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Tripolar, medium voltage disconnector with earthing switch

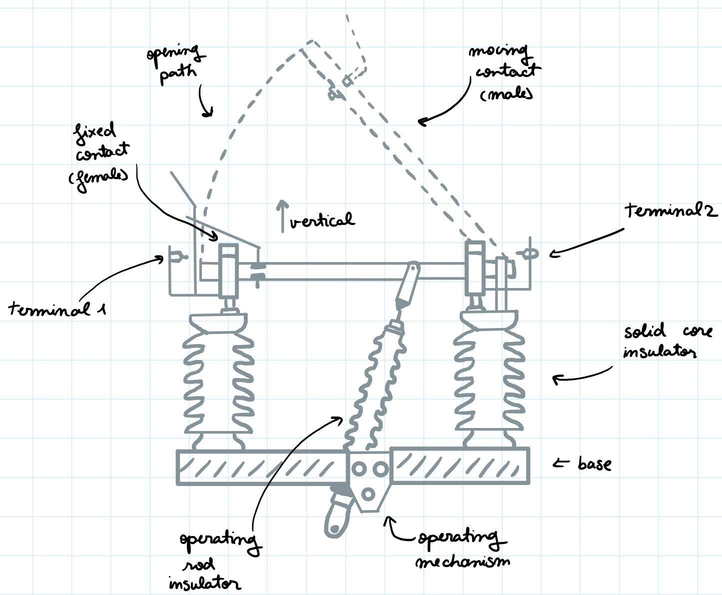
Introduction

→ Disconnector

Def: type of switching device with visible contacts, used to close & open off-load circuits, used to ensure that an electrical circuit is completely de-energized for service or maintenance.

Usage & main purposes:
- high-voltage disconnectors are used in electrical substations to allow isolation of electrical substations to allow isolation for apparatus such as circuit breakers, transformers & transmission lines for maintenance.
- usually not intended for normal control of the circuit, but only for safety isolation. Unlike load switches & circuit breakers, the disconnector lacks a mechanism for suppresion of electric arcs which occur when conductors carrying high currents are mechanically interrupted.
- off-load devices with very low breaking capacity, intended to be opened only after the current has been interrupted by some other control device.
- often found in electrical distribution & industrial applications, where machinery must have its source of driving power removed for adjustment or repair.
- can be operated manually / by a motor & may be paired with an earthing switch to ground the portion that has been isolated from the system for ensuring the safety of equipment & the personnel working on it.

Components:



→ base - allows for the disconnector to be mounted / installed easily; its role is to sustain all the other components, made of steel;

→ fixed contact (female) + moving contact (male) - effective connection of 2 circuits, made of copper (material with high conductivity), represent the point where the disconnector makes / breaks the electrical circuit;

→ solid core insulators - made of an insulating material, role to separate the electric potential of the line from that of the base, which is grounded;

→ operating rod insulator - used to actuate (make / break) the disconnector (usually an electric motor is used), made of an insulating material;

→ terminals - used to connect the disconnector in the electric circuit (mainly with screw & nuts);

→ operating rod insulator – used to actuate (make / break) the disconnector (usually an electric motor is used), made of an insulating material;
→ terminals – used to connect the disconnector in the electric circuit (mainly with screw & nuts);
→ operating mechanism – allows for the moving contact & the operating rod insulator to be moved by the operator (manual / motor mechanism).

Chapters:

I Dimensioning the insulation components of the disconnector

II Dimensioning the current bars

III Computation of the electric contact pressure

IV Computation of the thermal stress on the bus bars & electric contacts

V Computation of electrodynamic forces on bus bars

VI Verification of the electric contacts in nominal & short circuit functioning of the disconnector

Project objectives

design & determine the main parameters for a tripolar, medium voltage disconnector with earthing switch with the following nominal parameters:

