1146}\ \Omega$

Subtransient: $X = \mathbf{0.3235}\ \Omega$, $R = \mathbf{0.1121}\ \Omega$



Application of relative impedance formula

$$R\ (\text{downstr.}) = R\ (\text{upstr.}) \frac{U^2\ (\text{sec})}{U^2\ (\text{pri})} = R \left(\frac{3}{10}\right)^2 = 0.09R$$

1 Impedance, Ik3 and breaking capacity in transient

R (sec) = R (upstream) x 0.09 = 0.1146 . 0.09 = **0.01031 Ω**
X (sec) = X (upstream) x 0.09 = 0.3402 . 0.09 = **0.03062 Ω**

Impedance of transformer

$$Z = \frac{U^2}{Pn} \bullet \frac{e}{100} = \frac{(3 \bullet 10^3)^2}{10 \bullet 10^6} \bullet 0.08 = 0.072\ \Omega$$

With R/X = 0.15

X = 0.0712 Ω (X = Z / 1.0112)
R = 0.15 X = 0.0107 Ω

$$\sum R = 0.01031 + 0.0107 = 0.02101\ \Omega$$
$$\sum X = 0.0306 + 0.0712 = 0.1018\ \Omega$$
$$Z = 0.1039\ \Omega$$

Reminder: 1 single transformer in service on both

Isc and breaking capacity of CB12 and CB13

$$Ik3\ (3kV) = \frac{1.1 \bullet 3 / \sqrt{3}}{0.1039} = 18.34\ \text{kA rms}$$

Breaking capacity=18.34 kA rms min.

2) Impedance, I''k3 and making capacity in subtransient

R(sec) = R (upstream) x 0.09 = 0.1121 . 0.09 = **0.010089** Ω

X(sec) =X(upstream) x 0.09 = 0.3235 . 0.09 = **0.0291** Ω

$$\sum R = 0.01009 + 0.0107 = 0.02079 \ \Omega$$

$$\sum X = 0.0291 + 0.0712 = 0.1003 \ \Omega$$

$$Z = 0.1024 \ \Omega$$

Isc and making capacity of CB12 and CB13

$$I''k3 = \frac{1.1 \bullet 3 / \sqrt{3}}{0.1015} = 18.6 \text{ kA rms}$$

$$\text{Making capacity} = 18.6 \bullet 2.5 = 46.5 \text{ kÂ min.}$$

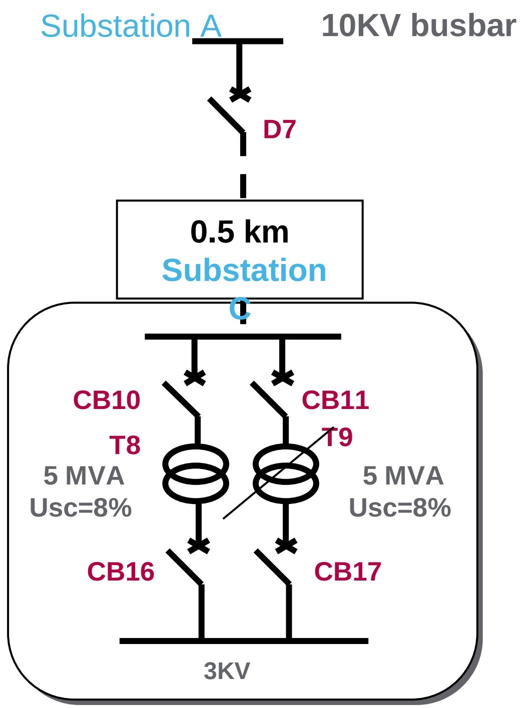
Calculation of short-circuit currents with 3 kV in substation C

Reminder of values with 10 kV in substation C:

- Transient X = 0.3402 Ω
  R = 0.13688 Ω
- Subtransient: X = 0.3235 Ω
  R = 0.13439 Ω

Application of relative impedance formula:

$$R(\text{downstream}) = R(\text{upstream})\,\frac{U^2(\text{sec})}{U^2(\text{pri})} = R\,\frac{3^2}{10^2} = 0.09\ \mathrm{R}(\text{upstream})$$



1) Impedance, Ik3 and breaking capacity in transient

R (sec) = R (upstream) x 0.09 = 0.13688 . 0.09 = 0.01231 Ω

X (sec) = X (upstream) x 0.09 = 0.3402 . 0.09 = 0.03062 Ω

Impedance of transformer

$$Z = \frac{U^2}{Pn}\bullet\frac{e}{100} = \frac{(3.10^3)^2}{5.10^6}\bullet 0.08 = 0.144\ \Omega$$

