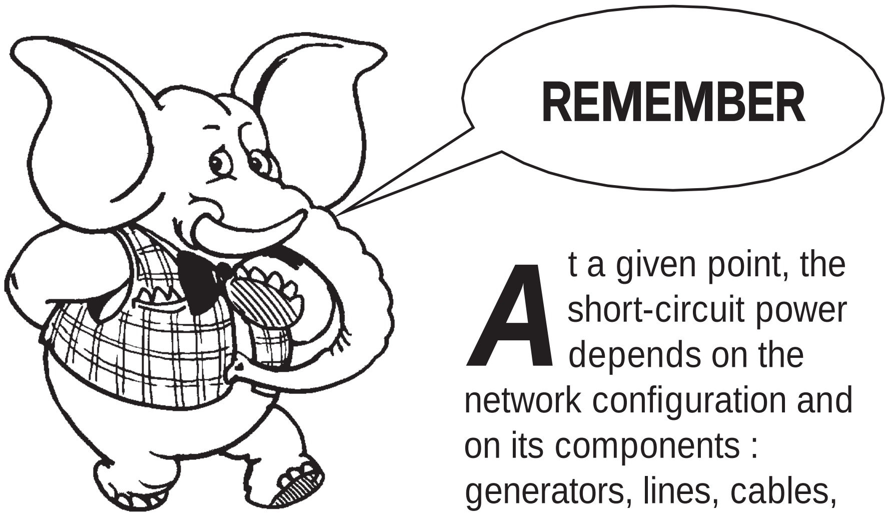
MT Partenaire

Voltage, current and frequency are the three basic values that are involved in defining electrical equipment.

The type of network requires us to consider a fourth one that of short-circuit power.

Short-circuit power



At a given point, the short-circuit power depends on the network configuration and on its components : generators, lines, cables, transformers, motors…

Short-circuit power is the maximum power that a network can supply to equipment with a fault in it. It is expressed either in MVA or in effective kA for a given service voltage.

The rated short time withstand current and its peak value are dependent on the short-circuit current at a given point of the panel.
The breaking and closing capacities required in circuit breakers are determined on the basis of these values.

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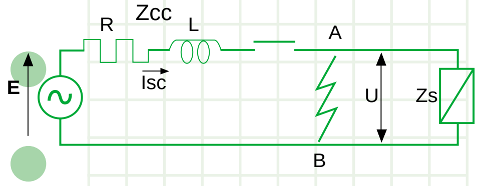
Short-circuit power

Introduction

Example 1:
25 kA at an operating voltage of 11 kV



$S_{sc} = \sqrt{3} \cdot U \cdot I_{sc}$

■ The short-circuit power depends directly on the network configuration and the impedance of its components:
lines, cables, transformers, motors... through which the short-circuit current passes.

■ It is the maximum power that the network can provide to an installation during a fault, expressed in kA rms for a given operating voltage or in MVA.

U	:	operating voltage (kV)
Isc	:	short-circuit current (kA rms.) Ref: following pages

The short-circuit power can be assimilated to an apparent power.

■ The value of short-circuit power is generally imposed to us because we rarely have the information required to calculate it.
Determination of the short-circuit power requires analysis of the power flows feeding the short-circuit in the worst possible case.

Possible sources are:

■ Network incomer via power transformers.

■ Generator incomer.

■ Power feedback due to rotary sets (motors, etc); or via MV/LV transformaters.

Example 2:

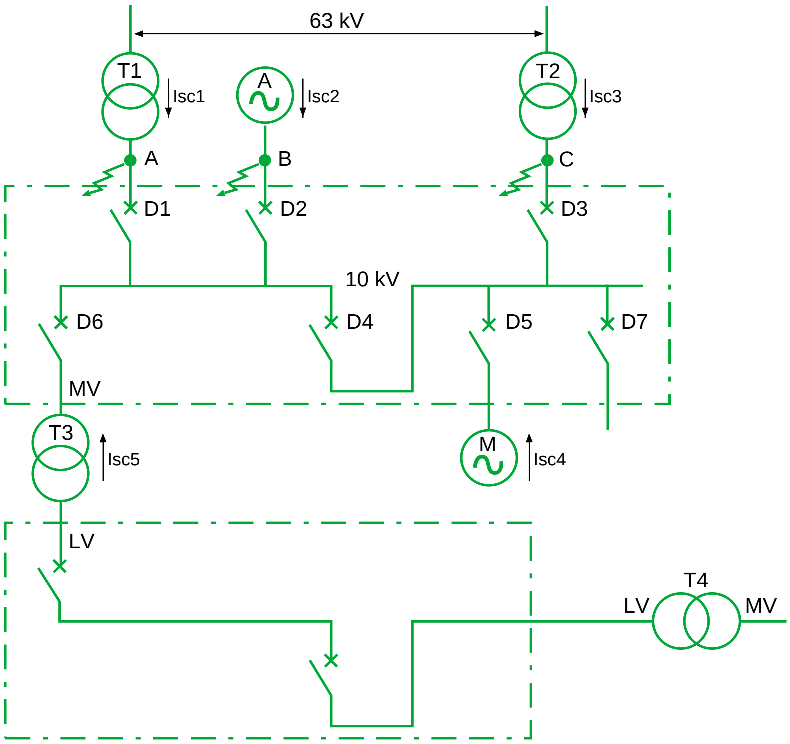
■ *Feedback via LV Isc5 is only possible if the transformer (T4) is powered by another source.*

■ *Three sources (T1-A-T2) are flowing in the switchboard*

□ ***short circuit at A :the CB (D1)*** *sees Isc2 + Isc3 + Isc4 + Isc5*

□ ***short circuit at B :the CB (D2)*** *sees Isc1 + Isc3 + Isc4 + Isc5*

o ***short circuit at C :the CB (D3*** *sees Isc1 + Isc2 + Isc4 + Isc5*



We have to calculate each of the Isc currents.

All electrical installations have to be protected against short-circuits, without exception, whenever there is an electrical discontinuity; which more generally corresponds to a change in conductor cross-section.
The short-circuit current must be calculated at each stage in the installation for the various configurations that are possible within the network; this is in order to determine the characteristics that the equipment has to have withstand or break this fault current.

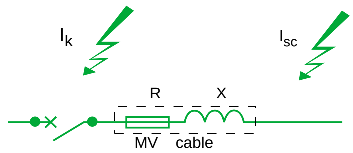
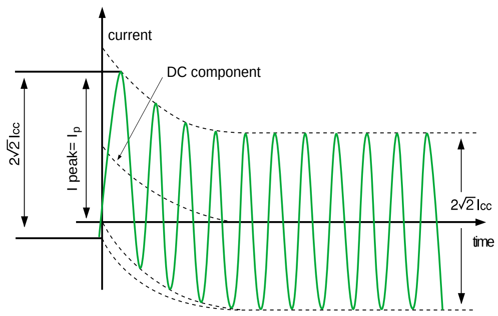


figure 1



■ In order to choose the right switchgear (circuit breakers or fuses) and set the protection functions, three short-circuit values must be known:

□ **minimal short-circuit current:**

Isc = kA (rms) *(example: 19 kA rms)*

This corresponds to a short-circuit at one end of the protected link (fault at the end of a feeder (see fig.1)) and not just behind the breaking mechanism. Its value allows us to choose the setting of thresholds for overcurrent protection devices and fuses; especially when the length of cables is high and/or when the source is relatively impedant (generator, UPS).

□ **short-time withstand current (rms value) :**

I_k = kA (rms.) 1 s or 3 s *(example: 25 kA rms. 1 s)*

This corresponds to a short-circuit in the immediate vicinity of the upstream terminals of the switching device (see fig.1). It is defined in kA for 1 or 3 second(s) and is used to define the thermal withstand of the equipment.