→ rated working voltage: $U_n = 10\ kV$
→ rated thermal current: $i_n = 900A$
→ rated short time current (for 1s): $i_{t1s} = 15\ kA$
→ rated dynamic current: $i_d = 38\ kA$
→ dielectric withstand test between earth switch & fixed contact at 50 Hz: $U_1 = 45\ kV$
→ ——— poles at 50 Hz: $U_2 = 35\ kV$
→ lighting impulse voltage test between earth switch & fixed: $U_3 = 85\ kV$
→ ——— poles: $U_4 = 75\ kV$
→ safety factor: $k_s = 1{,}2$

(I) Dimensioning the insulation system:

(a) compute the air distance, in open position, between movable contact & fixed contact

- nominal grid frequency (50 Hz): $\boxed{a_1 = \frac{k_s \cdot \sqrt{2}\, U_1 - 19{,}8}{4{,}45}} = \frac{1{,}2 \cdot \sqrt{2} \cdot 45 - 19{,}8}{4{,}45} = 12{,}6\ cm$

- lighting impulse: $\boxed{a_3 = \frac{k_s \cdot U_3 - 45}{5{,}7}} = \frac{1{,}2 \cdot 85 - 45}{5{,}7} = 10\ cm$

(b) compute the air distance, in open position, between disconnector's poles:

- nominal grid efficiency (50 Hz): $\boxed{a_2 = \frac{k_s \cdot \sqrt{2} \cdot U_3 - 19{,}8}{4{,}45}} = \frac{1{,}2 \cdot \sqrt{2} \cdot 35 - 19{,}8}{4{,}45} = 8{,}85\ cm$

- lighting impulse: $\boxed{a_4 = \frac{k_s \cdot U_3 - 45}{\ }} = \frac{1{,}2 \cdot 75 - 45}{\ } = 7{,}9\ cm$

- nominal grid efficiency (50 Hz): $a_2 = \frac{\ldots}{4{,}45} = \frac{\ldots}{4{,}45} = 8{,}85\ cm$
- lighting impulse : $\boxed{a_4 = \frac{K_S \cdot U_4 - 45}{5{,}7}} = \frac{1{,}2 \cdot 75 - 45}{5{,}7} = 7{,}9\ cm$

ⓒ compute the length of the creepage distance on the insulator:

- nominal grid efficiency (50 Hz): $\boxed{a'_2 = \frac{K_S \cdot \sqrt{2} \cdot U_2 - 20}{3{,}35}} = \frac{1{,}2 \cdot \sqrt{2} \cdot 35 - 20}{3{,}35} = 11{,}75\ cm$
- lighting impulse: $\boxed{a'_4 = \frac{K_S \cdot U_4 - 60}{5{,}2}} = \frac{1{,}2 \cdot 75 - 60}{5{,}2} = 5{,}75\ cm$

Between the computed values, the higher one is chosen. In order to have the air distance measured in cm, in each equation the voltages will be expressed in kV.

Ⅱ Dimensioning the current (live) parts of the disconnector:

The live part of the disconnector is made of 2 components :

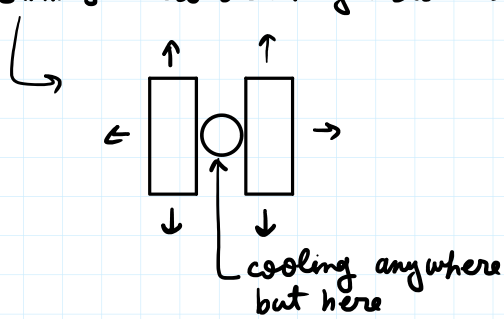
- fixed contact (female)
- mobile contact (male) = 2 bus bars mounted in parallel

The cross section of the fixed contact & bus bars can be det. in the following manner:

$$\boxed{A_B = \frac{i_n}{J}}$$

$$\boxed{A_C = 1{,}25 \cdot \frac{i_n}{2J}}$$

$A_B\ [mm^2]$ = cross section of the fixed contact
$i_n\ [A]$ = rated thermal current of the disconnector
$J\ [A/mm^2]$ = current density at full load current
$A_C\ [mm^2]$ = cross section of 1 bus bar