With R/X = 0.15

X = 0.142 Ω (X = Z / 1.0112)

R = 0.15 X = 0.0213 Ω

$$\sum R = 0.01231 + 0.0213 = 0.03362\ \Omega$$

$$\sum X = 0.0306 + 0.142 = 0.1726\ \Omega$$

$$Z = 0.17584\ \Omega$$

Isc and breaking capacity of CB16 and CB17 in transient

$$Ik\,3\,(3\ \text{kV}) = \frac{1.1\,.3\,/\sqrt{3}}{0.1758} = 10.83\ \text{kA rms}$$

Breaking capacity = 10.83 kA rms min.

2) Impedance, I’’k3 and making capacity in subtransient

R(sec) = R (upstream) x 0.09 = 0.13439 . 0.09 = 0.01209 Ω
X(sec) =X (upstream) x 0.09 = 0.3235 . 0.09 = 0.0291 Ω

$\sum R = 0.01209 + 0.0213 = \mathbf{0.03339}\ \Omega$

$\sum X = 0.0291 + 0.142 = \mathbf{0.1711}\ \Omega$

$Z = \mathbf{0.1743}\ \Omega$

Isc and making capacity of CB16 and CB17

$$I''k3 = \frac{1.1.3/\sqrt{3}}{0.1711} = 10.93 \text{ kA rms}$$

$$\text{Making capacity} = 10.93 \bullet 2.5 = 27.32 \text{ k}\hat{\text{A}}$$

Exercise 7: CTs for MV metering

Summary of data
U= 5.5 KV
Predicted active power P = 760 KW
p.f. = 0.93
Isc = 8.5 kA
Power consumed by meter 2.5 VA
Meter input 5A
CT line < > meter = 20m (total 2 ways)
in $6mm^2$

- P= 760 kW p.f. 0.93 ==> S= 817.2 KVA (760/0.93)
  ==> I primary = 85.78A with 5.5 kV
- Isc = 8.5 KA ==> Ith = category 12.5 kA / 1s
- U= 5.5 kV ==> Rated voltage 7.2 kV
- 5A meter ==> CT secondary=5A
  (consistent with the 20m (2 ways) to be covered, reminder: long distances=1A)
- $6\ mm^2$ wire over 20m consumes P(va)= K..L(m) / S (mm^2)
  K = 0.44 if Is=5A or K = 0.0176 if Is= 1A ==> K=0.44
  P= 0.44 x 20 / 6 = 1.47 VA
- Approximate total consumption of line +metering
  P= 1.47 VA + meter 2.5 VA = 3.96 VA
- Choice of CT rated output >> 4 VA ==> standard= 7.5 VA
- Accuracy: metering application ==> need for good accuracy
  ==> 0.5% ==> Class 0.5 or 0.5S or 0.2S
  (0.5S and 0.2S reliable for low currents 1% of In)

CT => 100 /200 / 5 7.5VA Class 0.5
Ith 12.5KA / 1s

Exercise 8: CTs for MV protection

Summary of data
U= 6 KV
Large Motor Feeder, 2500 KW p.f. 0.9 effic. 0.94
Starting I : 6 x In
Isc = 8.5 KA
Power consumed by protection relay: 1.8 VA
Relay input: 5A
Line 42m (total 2 ways); 6 mm^2

- P = 2500kW efficiency 0.94 ==> P= 2660 kW (2500/0.94)
- p.f. = 0.9 ==> S= 2955 kVA (2660 /0.9) ==> **I primary = 285 A** (/6kV)
  Starting current = 6x 285A= 1.71 kA rms
- Isc=8.5 KA ==> **Ith = category 12.5 kA / 1s**
- U= 6kV ==> Rated voltage **7.2 kV**
- 5A relay ==> **CT secondary = 5A**
- **6mm² wire** over 42m consumes P(va)= K.L(m) / S (mm^2)
  K = 0.44 if Is=5A ==> **K = 0.44** P= 0.44 x 42 / 6 = **3.08 VA**
- Approximate total consumption line +relay P= 3.08 VA + relay 1.8 VA = **4.88 VA**
- Choice of CT rated output >> 4.88 VA ==> **5VA too close, take 7.5VA**
  (do not exceed 80 to 85% of load => or else: next highest rating)
- Accuracy: application=protection ==> average accuracy
  OK at 10% ==> **10P**
- Saturation elbow (Accuracy Limit Factor) in principle on protection 5 / **10** / 15 / 20
  (10% error at **10 In)** also, the 6 In for starting must be detected correctly,
  so have an elbow at approx. 2 x Id near 3000A ==> CT In approx. 300A