□ **peak value of the short-circuit current:**
(value of the **initial peak** in the transient period)

Ip = (kA peak)

(example: 2.5 • 25 kA = 63.75 kA peak IEC 60 056 or 2.7 • 25 kA = 67.5 kA peak ANSI)

- **Ip** is equal to:

2.5 • Isc at 50 Hz (IEC) or,
2.6 • Isc at 60 Hz (IEC) or,
2.7 • Isc (ANSI) **(I_{sc} short-circuit current calculated at a given point in the network).**

It determines the breaking capacity and closing capacity of circuit breakers and switches, as well as the electrodynamic withstand of busbars and switchgear.

- **The IEC** uses the following values:
8 - 12.5 - 16 - 20 - 25 - 31.5 - 40 kA rms.
These are generally used in the specifications.

N.B.:
■ *A specification may give one value in kA rms and one value in MVA as below:*
Isc = 19 kA rms or 350 MVA at 10 kV
□ *if we calculate the equivalent current at 350 MVA we find:*

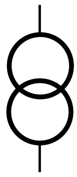
$$Isc = \frac{350}{\sqrt{3} \cdot 10} = 20.2 \text{ kA rms}$$

The difference lies in the way in which we round up the value and in local habits.
The value 19 kA rms is probably the most realistic.
□ *another explanation is possible: in medium and high voltage, IEC 60909 applies a coefficient of 1.1 when calculating maximal Isc.*

$$Isc = 1{,}1 \cdot \frac{U}{\sqrt{3} \cdot Zsc} = \frac{E}{Zsc}$$

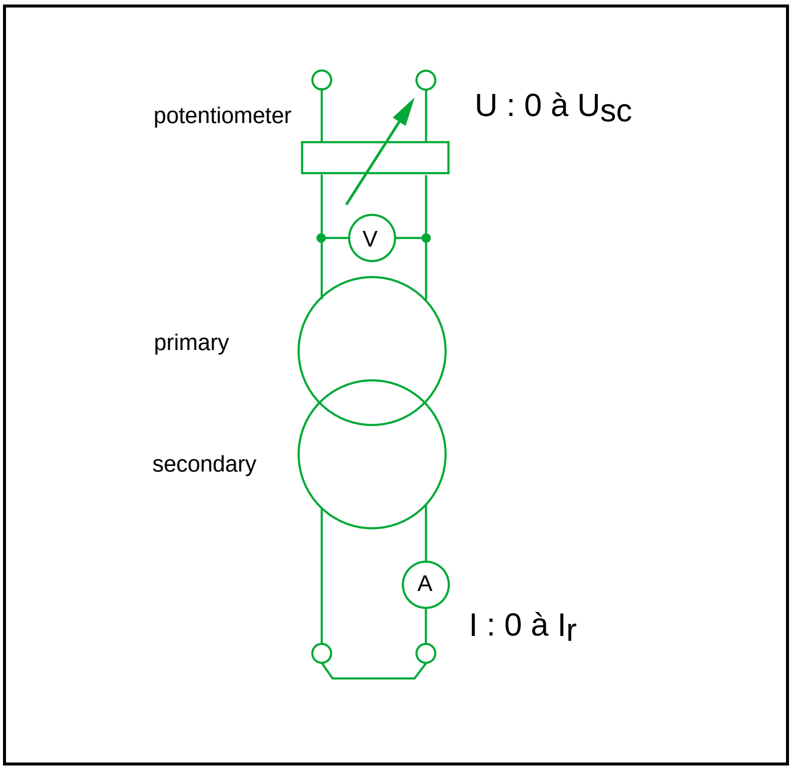
This coefficient of 1.1 takes account of a voltage drop of 10 % across the faulty installation (cables, etc).

Transformer



In order to determine the short-circuit current across the terminals of a transformer, we need to know its short-circuit voltage (Usc %).

■ Usc % is defined in the following way:



The short-circuit current depends on the type of equipment installed on the network (transformers, generators, motors, lines, etc).

❶ the voltage transformer is not powered: U = 0
❷ **place** the secondary in short-circuit
❸ gradually **increase** voltage U at the primary up to the rated current I_r in the transformer secondary circuit.

$$U_{sc\%} = U_{sc} * 100 / U_r$$

■ The short-circuit current, expressed in kA, is given by the following equation:

$$I_k = \frac{I_r}{U_{sc\%}}$$

Example:

- ■ *Transformer S_r=20 MVA*
- ■ *Voltage U_r=10 kV*
- ■ *Usc% = 10 %*
- ■ *Upstream power: infinite*

$$I_r = \frac{S_r}{\sqrt{3} * U_r} = \frac{20\ 000}{\sqrt{3} \cdot 10} = 1\ 150\ A$$

$$I_k = \frac{I_r}{U_{sc\%}} = \frac{1\ 150}{10 \div 100} = 11\ 500\ A = 11.5\ kA$$

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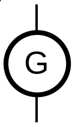
Synchronous generators (alternators and motors)



Calculating the short-circuit current across the terminals of a synchronous generator is very complicated because the internal impedance of the latter varies according to time.

■ The short circuit power increases progressively with the current decreasing correspondingly and passing through three typical stages:

□ **sub-transient** (enabling determination of the closing capacity of circuit breakers and electrodynamic contraints), average duration, 10 ms

□ **transient** (sets the breaking capacity of circuit breakers), average duration 250 ms

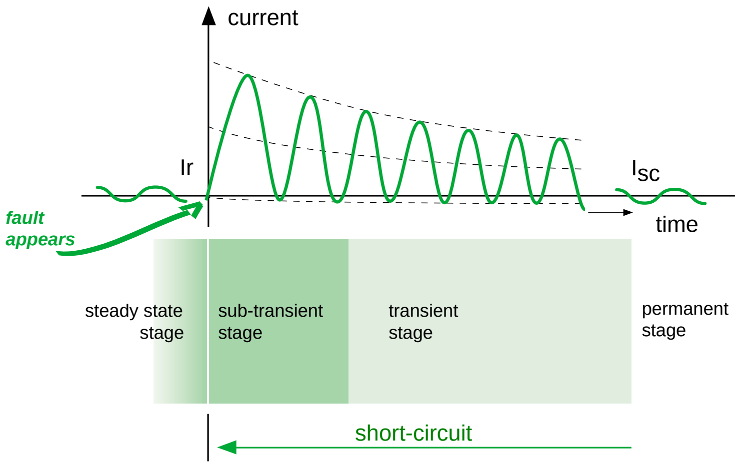
□ **permanent** (this is the value of the short-circuit current in steady state).

■ The short-circuit current is calculated in the same way as for transformers but the different states must be taken account of.

Example:
Calculation method for an alternator or a synchronous motor
■ *Alternator 15 MVA*
■ *Voltage U = 10 kV*
■ *X'd = 20 %*

$$I_r = \frac{Sr}{\sqrt{3} \cdot Ur} = \frac{15}{\sqrt{3} \cdot 10\ 000} = 870\ A$$

$$I_{sc} = \frac{Ir}{Xsc\ trans.} = \frac{870}{20/100} = 4\ 350\ A = 4.35\ kA$$



■ The short-circuit current is given by the following equation:

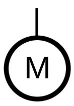
$$I_{sc} = \frac{I_r}{X_{sc\%}}$$

Xsc : short-circuit reactance in %

■ The most common values for a synchronous generator are:

Stage	Sub-transient X"d	Transient X'd	Permanent Xd
Xsc	10 - 20 %	15 - 25 %	200 - 350 %

Asynchronous motor



■ **For asynchronous motors**

□ the short-circuit current across the terminals equals the start-up current

$$I_{sc} \simeq 5 \text{ at } 8\ I_r$$

□ the contribution of the motors (current feedback) to the short-circuit current is equal to**:**

$$I \simeq 3\ \Sigma\ I_r$$

The coefficient of 3, takes account of motors when stopped and the impedance to go right through to the fault.