If we consider a current density $J = 3\ A/mm^2$ we obtain:

$A_B = \frac{i_n}{J} = \frac{900}{3} = 300\ mm^2 \Rightarrow \begin{matrix} x_B = 10\ mm \\ y_B = 30\ mm \end{matrix} \Big| \rightarrow 10\ mm \times 30\ mm$ (we choose a bus bar with these dimensions)

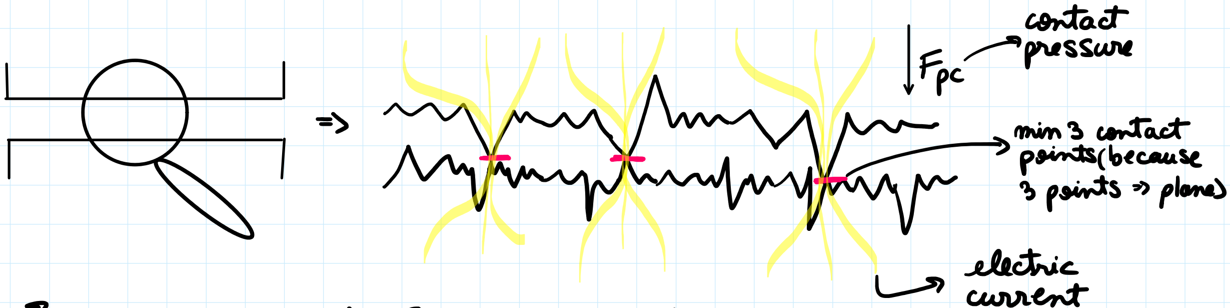
$A_C = 1{,}25 \cdot \frac{i_n}{2J} = 1{,}25 \cdot \frac{900}{2 \cdot 3} = 187{,}5\ mm^2 \Rightarrow \begin{matrix} x_C = 10\ mm \\ y_C = 20\ mm \end{matrix} \Big| \Rightarrow 10\ mm \times 20\ mm$ (we choose a bus bar with these dimensions)

When we choose the standardized busbars for the mobile & fixed contacts, we choose dimensions which are multiples of 4 / 5.

III Computing the force exerted between contacts:

For the proposed disconnector which needs to be dimensioned, the fixed contact can be realised of silvered copper.

The force exerted upon the contacts is important, regarding the thermal stability & stress exerted upon the electrical contacts. If the force exerted upon the electrical contacts is high, the electrical resistance of the contacts is low as is the temperature rise. If the force exerted between the contacts is low, the electrical resistance of the contacts is high & the temperature rise will also be high.



$F_{pc} \nearrow \Rightarrow$ no. of micropoints $\nearrow$ $\Rightarrow$ resistivity $\downarrow$
$A_{pc} \nearrow$
$J \downarrow$ (Joule-Lenz losses $\downarrow$ because the heating is reduced)

For the proper functioning of the disconnector, we consider a specific force between the moving contact & fixed contact $F_0 = (15...25)\ gf/A$.

We take: $F_0 = 20\ gf/A$

The minimal force exerted between contacts can be det. with the following expression:

$$\boxed{F_1 = 3{,}5 \cdot F_0 \cdot \frac{i_m}{2}} = 3{,}5 \cdot 20 \cdot \frac{900}{2} = 31500 \cdot 10^{-3} = 31{,}5\ Kgf$$

$1\ Kgf = 9{,}8\ N$

$\Rightarrow F_1 = 308{,}7\ N$ - which is the minimal force exerted between the el. contacts in order to avoid the welding