Standard CT => 300 / 5 7.5VA 10P10 Ith 12.5 kA / 1s 7.2 kV

Exercise 9: Earth-fault relay settings

1. Position the earth fault protection devices in the diagram so as to have discrimination.

2. Calculate the capacitive currents generated when faults occur.

3. The protection setting range starts at 2 A.

   3.1. To what should IL be limited by the earth fault resistance in order to protect 90% of the star winding of the motor or motors?

   3.2. is the value compatible with: 2.Ic<IL ?

   3.3. what is the continuous permissible current for the earth fault resistance (zero-sequence generator) ?

   3.4. if the protection of motor 9.2 does not work:
   - what back-up protection is there?
   - what is its pick-up setting?
   - what happens with the earth fault resistance? (zero-sequence generator)

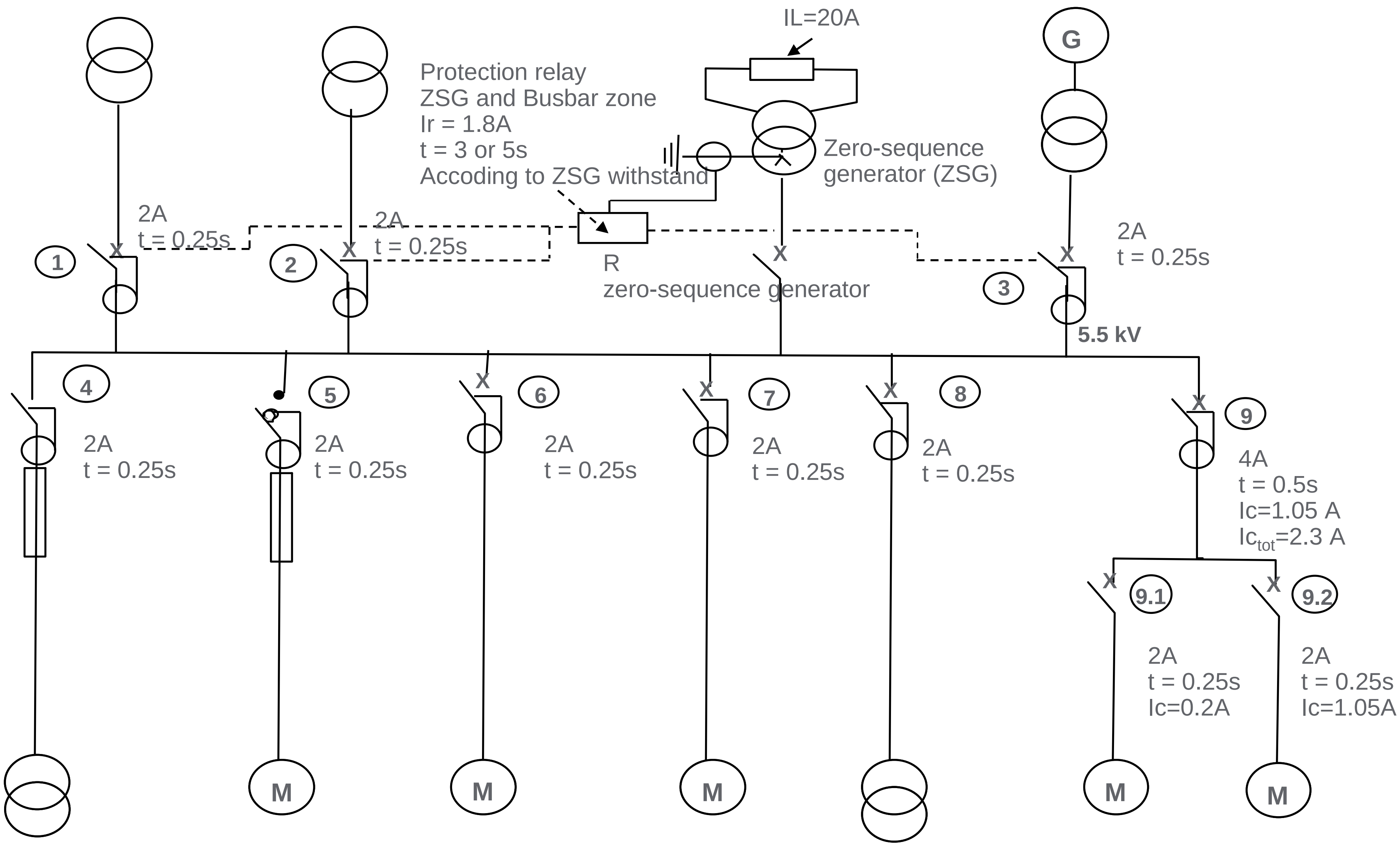
   3.5. what are the settings for the zero-sequence generator?