Reminder concerning the calculation of three-phase short-circuit currents

■ **Three-phase short-circuit**

$$S_{sc} = 1.1 * U * I_{sc} * \sqrt{3} = \frac{U^2}{Z_{sc}}$$

$$I_{sc} = \frac{1.1 * U}{\sqrt{3} * Z_{sc}} \quad \text{with} \quad Z_{sc} = \sqrt{R^2 + X^2}$$

■ **Upstream network**

$$Z = \frac{U^2}{S_{sc}}$$

$$\frac{R}{X} = \begin{cases} 0.3 \text{ at } 6 \text{ kV} \\ 0.2 \text{ at } 20 \text{ kV} \\ 0.1 \text{ at } 150 \text{ kV} \end{cases}$$

■ **Overhead lines**

$$R = \rho \cdot \frac{L}{S}$$

X = 0.4 Ω/km	HV
X = 0.3 Ω/km	MV/LV
$\rho = 1.8 \cdot 10^{-6}$ Ω cm	copper
$\rho = 2.8 \cdot 10^{-6}$ Ω cm	aluminium
$\rho = 3.3 \cdot 10^{-6}$ Ω cm	almélec

■ **Synchronous generators**

$$Z(\Omega) = X(\Omega) = \frac{U^2}{S_r} \cdot \frac{X_{sc}(\%)}{100}$$

X_{sc}	sub-transient	transient	permanent
turbo	10 to 20 %	15 to 25 %	200 to 350 %
exposed poles	15 to 25 %	25 to 35 %	70 to 120 %

■ **Transformers**

(order of magnitude: for real values, refer to data given by manufacturer)

E.g.: ⚭ 20 kV/410 V; Sr = 630 kVA; U_{sc} = 4 %
⚭ 63 kV/11 V; Sr = 10 MVA; U_{sc} = 9 %

$$Z(\Omega) = \frac{U^2}{S_r} \cdot \frac{U_{sc}(\%)}{100}$$

Sr (kVA)	100 to 3150	5000 to 5000
Usc (%)	4 to 7.5	8 to 12
⚭	MV/LV	HV/MV

■ **Cables**

X = 0.10 at 0.15 Ω/km
three-phased or single-phased

■ **Busbars**

X = 0.15 Ω/km

Short-circuit currents

■ Synchronous motors and compensators

Xsc	Sub-transient	transient	permanent
high speed motors	15 %	25 %	80 %
low speed motors	35 %	50 %	100 %
compensators	25 %	40 %	160 %

■ Asynchronous motors

only sub-transient

$$Z(\Omega) = \frac{I_r}{I_d} \cdot \frac{U^2}{S_r}$$

$I_{sc} \simeq 5$ to $8\ I_r$

$I_{sc} \simeq 3\ \Sigma\ I_r$,

contribution to I_{sc} by current feedback (with I rated = I_r)

■ Fault arcing

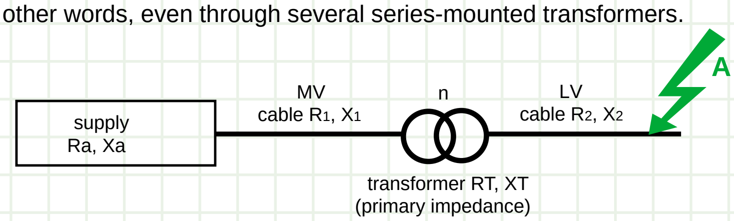
$$I_d = \frac{I_{sc}}{1.3 \text{ to } 2}$$

■ Equivalent impedance of a component through a transformer

□ for example, for a low voltage fault, the contribution of an HV cable upstream of an HV/LV transformer will be:

$$R_2 = R_1 \left(\frac{U_2}{U_1}\right)^2 \quad \text{et} \quad X_2 = X_1 \left(\frac{U_2}{U_1}\right)^2 \quad \text{ainsi} \quad Z_2 = Z_1 \left(\frac{U_2}{U_1}\right)^2$$

This equation is valid for all voltage levels in the cable, in other words, even through several series-mounted transformers.



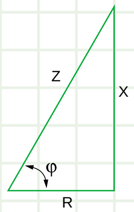
□ Impedance seen from the fault location A:

$$\Sigma R = R_2 + \frac{R_T}{n^2} + \frac{R_1}{n^2} + \frac{R_a}{n^2} \qquad \Sigma X = X_2 + \frac{X_T}{n^2} + \frac{X_1}{n^2} + \frac{X_a}{n^2}$$

***n**: transformation ratio*

■ Triangle of impedances

$$Z = \sqrt{(R^2 + X^2)}$$



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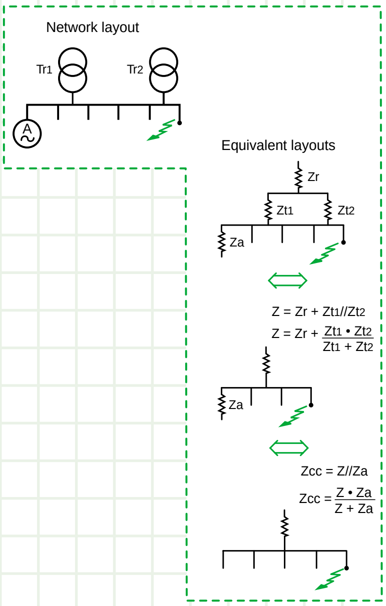
Example of a three-phase calculation

The complexity in calculating the three-phase short-circuit current basically lies in determining the impedance value in the network upstream of the lault location.

Example 1:



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Impedance method

All the components of a network (supply network, transformer, alternator, motors, cables, bars, etc) are characterised by an impedance (Z) comprising a resistive component (R) and an inductive component (X) or so-called reactance. X, R and Z are expressed in ohms.

■ The relation between these different values is given by:

$$Z = \sqrt{(R^2 + X^2)}$$

(cf.example 1 opposite)

■ The method involves:

□ breaking down the network into sections
□ calculating the values of R and X for each component
□ calculating for the network:
- the equivalent value of R or X
- the equivalent value of impedance
- the short-circuit current.

■ The three-phase short-circuit current is:

$$I_{sc} = \frac{U}{\sqrt{3} \bullet Z_{sc}}$$

Isc	:	short-circuit current (in kA)
U	:	phase to phase voltage at the point in question before the appearance of the fault, in kV.
Zsc	:	short-circuit impedance (in ohms)

(cf. example 2 below)

Example 2:

■ *Zsc = 0.72 ohm*

■ *U = 10 kV*

$$I_{sc} = \frac{10}{\sqrt{3} \bullet 0{,}72} = 21.38\ kA$$

Short-circuit currents

Here is a problem to solve!

Exercice data

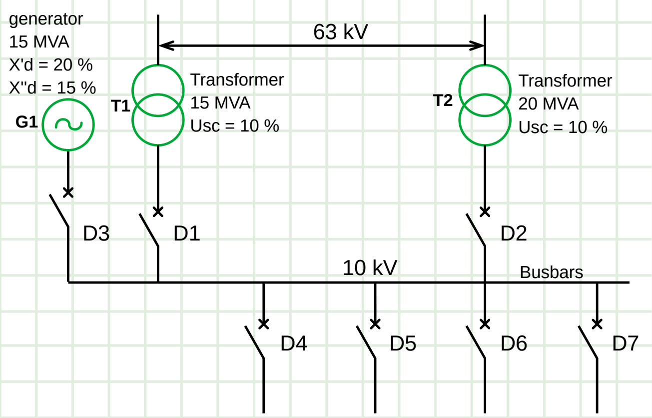
Supply at 63 kV
Short-circuit power of the source: 2 000 MVA

■ ***Network configuration:***
Two parallel mounted transformers and an alternator.