Theoretical notions

It is presumed that the bus bar of the disconnector has a constant cross section & it's made of an electrical conductive material with the electrical resistivity $\rho\ [\Omega m]$ with the cross section $A\ [m^2]$, the electric current $i\ [A]$ flows through the cross section. If we consider the skin effect negligible, the current density throughout the conductor is:

$$\boxed{J = \frac{i}{A}} \quad A/mm^2$$

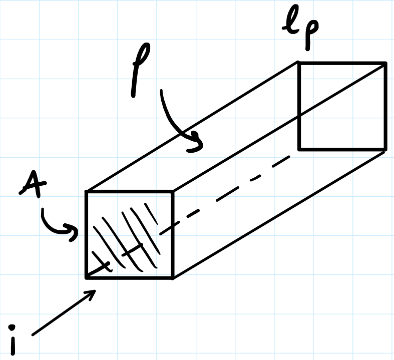
To det. the thermal regime of the bus bars, it is required to consider the resistivity, an electrical property which also depends on the rise of temperature in the bus bar:

$$\boxed{\rho(\theta) = \rho_0(1 + \alpha_R \cdot \theta)}$$

$\rho(\theta)\ [\Omega m]$ = el. resistivity as a function of temperature rise
$\rho_0\ [\Omega m]$ = resistivity before heating

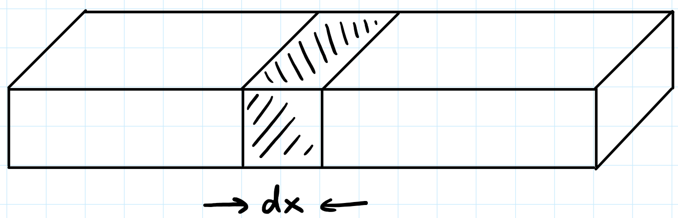
$$\boxed{\rho(\theta) = \rho_p(1 + \alpha_R \cdot \theta)}$$

$\rho(\theta)\ [\Omega m]$ = el. resistivity as a function of temperature rise
$\rho_p\ [\Omega m]$ = resistivity before heating
$\theta\ [°C]$ = rise in temperature
$\alpha_R\ [grd^{-1}]$ = temperature coeficient of the el. resistivity



$$R = \frac{\rho L}{i}$$
$$P = U \cdot i^2$$
$$i = J \cdot A$$
$$\Rightarrow P_{J\text{-}L} = \frac{\rho L}{A}(J A)^2 = \rho L J^2 A = \rho J^2 V$$

In order to write the equation which describes the thermal regime of the conductor during heating, it is required to describe the thermal energies which appears during the heating process.



The energy produced by the Joule-Lenz effect is equal to the sum of the energy accumulated in the bus bar & the energy transferred to the environment:

$$\boxed{W_{J\text{-}L} = W_{acc} + W_{env}}$$

The energy produced by Joule-Lenz effect (in the length element dx) can be described using the following formula:

$$\boxed{W_0 = p_1 A\, dx\, dt}$$
$$\boxed{p_1 = \rho J^2}$$

$p_1\ [W/m^3]$ = power density produced by J-L effect
$A\ [m^2]$ = cross section of the conductor
$dx\ [m]$ = length element
$dt\ [s]$ = time in which the energy is produced

The energy accumulated in the length element dx can be described using the following formula:

$$\boxed{W_1 = c_1 \frac{d\theta}{dt} A\, dx\, dt}$$

$c_1\ [J/m^3 K]$ = specific heat
$\frac{d\theta}{dt}$ = time variation of the temperature rise

The energy transferred to the environment can be expressed using the following relation:

$$\boxed{W_2 = \alpha\, l_p\, \theta\, dx\, dt}$$

$\alpha\ [W/m^2 grd]$ = thermal transmittance
$l_p\ [m]$ = peripheral length
$\theta\ [°C]$ = rise in temperature

Considering the above mentioned relations, the equation which describes the thermal regime of the conductor during heating is:

$$p_1 A\,dx\,dt = c_1 \frac{\partial \theta}{\partial t} A\,dx\,dt + \alpha\, l_p\, \theta\,dx\,dt$$

Considering the expression of the power density we have:

$$\rho J^2 A\,dx\,dt = c_1 \frac{\partial \theta}{\partial t} A\,dx\,dt + l_p\,\theta\,dx\,dt$$