4. Length of the double 9.2 power supply cable
   - can 90% of the motor winding still be protected?
   - what solutions do you propose?
   - case of delta motor?

Capacitive current of connections upon network earth fault

Conn.	Cable	Nb. of cables in // per phase	Length km	Linear capacity μF/km	Ic
1	1*240	2	0.1	0.5	0..3
2	1*240	1	0.1	0.5	0.15
3	3*70	1	0.05	0.3	0.05
4	3*70	1	0.05	0.3	0.05
5	3*70	1	0.2	0.3	0.2
6	3*95	1	0.2	0.35	0.2
7	3*95	1	0.2	0.35	0.2
8	1*150	1	0.15	0.41	0.2
9.1	3*95	1	0.2	0.35	0.2
9.2	3*95	1	1	0.35	1.05
9	3*95	2	0.5	0.35	1.05
TOTAL					3.65

Earth-fault relay settings



IL>2Ic of total network

IR>2Ic max. downstream

Exercise 10: Capacitors

- A transformer with power = 630 kVA (410 V) supplies a load with active power P_1 = 250 kW with an average p.f. of 0.75.
- There is a plan to double the installation and this will call for additional active power P_2: 250 kW with p.f. = 0.75.

QUESTIONS :

1) Without power factor correction, determine the apparent power at the transformer terminals. What do you notice?

2) Calculate the maximum reactive power that the 630 kVA transformer can supply for this project.

3) Calculate the total active power to be supplied to the load before power factor correction.

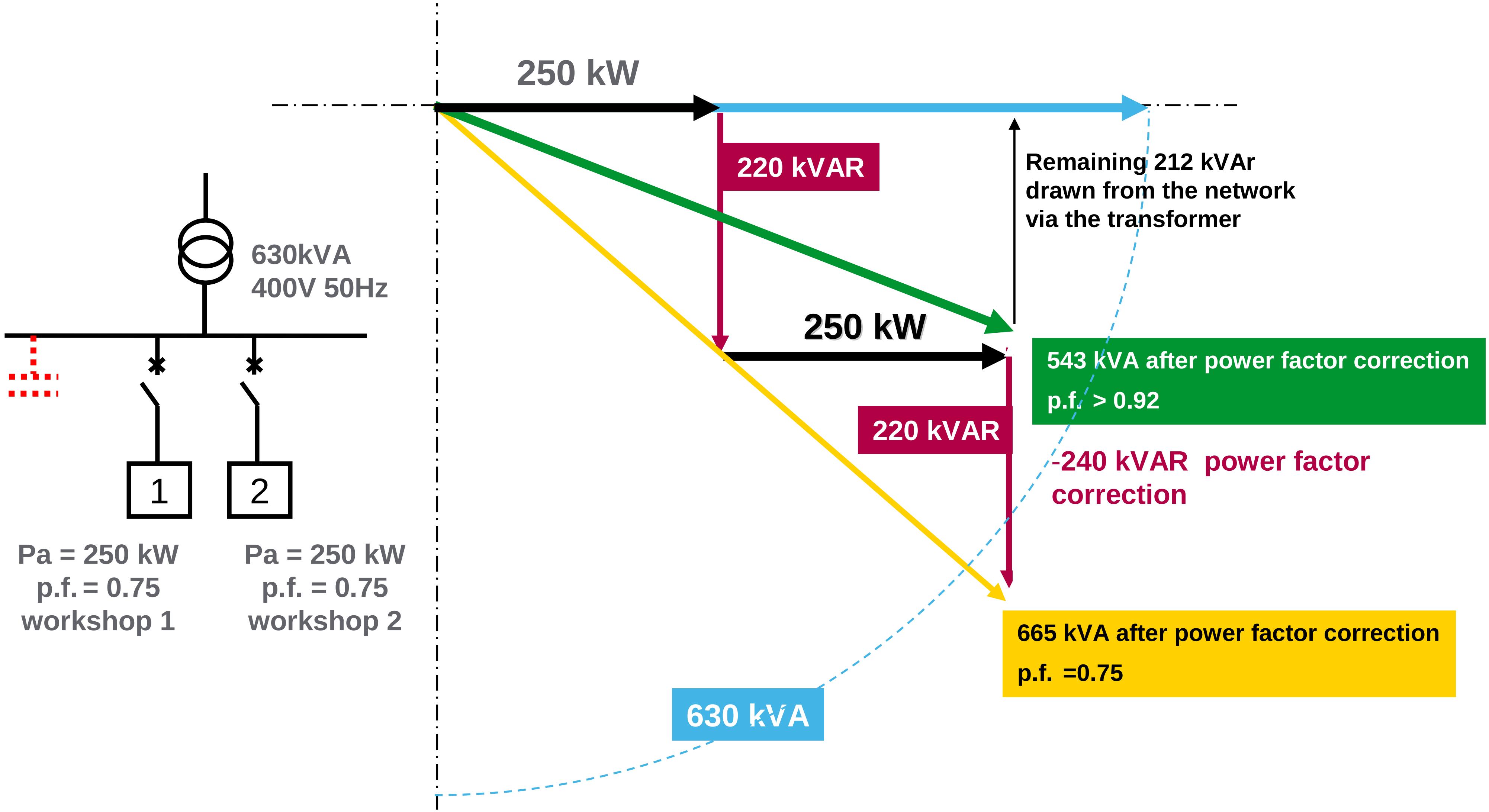
4) Determine the minimum power of the capacitor bank to be installed.