■ ***Equipment characteristics:***
☐ *transformers:*
- voltage 63 kV / 10 kV
- apparent power: 1 to 15 MVA, 1 to 20 MVA
- short-circuit voltage: U_{sc} *= 10 %*
☐ *Alternator :*
- voltage: 10 kV
- apparent power: 15 MVA
- X'd transient: 20 %
- X"d sub-transient: 15 %

■ ***Question:***
☐ *determine the value of short-circuit current at the busbars,*
☐ *the breaking and closing capacities of the circuit breakers D1 to D7.*

Single line diagram



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Here is the solution to the problem with the calculation method

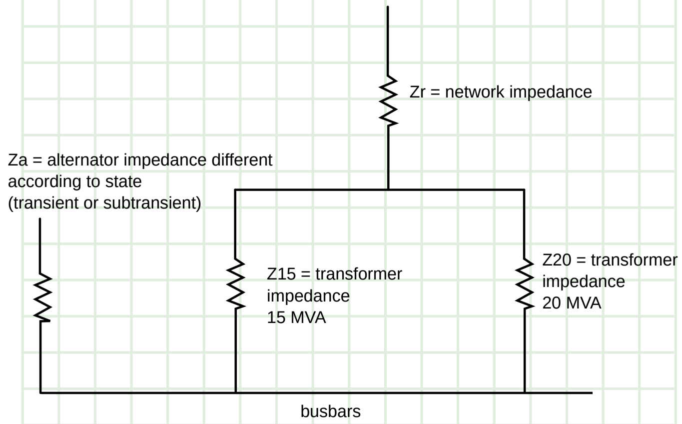
Solving the exercise

■ ***Determining the various short-circuit currents***

The three sources which could supply power to the short-circuit are the two transformers and the alternator.
We are supposing that there can be no feedback of power through D4, D5, D6 and D7.
In the case of a short-circuit upstream of a circuit breaker (D1, D2, D3, this then has the short-circuit current flow supplied by the two other sources

■ ***Equivalent diagram***

Each component comprises a resistance and an inductance.
We have to calculate the values for each component.
The network can be shown as follows:



Experience shows that the resistance is generally low compared with, reactance, so we can therefore deduce that the reactance is equal to the impedance (X = Z).

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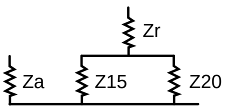
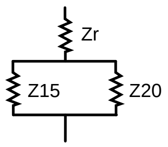
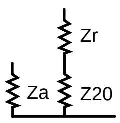
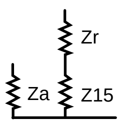
Short-circuit currents

And now here are the results!

Component	Calculation	Z = X (ohms)
Network Ssc = 2 000 MVA U op. = 10 kV	$Zr = \frac{U^2}{Ssc} = \frac{10^2}{2\,000}$	0.05
15 MVA transformer (Usc = 10 %) U op. = 10 kV	$Z15 = \frac{U^2}{Sr} \bullet Usc = \frac{10^2}{15} \bullet \frac{10}{100}$	0.67
20 MVA transformer (Usc = 10 %) U op. = 10 kV	$Z20 = \frac{U^2}{Sr} \bullet Usc = \frac{10^2}{20} \bullet \frac{10}{100}$	0.5
15 MVA alternator U op. = 10 kV Transient state (Xsc = 20 %) Sub-transient state (Xsc = 15 %)	$Za = \frac{U^2}{Sr} \bullet Xsc$ $Zat = \frac{10^2}{15} \bullet \frac{20}{100}$ $Zas = \frac{10^2}{15} \bullet \frac{15}{100}$	Zat = 1.33 Zas = 1
Busbars Parallel-mounted with the transformers Series-mounted with the network and the transformer impedance	$Z15 \| Z20 = \frac{Z15 \bullet Z20}{Z15 + Z20} = \frac{0.67 \bullet 0.5}{0.67 + 0.5}$ $Zr + Zet = 0.05 + 0.29$	Zet = 0.29 Zer = 0.34
Parallel-mounting of the generator set Transient state Sub-transient state	$Zer \| Zat = \frac{Zer \bullet Zat}{Zer + Zat} = \frac{0.34 \bullet 1.33}{0.34 + 1.33}$ $Zer \| Zat = \frac{Zer \bullet Zat}{Zer + Zat} = \frac{0.34 \bullet 1}{0.34 + 1}$	≃ 0.27 ≃ 0.25

***N.B.:** a circuit breaker is defined for a certain breaking capacity of an rms value in a steady state, and as a percentage of the aperiodic component which depends on the circuit breaker's opening time and on $\frac{R}{X}$ of the network (about 30 %).*

For alternators the aperiodic component is very high; the calculations must be validated by laboratory tests.

Circuit breaker	Equivalent circuit Z (ohm)	Breaking capacity in kA rms. $Isc = \frac{U^2}{\sqrt{3} \bullet Zsc} = \frac{10}{\sqrt{3}} \bullet \frac{1}{Zsc}$	Closing capacity 2.5 I_{sc} (in kA peak)
D4 to D7  Zt = [Zr + (Z15//Z20)]//Za	transient state Z_{SC} = 0.27 sub-transient state Z = 0.25	**21.40**	21.40 • 2.5 = **53.15**
D3 alternator  Zt = Zr + (Z15//Z20)	Z_{SC} = 0.34	**17**	17 • 2.5 = **42.5**
D1 15 MVA transformer  Zt = (Zr + Z20)//Za	transient state Z_{SC} = 0.39 sub-transient state Z = 0.35	**14.9**	14.9 • 2.5 = **37.25**
D2 20 MVA transformer  Zt = (Zr + Z15)//Za	transient state Z_{SC} = 0.47 sub-transient state Z = 0.42	**12.4**	12.4 • 2.5 = **31**

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Busbar calculation

Introduction

In reality, a busbar calculation involves checking that it provides sufficient thermal and electrodynamic withstand and non-resonance.

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■ The dimensions of busbars are determined taking account of **normal operating conditions.**
The voltage (kV) that the installation operates at determines the phase to phase and phase to earth distance and also determines the height and shape of the supports.
The rated current flowing through the busbars is used to determine the cross-section and type of conductors.

■ We then ensure that the supports (insulators) resist the **mechanical effects** and that the bars resist the **mechanical and thermal effects** due to short-circuit currents.
We also have to check that the period of vibration intrinsic to the bars themselves is not **resonant** with the current period.

■ To carry out a busbar calculation, we have to use the following physical and electrical characteristics :

Busbar electrical characteristics				
Ssc	:	network short-circuit power*		**MVA**
Ur	:	rated voltage		**kV**
U	:	operating voltage		**kV**
I_r	:	rated current		**A**

* ***N.B.:*** *It is is generally provided by the customer in this form or we can calculate it having the short-circuit current Isc and the operating voltage U: (Ssc = $\sqrt{3}$ • Isc • U; see chapter on "Short-circuit currents").*

Physical busbar characteristics				
S	:	busbar cross section		**cm²**
d	:	phase to phase distance		**cm**
l	:	distance between insulators for same phase		**cm**
θ_n	:	ambient temperature ($\theta n \le 40°C$)		**°C**
$(\theta - \theta_n)$	:	permissible temperature rise*		**°C**

profile :	flat ☐		
material :	copper ☐	aluminium ☐	
arrangement :	flat-mounted ☐	edge-mounted ☐	
no. of bar(s) per phase :			

* ***N.B.***: *see table V in standard ICE 60 694 on the 2 following pages.*

In summary:
______ bar(s) of ______ cm x ______ cm per phase

Temperature rise

Taken from table V of standard IEC 60 694

Type of device, of material and of dielectric (Cf: 1, 2 and 3)	**Temperature** θ (°C)	**(θ - $θ_n$)** with $θ_n$ = 40 °C
Bolt connected or equivalent devices (Cf: 7)		
bare copper, bare copper alloy or aluminium alloy in		
air	90	50
SF6 *	105	65
oil	100	60
silver or nickel plated in		
air	115	75
SF6	115	75
oil	100	60
tin-plated in		
air	105	65
SF6	105	65
oil	100	60

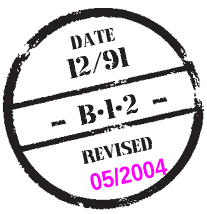
** SF6 (sulphur hexafluoride)*

1 According to its function, the same device may belong to several categories given in table V. In this case, the admissible values of temperature and temperature rise to take into consideration are the lowest for category concerned.