We consider the resistivity an electrical property which also depends on the rise of temperature in the bus bar:

$$\rho_p\, 1 + \alpha_R\,\theta\, J\, A\,dx\,dt = c_1 \frac{\partial \theta}{\partial t} A\,dx\,dt + \alpha\, l_p\,\theta\,dx\,dt$$

The previous equation can also be written as:

$$\rho_p J^2 A\,dx\,dt + \rho_p\,\alpha_R\,\theta J^2 A\,dx\,dt = c_1 \frac{\partial \theta}{\partial t} A\,dx\,dt + \alpha\, l_p\,\theta\,dx\,dt$$

By simplifying the previous expression with dx & dt, we obtain:

$$\rho_p J^2 A + \rho_p \alpha_R \theta J^2 A = c_1 A \frac{d\theta}{dt} + \alpha\, l_p\,\theta \quad \equiv \quad c_1 A \frac{d\theta}{dt} + \alpha\, l_p\,\theta - \rho_p \alpha_R \theta J^2 A = \rho_p J^2 A$$

In order to obtain a unit coefficient for the derivative term, we can write the previous equation as:

$$\frac{d\theta}{dt} + \frac{\alpha\, l_p\,\theta}{c_1 A} = \frac{\rho_p \alpha_R \theta J^2}{c_1} \cdot \frac{\rho_p J^2}{c_1}$$

The final form of the differential equation is: $\boxed{\dfrac{d\theta}{dt} + \theta\left(\dfrac{\alpha\, l_p}{c_1 A} - \dfrac{\rho_p \alpha_R J^2}{c_1 A}\right) = \dfrac{\rho_p J^2}{c_1}}$

The solution of the previous equation is:

$$\boxed{\theta(t) = \theta_{max}\left(1 - e^{-\frac{t}{T}}\right)}$$

$$\boxed{\theta_{max} = \frac{\theta_{0\,max}}{1 - \alpha_R\,\theta_{0\,max}}}$$

$$\boxed{\theta = \frac{\rho_p J^2 A}{\alpha\, l_p}}\ [^\circ C]$$

$$\boxed{T = \frac{T_1 T_0}{T_1 - T_0}}\ [s] \text{ with } \boxed{T_1 = \frac{c_1}{\alpha_R \rho_p J^2}} \quad \boxed{T_0 = \frac{c_1 \cdot A}{\alpha\, l_p}}$$

$\theta_{max}\,[^\circ C]$ = temperature rise of the bus bar in steady state assuming the electrical resistivity a temperature dependent property

$T\,[s]$ = time constant

α_R = temperature coefficient for the electrical resistivity

$\theta_{0\,max}\,[^\circ C]$ = temperature rise of the bus bar in steady state assuming the el. resistivity a constant specific property

Terminology

- electric current : i [A]
- current density: J [A/m^2]
- cross section of the conductor: A [m^2]
- el. resistivity before heating: ρ_P [Ωm]
- ——— as a function of temp. rise: $\rho(\theta)$ [Ωm]
- temp. coefficient of the el. resistivity : α_R [grd^{-1}]
- temp. rise of the bus bar : θ [K]
- energy produced by J-L effect (in length element dx): $W_{J-L} = W_0$ [J]
- power density produced by J-L effect: ρ_1 [W/m^3]
- length element of bus bar: dx [m]
- energy accumulated in dx: $W_{acc} = W_1$ [J]
- specific heat: c_1 [J/m^3K]
- time variation of the temp. rise: $\frac{d\theta}{dt}$ [grd/s]
- energy transferred to the environment through dx: $W_{transf.} = W_2$ [J]
- thermal transmittance: α [$W/m^2 grd$]
- peripheral length of bus bar: l_P [m]
- temp. rise of bus bar in steady state, assuming the el. resistivity a constant property: $\theta_{0\,max}$ [K]
- ——— temp. dependent property: θ_{max} [K]
- time constants: T, T_0, T_1 [s]