5) What is the p.f. value (transformer load 100%)?

6) A decision is made to raise the p.f. to 0.92. What is the minimum power of the capacitor bank to be installed?

7) Determine the rating of the circuit breaker to be installed.

Exercise 10: Capacitors



- For the first charge, determine**:**

apparent power: $S_1 = \frac{P_1}{p.f.} = \frac{250}{0.75} = 333$ A

reactive power: $Q_1 = \sqrt{S_1^2 - P_1^2} = \sqrt{333^2 - 250^2} = 220$ kVAR

- Determine for the second load:

apparent power: $S_2 = \frac{250}{0.75} = 333$ A

reactive power: $Q_2 = \sqrt{333^2 - 250^2} = 220$ kVAR

1) Without power factor correction, the apparent power at the transformer terminals would be:

$$S' = \sqrt{(P_1 + P_2)^2 + (Q_1 + Q_2)^2} = 665 \text{ kVA}$$

therefore greater than the transformer power.

Determine the minimum capacitor power needed to avoid replacing the transformer (transformer with (100% load).

The total active power to be supplied is:

$$P = P_1 + P_2 = 250 + 250 = 500 \text{ kW For } P=500 \text{ kW}$$

2) The maximum reactive power available on the 630 kVA transformer is:

$$Q_m = \sqrt{S^2 - P^2} = \sqrt{630^2 - 500^2} = 383\text{kVAR}$$

3) The total reactive power to be supplied to the load before power factor correction is:

$$Q_1 + Q_2 = 220 + 220 = 440\text{kVAR}$$

4) The minimum power of the capacitor bank to be installed is therefore:

$$Q_{CAP} = 440 - 383 = 57 \text{ kVAR}$$

5) Therefore, we obtain p.f. $= \frac{P}{S} = \frac{500}{630} = 0.79$

6) Minimum power of capacitors to raise the power factor to 0.92

$\frac{500}{0.92} = 543\,kVA$ needed, i.e. acceptable reactive value of $Q = \sqrt{543^2 - 500^2} = 212\text{kVAR}$

$S^2 - P^2$

Remainder to be corrected (220+220) – (212) = 228 kVAr => **240 kVAr**

7) Capacitor bank current $I = \frac{Q_{BAT}}{u\sqrt{3}} = \frac{240 \,.10^3}{400 \,.\sqrt{3}} = 346 \text{ A}$

Circuit breaker rating = 346 x 1.43 = 494 A min. (and cable)

N.B. Total power factor correction could be done (p.f. = 1), which would provide reserve power of 630-500=130 kW. The capacitor bank to be installed would be 440 kVAR (equal to the reactive value 2x220 WATT). Total PF correction would call for a large installation of capacitors for only a small gain in active power available.
(630 x 0.92 = 580 kW available at p.f. 0.92; what we've got left is 580 – 500 = 80 kW p.f. 0.92)