2 For vacuum switchgear, the limit values of temperature and temperature rise do not apply to vacuum devices. Other devices must not exceed the values for temperature and temperature rise given in table V.

3 All the necessary precautions must be taken so that absolutely no damage is caused to surrounding materials.

7 When contact components are protected in different ways, the temperature and temperature rises that are allowed are those for the element for which table V authorises the highest values.



Busbar calculation

Temperature rise

Extract from table V of standard IEC 60 694

Type of device, of material and of dielectric (Cf : 1, 2 and 3)	Temperature θ (°C)	$(\theta - \theta_n)$ with θ_n = 40 °C
Contacts (Cf: 4)		
copper or bare copper alloy in		
air	75	35
SF6 *	90	50
oil	80	40
silver or nickel plated (Cf: 5) in		
air	105	65
SF6	105	65
oil	90	50
tin-plated (Cf: 5 and 6) in		
air	90	50
SF6	90	50
oil	90	50

* SF6 (sulphur hexafluoride)

1

According to its function, the same device may belong to several categories given in table V. In this case, the admissible values of temperature and temperature rise to take into consideration are the lowest for category concerned.

2

For vacuum switchgear, the limit values of temperature and temperature rise do not apply to vacuum devices. Other devices must not exceed the values for temperature and temperature rise given in table V.

3

All the necessary precautions must be taken so that absolutely no damage is caused to surrounding materials.

4

When the contact components are protected in different manners, the temperatures and temperature rises that are allowed are those of the element for which table V authorises the lowest values.

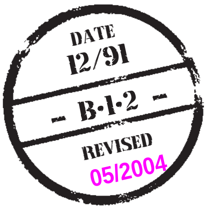
5

The quality of coating must be such that a protective layer remains in the contact zone:
- after the making and breaking test (if it exists),
- after the short time withstand current test,
- after the mechanical endurance test,

according to specifications specific to each piece of equipment. Should this not be true, the contacts must be considered as "bare".

6

For fuse contacts, the temperature rise must be in conformity with publications concerning high voltage fuses.



Thermal withstand...

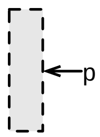
Let's check if the cross-section that has been chosen:
... bar(s) of ... x ... cm per phase
satisfies the temperature rises produced by the rated current and by the short-circuit current passing through them for 1 to 3 second(s).

For the rated current (I_r)

The MELSON & BOTH equation published in the "Copper Development Association" review allows us to define the permissible current in a conductor:

$$I = K \bullet \frac{24.9\,(\theta - \theta_n)^{0.61} \bullet S^{0.5} \bullet p^{0.39}}{\sqrt{\rho_{20}\,[1 + \alpha\,(\theta - 20)]}}$$

with:



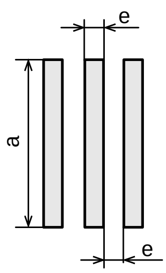
outside perimeter of the bars

I	:	permissible current expressed in amperes (A) *derating in terms of current should be considered:* *- for an ambient temperature greater than 40°C* *- for a protection index greater than IP5*		
θ_n	:	ambient temperature ($\theta_n \leq 40$°C)		**°C**
($\theta - \theta_n$)	:	permissible temperature rise*		**°C**
S	:	busbar cross section		**cm²**
p	:	outside busbar perimete *(opposite diagram)*		**cm**
ρ_{20}	:	conductor resistivity at 20°C		
	:	copper:	1.83 µΩ cm	
	:	aluminium:	2.90 µΩ cm	
α	:	temperature coefficient of the resistivity: 0,004		
k	:	conditions coefficient *product of 6 coefficients (k1, k2, k3, k4, k5, k6), described below*		

*(see table V of standard IEC 60 694 in the previous pages)

Definition of coefficients k1, 2, 3, 4, 5, 6:

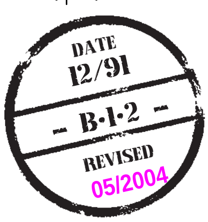
■ **Coefficient k1** is a function of the number of bar strips per phase for:
□ 1 bar (k1 = 1)
□ 2 or 3 bars, see table below:



				e/a					
	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
no. of bars per phase				**k1**					
2	1.63	1.73	1.76	1.80	1.83	1.85	1.87	1.89	1.91
3	2.40	2.45	2.50	2.55	2.60	2.63	2.65	2.68	2.70

In our case:

e/a =	
the number of bars per phase =	
giving k1 =	



■ **Coefficient k2** is a function of surface condition of the busbars:
□ bare: k2 = 1
□ painted: k2 = 1.15

■ **Coefficient k3** is a function of the position of the bars:
□ edge-mounted bars (vertical): k3 = 1
□ 1 bar base-mounted (horizontal): k3 = 0.95
□ several base-mounted bars (horizontal): k3 = 0.75

■ **Coefficient k4** is a function of the place where the bars are installed:
□ calm indoor atmosphere: k4 = 1
□ calm outdoor atmosphere: k4 = 1.2
□ bars in non-ventilated ducting: k4 = 0.80

■ **Coefficient k5** is a function of the artificial ventilation:
□ without artificial ventilation: k5 = 1
□ ventilation should be dealt with on a case by case basis and then validated by testing.

■ **Coefficient k6** is a function of the type of current:
□ for a alternatif current of frequency ≤ 60 Hz, k6 is a function of the number of bars **n** per phase and of their spacing.
The value of k6 for a spacing equal to the thickness of the bars:

n	1	2	3
k6	1	1	0.98

In our case:

n = ______ **giving k6 =** ______

In fact we have:

k = ______ • ______ • ______ • ______ • ______ • ______ = ______

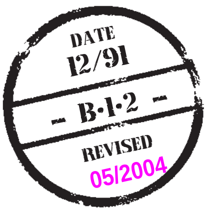
$$I = \_\_\_ \cdot \frac{24.9\,(\_\_\_ - \_\_\_)^{0.61} \cdot \_\_\_^{0.5} \cdot \_\_\_^{0.39}}{\sqrt{\_\_\_\,[1+ 0.004\,(\_\_\_ - 20)]}}$$

$$I = K \cdot \frac{24.9\,(\theta - \theta_n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}\,[1+ \alpha\,(\theta - 20)]}}$$

I = ______ **A**

The chosen solution ______ bar(s)
of ______ • ______ cm per phase

Is appropriate if I_r of the required busbars ≤ **I**



For the short-time withstand current (I_k)

■ We assume that for the whole duration (1 or 3 seconds):

□ all the heat that is given off is used to increase the temperature of the conductor

□ radiation effects are negligible.

The equation below can be used to calculate the short-circuit temperature rise:

$$\Delta\theta_{cc} = \frac{0.24 \bullet \rho_{20} \bullet I_k^2 \bullet t_k}{(n \bullet S)^2 \bullet c \bullet \delta}$$

with:

$\Delta\theta_{sc}$	:	short-circuit temperature rise		
c	:	specific heat of the metal copper: aluminium:	 0.091 kcal/kg°C 0.23 kcal/kg °C	
S	:	cross section of one bar		cm²
n	:	number of bar(s) per phase		
I_k	:	is the short-time withstand current: (maximum short-circuit current, rms value)		A rms
t_k	:	short-time withstand current duration (1 to 3 s)		s
δ	:	density of the metal copper: aluminium:	 8.9 g/cm³ 2.7 g/cm³	
ρ_{20}	:	resistivity of the conductor at 20°C copper: aluminium:	 1.83 μΩ cm 2.90 μΩ cm	
(θ - θn)	:	permissible temperature rise		°C

$$\Delta\theta_{sc} = \frac{0.24 \bullet \_\_\_ \; 10^{-6} \bullet (\_\_\_)^2 \bullet \_\_\_}{(\_\_\_)^2 \bullet \_\_\_ \bullet \_\_\_}$$

$\Delta\theta_{sc}$ = ____ °C

The temperature, θ_t of the conductor after the short-circuit will be:

$$(\theta_t = \theta_n + (\theta - \theta_n) + \Delta\theta_{sc})$$

θ_t = ____ °C $\qquad \theta_n$ = ambiant temperature

Check:

$\theta_t \leq$ maximum admissible temperature by the parts in contact with the busbars.