IV Computation of the thermal stress on bus bars & electric contacts

ⓐ Temperature rise of the fixed contact in steady state, assuming the electrical resistivity a temperature dependent property, for the rated current, can be det. with the following expression:

$$\boxed{\theta_{max,B} = \frac{\theta_{0\,max,B}}{1-\alpha_R \cdot \theta_{0\,max,B}}} \quad \text{with} \quad \boxed{\theta_{0\,max,B} = \frac{\rho_P J^2_{B,S} A_{B,S}}{\alpha \cdot l_{P B,S}}}$$

We will consider the following constants for the computation of the temperature rise:

- resistivity of the Copper before heating: $\rho_P = 1{,}73 \cdot 10^{-8}\ \Omega m$
- temperature coefficient of the electrical resistivity of copper: $\alpha_R = 4 \cdot 10^{-3}\ grd^{-1}$
- thermal transmittance: $\alpha = 8\ W/m^2 grd$

The peripheral length of the fixed contact can be computed with the following expression:

$$\boxed{l_{P B,S} = 2(x_B + y_B)} \quad \Rightarrow l_{P B,S} = 2 \cdot (10+30) = 80 \cdot 10^{-3}\ m$$

$x_B = 10$ mm
$y_B = 30$ mm

The temperature rise of the fixed contact in steady state, assuming the electrical resistivity a constant property is:

The temperature rise of the fixed contact in steady state, assuming the electrical resistivity a constant property is:

$$\theta_{o\,max,B} = \frac{1{,}73\cdot 10^{-8}\cdot J_{B,s}^2 \cdot A_{B,s}}{8\cdot 80\cdot 10^{-3}} \Rightarrow \theta_{o\,max,B} = \frac{1{,}73\cdot 10^{-8}\cdot (3\cdot 10^6)^2\cdot 300\cdot 10^{-6}}{8\cdot 80\cdot 10^{-3}} = \frac{4671\cdot 10^{-2}}{640\cdot 10^{-3}} = 73^\circ C$$

$$\boxed{J_{B,s} = \frac{\dot{i}_m}{A_{B,s}}} = \frac{\dot{i}_m}{x_B\cdot y_B} = \frac{900}{10\cdot 30} = 3\cdot 10^6\ A/m$$

The temperature rise of the fixed contact in steady state, assuming the electrical resistivity a temperature dependent property is:

$$\theta_{max,B} = \frac{\theta_{o\,max,B}}{1-\alpha_R\,\theta_{o\,max,B}} = \frac{73}{1-4\cdot 10^{-3}\cdot 73} = \frac{73}{1-292\cdot 10^{-3}} = \frac{73}{0{,}708} = 103{,}1\ ^\circ C$$

We assume the temperature of the environment has a maximum value of $\theta_{ma} = 40^\circ C$.
The temperature of the fixed contacts in steady state has the following value:

$$\boxed{\theta_B = \theta_{ma} + \theta_{max,B}} = 40 + 103{,}1 = 143{,}1\ ^\circ C$$

(b) The temperature of the mobile contact in steady state, assuming the electrical resistivity a temperature dependent property is:

$$\boxed{\theta_{max,c} = \frac{\theta_{o\,max,c}}{1-\alpha_R\,\theta_{o\,max,c}}} \text{ with } \boxed{\theta_{o\,max,c} = \frac{\rho_p\cdot J_{c,s}^2\cdot A_{c,s}}{\alpha\cdot \ell_{p_{c,s}}}}$$

$$\boxed{\ell_{p_{c,s}} = 2(x_c+y_c)} \Rightarrow \ell_{p_{c,s}} = 2(10+20) = 60\cdot 10^{-3}\ m$$

$x_c = 10\ mm$
$y_c = 20\ mm$

$$A_{c,s} = x_c\cdot y_c = 10\cdot 20 = 2\cdot 10^{-4}\ m^2$$

$$J_{c,s} = \frac{i_m}{2A_{c,s}} = \frac{900}{2\cdot 10^{-4}\cdot 2} = 225\cdot 10^4\ A/m$$

$$\Rightarrow \theta_{o\,max,c} = \frac{1{,}73\cdot 10^{-8}\cdot (225\cdot 10^4)^2\cdot 2\cdot 10^{-4}}{8\cdot 60\cdot 10^{-3}} = \frac{1{,}73\cdot 10^{-8}\cdot 50625\cdot 10^{8}\cdot 2\cdot 10^{-4}}{480\cdot 10^{-3}} = \frac{175162{,}5\cdot 10^{-14}}{480\cdot 10^{-3}} = \simeq 36{,}5\ ^\circ C \Rightarrow$$

$$\Rightarrow \theta_{max,c} = \frac{36{,}5}{1-4\cdot 10^{-3}\cdot 36{,}5} = \frac{36{,}5}{1-146\cdot 10^{-3}} = 42{,}74\ ^\circ C$$

We assume the temperature of the environment has a maximum value of $\theta_{ma} = 40^\circ C$.
The temperature of the mobile contacts in steady state has the following value:

$$\boxed{\theta_c = \theta_{ma} + \theta_{max,c}} = 40 + 42{,}74 = 82{,}74\ ^\circ C$$

Terminology

→ current density in fixed contacts : $J_{B,s}$ [A/m]
mobile contacts : $J_{c,s}$ [A/m]

→ current density in
- fixed contacts : $J_{B,S}$ [A/m]
- mobile contacts : $J_{C,S}$ [A/m]

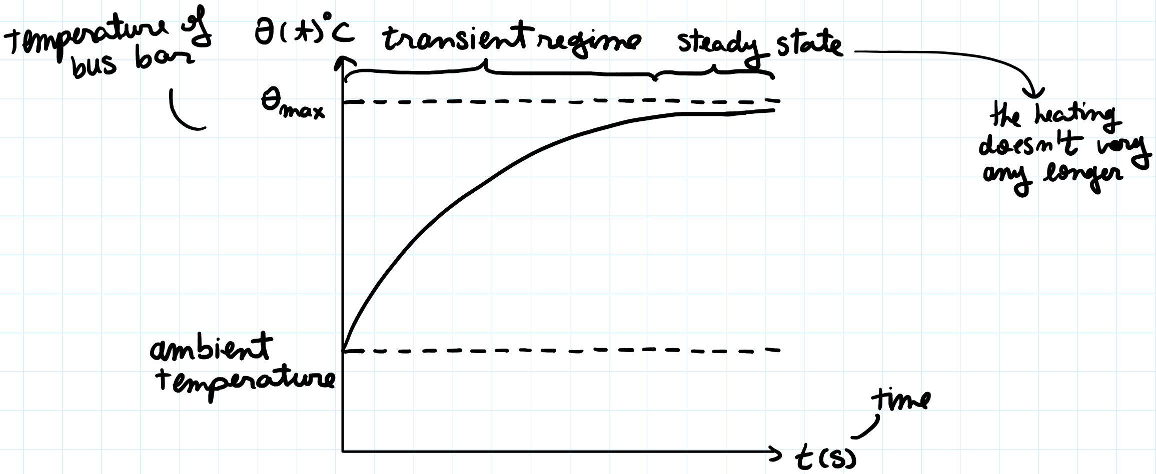
→ standardized value for the cross section of
- fixed contacts: $A_{B,S}$ [m^2]
- mobile contacts: $A_{C,S}$ [m^2]

→ peripheral length of the cross section of
- fixed contacts: $l_{p\,B,S}$ [
- mobile contacts: $l_{p\,C,S}$ [

→ Temperature rise of the
- fixed contact in steady state, assuming the electrical resistivity a
  - constant property: $\theta_{0max,B}$
  - temperature dependent property: $\theta_{max,B}$
- mobile contact / ——— /
  - constant property: $\theta_{0max,C}$
  - temp. dependent property: $\theta_{max,C}$

ⓒ thermal stress of the fixed contact for the rated short time current:

The rated short time current is the max (RMS) withstand value for the electric current (which flows in the bus bar for 1s) which the equipment can carry without damage.
The heating of the bus bars during a short-circuit can be considered, physically, an adiabatic process, without transfering heat to the environment. During a short-circuit, the value of the electric current can rise tens of times & the power dissipated can rise hundreds of times & the bus bar can't evacuate the heat produced in it.