Check that this temperature θ_t is compatible with the maximum temperature of the parts in contact with the busbars (especially the insulator).

Example :
How can we find the value of Ith for a different duration?
Knowing: $(I_k)^2 \bullet t$ = constant

■ ***If $I_{k\,2}$ = 26.16 kA rms. 2 s, what does I_{th_1} correspond to for t_k = 1 s ?***

$(I_{k\,2})^2 \bullet t$ = constant
$(26.16 \bullet 10^3)^2 \bullet 2 = 137 \bullet 10^7$

$$\text{so } I_{k\,1} = \sqrt{\left(\frac{constant}{t}\right)} = \sqrt{\left(\frac{137 \bullet 10^7}{1}\right)}$$

$I_{k\,1}$ = 37 kA rms. for 1 s

■ ***In summary :***

□ *at 26.16 kA rms. 2 s, it corresponds to 37 kA rms. 1 s*

□ *at 37 kA rms. 1 s, it corresponds to 26.16 kA rms. 2 s*

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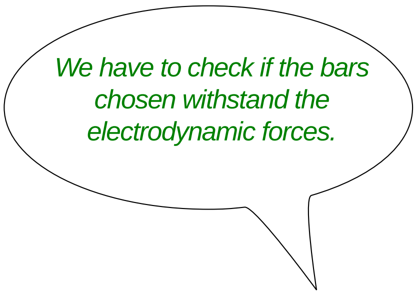
Electrodynamic withstand



Forces between parallel-mounted conductors

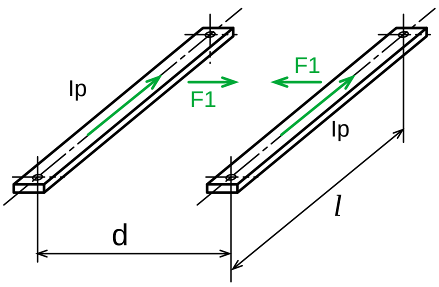
The electrodynamic forces are given by the equation:

$$F_1 = 2\frac{l}{d} \bullet I_{dyn}^2 \bullet 10^{-8}$$

with

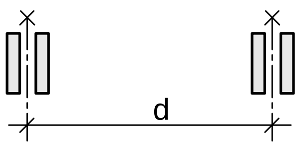
F_1	:	force expressed in daN
I_{dyn}	:	is the peak value of short-circuit expressed in A, to be calculated with the equation below:

$$I_p = k \bullet \frac{S_{sc}}{U\sqrt{3}} = k \bullet I_k$$



S_{sc}	:	short-circuit power		kVA
I_k	:	short-time withstand current		A rms
U	:	operating voltage		kV
l	:	distance between insulators on the same phase		cm
d	:	phase to phase distance		cm
k	:	2.5 for 50 Hz ; 2.6 for 60 Hz for IEC and 2.7 according to ANSI		

Giving : I_p= ______ **A and F_1 =** ______ **daN**



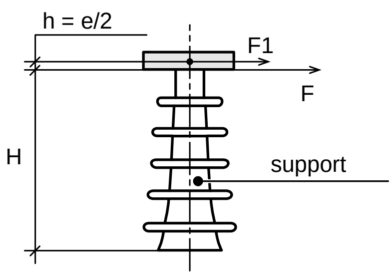
Forces at the head of supports or busducts

Equation to calculate the forces on a support:

$$F = F_1 \bullet \frac{H + h}{H}$$

with

F	:	force expressed		daN
H	:	insulator height		cm
h	:	distance from insulator head to busbar centre of gravity		cm



Calculation of forces if there are N supports

■ The force **F** absorbed by each support is at most equal to the calculated force F_1 (see previous chapter) multiplied by a coefficient k_n which varies according to the total number **N** of equidistant supports that are installed.

□ number of supports ______ **= N**

□ we know **N**, let us define k_n with the help of the table below:

giving F = ______ (F_1)• ______ (k_n) = ______ **daN**

N	2	3	4	≥5
k_n	0.5	1.25	1.10	1.14

■ The force found after applying a coefficient **k** should be compared with the mechanical strength of the support to which we will apply a safety coefficient:

□ the supports used have a bending resistance

F' = ______ **daN**

□ we have a safety coefficient of

$\frac{F'}{F}$ = ______

check if F' > F

Busbar calculation

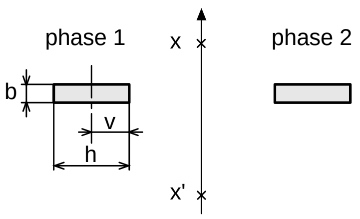
Mechanical busbar strength

■ By making the assumption that the ends of the bars are sealed, they are subjected to a bending moment whose resultant strain is:

$$\eta = \frac{F_1 \bullet l}{12} \bullet \frac{v}{I}$$

with

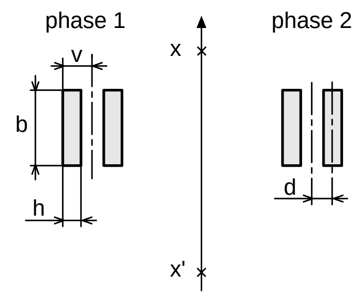
η	:	is the resultant strain, it must be **less than** the **permissible strain** for the bars this is: copper 1/4 hard: 1 200 daN/cm² copper 1/2 hard: 2 300 daN/cm² copper 4/4 hard: 3 000 daN/cm² tin-plated alu: 1 200 daN/cm²		
F1	:	force between conductors		**daN**
l	:	distance between insulators in the same phase		**cm**
I/v	:	is the modulus of inertia between a bar or a set of bars *(choose the value in the table on the following page)*		**cm³**
v	:	distance between the fibre that is neutral and the fibre with the highest strain (the furthest)		



■ **One bar per phase:**

$$I = \frac{b \bullet h^3}{12}$$

$$\frac{I}{v} = \frac{b \bullet h^2}{6}$$



■ **Two bars per phase:**

$$I = 2\left(\frac{b \bullet h3}{12} + S \bullet d^2\right)$$

$$\frac{I}{v} = \frac{2\left(\frac{b \bullet h^3}{12} + S \bullet d^2\right)}{1.5 \bullet h}$$

S	:	cross section of one bar (in cm²)

xx': perpendicular to the plane of vibration

Check:

η [ ] < η Bars Cu or Al [ ] (in daN/cm²)

Busbar calculation

Choose your cross-section **S**, linear mass **m**, modulus of inertia **I/v**, moment of inertia **I** for the bars defined below:

Busbar dimensions (mm)											
			100 x 10	80 x 10	80 x 6	80 x 5	80 x 3	50 x 10	50 x 8	50 x 6	50 x 5
Arrangement*	S	cm^2	10	8	4.8	4	2.4	5	4	3	2.5
	m	Cu	0.089	0.071	0.043	0.036	0.021	0.044	0.036	0.027	0.022
	linear mass	kg/cm	0.027	0.022	0.013	0.011	0.006	0.014	0.011	0.008	0.007
	I	cm^4	0.83	0.66	0.144	0.083	0.018	0.416	0.213	0.09	0.05
	I/v	cm^3	1.66	1.33	0.48	0.33	0.12	0.83	0.53	0.3	0.2
	I	cm^4	83.33	42.66	25.6	21.33	12.8	10.41	8.33	6.25	5.2
	I/v	cm^3	16.66	10.66	6.4	5.33	3.2	4.16	3.33	2.5	2.08
	I	cm^4	21.66	17.33	3.74	2.16	0.47	10.83	5.54	2.34	1.35
	I/v	cm^3	14.45	11.55	4.16	2.88	1.04	7.22	4.62	2.6	1.8
	I	cm^4	166.66	85.33	51.2	42.66	25.6	20.83	16.66	12.5	10.41
	I/v	cm^3	33.33	21.33	12.8	10.66	6.4	8.33	6.66	5	4.16
	I	cm^4	82.5	66	14.25	8.25	1.78	41.25	21.12	8.91	5.16
	I/v	cm^3	33	26.4	9.5	6.6	2.38	16.5	10.56	5.94	4.13
	I	cm^4	250	128	76.8	64	38.4	31.25	25	18.75	15.62
	I/v	cm^3	50	32	19.2	16	9.6	12.5	10	7.5	6.25

***arrangement:** cross-section in a perpendicular plane to the busbars (2 phases are shown)*

Intrinsic resonant frequency

The intrinsic frequencies **to avoid** for the busbars subjectes to a 50 Hz current are frequencies of around 50 and 100 Hz.
This intrinsic frequency is given by the equation:

$$f = 112 \sqrt{\frac{E \cdot I}{m \cdot l^4}}$$

Check that the chosen busbars will not resonate.

f	:	resonant frequency in Hz	
E	:	modulus of elasticity: for copper = $1.3 \cdot 10^6$ daN/cm² for aluminium A5/L = $0.67 \cdot 10^6$ daN/cm²	
m	:	linear mass of the busbar (choose the value on the table above)	**kg/cm**
l	:	length between 2 supports or bushings	**cm**
I	:	moment of inertia of the busbar cross-section relative to the axis x'x, perpendicular to the vibrating plane	**cm⁴**

(see formula previously explained or choose the value in the table above)

giving **f =** ______ **Hz**

We **must check** that this frequency for 50Hz: is outside of the values that must be avoided, in other words between 42 and 58and 80 and 115 Hz.

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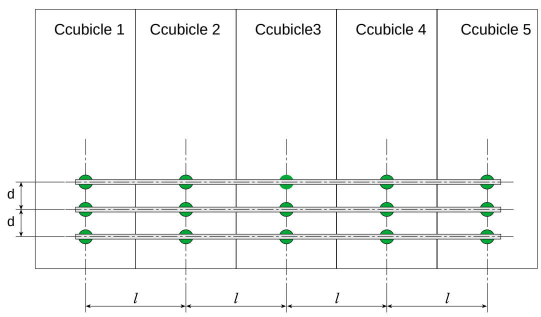
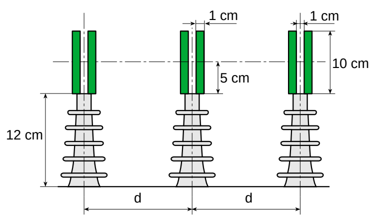
Busbar calculation example

Here is a busbar calculation to check.





Exercise data

■ *Consider a switchboard comprised of at least 5 MV cubicles. Each cubicle has 3 insulators(1 per phase). Busbars comprising 2 bars per phase, inter-connect the cubicles electrically.*

Busbar characteristics to check:

S	:	busbar cross-section (10 •1)	*10*	**cm²**
d	:	phase to phase distance	*18*	**cm**
l	:	distance between insulators on the same phase	*70*	**cm**
θ_n	:	ambient température	*40*	**°C**
(θ - θ_n)	:	permissible **temperature rise** (90-40=50)	*50*	**°C**
profile	:	flat		
material	:	busbars in copper 1/4 hard, with a permissible strain η = 1 200 daN/cm²		
arrangement:		edge-mounted		
number of busbar(s) per phase:			*2*	

■ *The busbars must be able to withstand a rated current* ***Ir = 2,500 A*** *on a permanent basis and a short-time withstand current* ***I_k = 31,500 A r m s.*** *for a time of* ***t_k = 3 seconds.***

■ *Rated frequency* ***fr = 50 Hz***

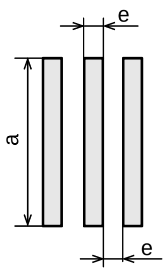
■ *Other characteristics:*

☐ *parts in contact with the busbars can withstand a maximum temperature of* ***θ max = 100°C***

☐ *the supports used have a bending resistance of* ***F' = 1 000 daN***

Busbar calculation

Let's check the thermal withstand of the busbars!



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For the rated current (Ir)

The MELSON & BOTH equation allows us to define the permissible current in the conductor:

$$I = K \cdot \frac{24.9\,(\theta - \theta_n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}\,[1 + \alpha\,(\theta - 20)]}}$$

with:

I	:	permissible current expressed in amperes (A)		
θ_n	:	ambient temperature	*40*	**°C**
(θ - θ_n)	:	permissible temperature rise*	*50*	**°C**
S	:	busbar cross-section	*10*	**cm^2**
p	:	busbar perimeter	*22*	**cm**
ρ_{20}	:	resistivity of the conductor at 20°C		
		copper:	*1.83 μΩ cm*	
α	:	temperature coefficient for the resistivity:	*0.004*	
K	:	condition coefficient *product of 6 coefficients (k1, k2, k3, k4, k5, k6), described below*		

*(see table V in standard CEI 60 694 pages 22 and 23)

Definition of coefficients k1, 2, 3, 4, 5, 6:

■ **Coefficient k1** is a function of the number of bar strips per phase for:
- □ 1 bar (k1 = 1)
- □ 2 or 3 bars, see table below:

	e / a								
	0.05	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
number of bars per phase					**k1**				
2	1.63	1.73	1.76	1.80	1.83	1.85	1.87	1.89	1.91
3	2.40	2.45	2.50	2.55	2.60	2.63	2.65	2.68	2.70

In our case:

e/a =	*0.1*
number of bars per phase =	*2*
giving k1 =	*1.80*

Busbar calculation

■ **Coefficient k2** is a function of the surface condition of the bars:

□ bare:	k2 = *1*
□ painted:	k2 = 1.15

■ **Coefficient k3** is a function of the busbar position:

□ edge-mounted busbars:	k3 = *1*
□ 1 bar flat-mounted:	k3 = 0.95
□ several flat-mounted bars:	k3 = 0.75

■ **Coefficient k4** is a function of where the bars are installed:

□ calm indoor atmosphere:	k4 = 1
□ calm outdoor atmosphere:	k4 = 1.2
□ bars in non-ventilated ducting:	k4 = *0.80*

■ **Coefficient k5** is a function of the artificial ventilation:

□ without artificial ventilation: k5 = *1*

□ cases with ventilation must be treated on a case by case basis and then validated by testing.

■ **Coefficient k6** is a function of the type of current:

□ for alternatif current at a frequency of 60 Hz, k6 is a function of the number of busbars **n** per phase and of their spacing.

The value of k6 for a spacing equal to the thickness of the busbars:

n	1	*2*	3
k6	1	*1*	0.98

In our case:

n = *2* **giving k6 =** *1*

In fact, we have:

$$k = 1.80 \cdot 1 \cdot 1 \cdot 0.8 \cdot 1 \cdot 1 = 1.44$$

$$I = 1.44 \cdot \frac{24.9(90 - 40)^{0.61} \cdot 10^{0.5} \cdot 22^{0.39}}{\sqrt{1.83\,[1 + 0.004(90 - 20)]}}$$

$$I = K \cdot \frac{24.9(\theta - \theta n)^{0.61} \cdot S^{0.5} \cdot p^{0.39}}{\sqrt{\rho_{20}[1 + \alpha(\theta - 20)]}}$$

I = *2 689* **A**

The chosen solution: *2* *busbars of* *10 • 1* *cm per phase is appropriate:*

Ir < I *either* ***2 500 A < 2 689 A***

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Busbar calculation

For the short-time withstand current (I_{th})

■ we assume that, for the whole duration (3 seconds) :

□ all the heat given off is used to increase the temperature of the conductor

□ the effect of radiation is negligible.

The equation below can be used to calculate the temperature rise due to short-circuit:

$$\Delta\theta_{cc} = \frac{0.24 \bullet \rho_{20} \bullet I_{th}^2 \bullet t_k}{(n \bullet S)^2 \bullet c \bullet \delta}$$

with:

c	:	specific heat of the metal		
		copper:	***0.091 kcal / daN°C***	
S	:	is the cross section expressed in cm²	*10*	**cm²**
n	:	number of bars per phase	*2*	
I_{th}	:	is the short-time withstand current *(rms. value of the maximum short-circuit current)*	*31 500*	**A rms.**
t_k	:	short-time withstand current duration (1 to 3 secs)	*3*	**in secs**
δ	:	density of the metal		
		copper:	***8.9 g/cm³***	
ρ_{20}	:	resistivity of the conductor at 20°C		
		copper:	***1.83 µΩ cm***	
(θ - θ_n)	:	permissible temperature rise	*50*	**°C**

□ The temperature rise due to the short circuit is:

$$\Delta\theta_{cc} = \frac{0.24 \bullet 1.83 \; 10^{-6} \bullet (31\,500)^2 \bullet 3}{(2 \bullet 10)^2 \bullet 0.091 \bullet 8.9}$$

$\Delta\theta_{cc}$ = *4* °C

The temperature θ_t of the conductor after short-circuit will be:

$$\theta t = \theta n + (\theta - \theta n) + \Delta\theta_{cc}$$

$$= 40 + 50 + 4$$

$$= 94 \text{ °C}$$

for I = *2 689* A *(see calculation in the previous pages)*

Calculation of θt must be looked at in more detail because the required busbars have to withstand Ir = 2 500 A at most and not 2 689 A.

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Busbar calculation

■ ***Let us fine tune the calculation for θ_t for I_r = 2 500 A***
(rated current for the busbars)

□ *the MELSON & BOTH equation (cf: page 31), allows us to deduce the following:*

$$I = constant \cdot (\theta - \theta_n)^{0.61} \text{ et}$$

$$I_r = constant \cdot (\Delta_\theta)^{0.61}$$

$$\text{therefore } \frac{I}{I_r} = \left(\frac{(\theta - \theta_n)}{(\Delta\theta)}\right)^{0.61}$$

$$\frac{2\,689}{2\,500} = \left(\frac{50}{(\Delta\theta)}\right)^{0.61}$$

$$\frac{50}{\Delta\theta} = \left(\frac{2\,689}{2\,500}\right)^{\frac{1}{0.61}}$$

$$\frac{50}{\Delta\theta} = 1.126$$

$$\boxed{\Delta\theta = 44.3\ °C}$$

□ *temperature θ_t of the conductor after short-circuit, for a rated current I_r = 2 500 A is:*

$$\theta_t = \theta_n + \Delta\theta + \Delta\theta_{cc}$$

$$= \boxed{40} + \boxed{44.3} + \boxed{4}$$

$$= \boxed{88.3}\ °C \text{ for } I_r = 2\,500\text{ A}$$

The busbars chosen are suitable because:

$$\boxed{\theta_t = 88.3\ °C \text{ is less than } \theta_{max} = 100\ °C}$$

(θ_{max} = maximum temperature that can be withstood by the parts in contact with the busbars).

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Busbar calculation

Let's check the electrodynamic withstand of the busbars.

Forces between parallel-mounted conductors

Electrodynamic forces due to the short-circuit current are given by the equation:

$$F_1 = 2 \frac{l}{d} \cdot Idyn^2 \cdot 10^{-8}$$

(see drawing 1 at the start of the calculation example)

l	:	distance between insulators in the same phase	*70*	cm
d	:	phase to phase distance	*18*	cm
k	:	*2.5* for 50 Hz according to IEC		
I_{dyn}	:	peak value of short-circuit current		

$= k \cdot I_{th}$
$= 2.5 \cdot 31\,500$
$=$ *78 750* A

$F_1 = 2 \cdot (70/18) \cdot 78\,750^2 \cdot 10^{-8} =$ *482.3* daN

Forces at the head of the supports or busducts

Equation to calculate forces on a support :

$$F = F_1 \cdot \frac{H + h}{H}$$

with

F	:	force expressed in daN		
H	:	insulator height	*12*	cm
h	:	distance from the head of the insulator to the busbar centre of gravity	*5*	cm

Calculating a force if there are N supports

■ The force **F** absorbed by each support is at most equal to the force **F_1** that is calculated multiplied by a coefficient **k_n** which varies according to the total number **N** of equi-distant supports that are installed.

□ number of supports *≥5* **= N**

□ we know **N**, let us define **k_n** using the table below:

N	2	3	4	≥ 5
k_n	0.5	1.25	1.10	*1,14*

giving F = *683* (F1)• *1.14* (k_n) = *778* **daN**

The supports used have a bending resistance
F' = 1 000 daN** calculated force **F = 778 daN.

The solution is OK

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Busbar calculation

Mechanical strength of the busbars

Assuming that the ends of the bars are sealed, they are subjected to a bending moment whose resultant strain is:

$$\eta = \frac{F_1 \cdot l}{12} \cdot \frac{v}{I}$$

with

η	:	is the **resultant strain in daN/cm²**		
l	:	distance between insulators in the same phase	70	cm
I/v	:	is the modulus of inertia of a busbar or of a set of busbars *(value chosen in the table below)*	14.45	cm³

$$\eta = \frac{482.3 \cdot 70}{12} \cdot \frac{1}{14.45}$$

$$\eta = 195 \ daN / cm^2$$

*The calculated resultant strain (η = **195 daN / cm²**) is less than the permissible strain for the copper busbars 1/4 hard (**1200 daN / cm²**) :*

The solution is OK

Busbar dimensions (mm)

			100 x 10
Arrangement	S	cm²	10
	m	Cu	0.089
	daN/cm	A5/L	0.027
	I	cm⁴	0,83
	I/v	cm³	1.66
	I	cm⁴	83.33
	I/v	cm³	16.66
	I	cm⁴	*21.66*
	I/v	cm³	*14.45*
	I	cm⁴	166.66
	I/v	cm³	33.33
	I	cm⁴	82.5
	I/v	cm³	33
	I	cm⁴	250
	I/v	cm³	50

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Let us check that the chosen busbars do not resonate.

Inherent resonant frequency

The inherent resonant frequencies to avoid for busbars subjected to a current at 50 Hz are frequencies of around 50 and 100 Hz.
This inherent resonant frequency is given by the equation:

$$f = 112\sqrt{\frac{E \cdot I}{m \cdot l^4}}$$

f	:	frequency of resonance in Hz		
E	:	modulus of elasticity for copper =	$1.3 \cdot 10^6$ daN/cm²	
m	:	linear mass of the bar	0.089	**daN/cm**
l	:	length between 2 supports or busducts	70	**cm**
I	:	moment of inertia of the busbar section relative to the axis x'x perpendicular to the vibrating plane	21.66	**cm⁴**

(choose m and I on the table on the previous page)

$$f = 112\sqrt{\left(\frac{1.3 \cdot 10^6 \cdot 21.66}{0.089 \cdot 70^4}\right)}$$

***f* = 406 Hz**

***f** is outside of the values that have to be avoided, in other words 42 to 58 Hz and 80 to 115 Hz:*

The solution is OK

In conclusion

The busbars chosen, i.e. 2 bars of 10 • 1 cm per phase, are suitable for an Ir = 2 500 A and Ith = 31.5 kA 3 sec.

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