The equation for the heating of the bus bar during a short-circuit can be expressed with the following expression:

$$\boxed{\theta_{sc} = \left(\theta_2 + \frac{1}{\bar{\alpha}_R}\right)\left(e^{\frac{K_a \bar{\alpha}_R \rho_p J_{ma}^2}{c_{01}}} - 1\right)}$$

The maximum current density in the bus bars during a short circuit is:

$$\boxed{J_{ma,B} = \sqrt{\frac{c_{01}}{K_a \bar{\alpha}_R \rho_p t}} \cdot \ln \frac{1 + \bar{\alpha}_R(\theta_B + \theta_{SC})}{1 + \bar{\alpha}_R \theta_B}}$$

We will consider the following constants for the computation

→ specific heat for the copper Cu at 0°C : $c_{01} = 3.76 \cdot 10^6$ J/m^3 grd

→ skin effect coefficient: $K_a = 1{,}1$

→ medium temperature coefficient of the electrical resistivity of copper: $\bar{\alpha}_R = 4{,}1 \cdot 10^{-3}$

→ resistivity of the copper before heating (at 0°C): $\rho_0 = 1{,}68 \cdot 10^{-8}\ \Omega m$

→ temperature of the fixed contacts c in steady state, for the rated currents: $\theta_B = \theta_{ma} + \theta_{max}$

→ maximum permissible temperature of the fixed contacts during a short circuit: $\theta_{sc} + \theta_B = 200°C$

$$J_{ma,B} = \sqrt{\frac{3{,}76 \cdot 10^6}{1{,}1 \cdot 4{,}1 \cdot 10^{-3} \cdot 1{,}68 \cdot 10^{-8} \cdot 1} \ln \frac{1 + 4{,}1 \cdot 10^{-3} \cdot 200}{1 + 4{,}1 \cdot 10^{-3} \cdot 143{,}1}} = 0{,}82 \cdot 10^8 = 82 \cdot 10^6\ A/m^2$$

The maximum withstand current which can flow through the fixed contact during a short circuit, without exceeding the maximum permissible temperature (200°C) is:

$$\boxed{i_{ma,B} = A_{B,s} \cdot J_{ma,B} \cdot \sqrt{t}} = 200 \cdot 10^{-6} \cdot 82 \cdot 10^8 \sqrt{1} = 16400\ A = 16{,}4\ kA > 15\ kA \quad T \text{ (condition fulfilled)}$$

(d) thermal stress of the mobile contact for the rated short time current:

The maximum current density in the bus bars during a short circuit is:

$$\boxed{J_{ma,c} = \sqrt{\frac{c_{01}}{K_a \bar{\alpha}_R \rho_0 t} \cdot \ln \frac{1 + \bar{\alpha}_R(\theta_B + \theta_{sc})}{1 + \bar{\alpha}_R \theta_c}}} = \sqrt{\frac{3{,}76 \cdot 10^6}{1{,}1 \cdot 4{,}1 \cdot 10^{-3} \cdot 1{,}68 \cdot 10^{-8} \cdot 1} \cdot \ln \frac{1 + 4{,}1 \cdot 10^{-3} \cdot 200}{1 + 4{,}1 \cdot 10^{-3} \cdot 82{,}74}} = 1{,}21 \cdot 10^8\ A/m^2$$

The maximum withstand current which can flow through the fixed contact during a short circuit, without exceeding the maximum permissible temperature (200°C) is:

$$\boxed{i_{ma,c} = A_{c,s} \cdot J_{ma,c} \cdot \sqrt{t}} = 200 \cdot 10^{-6} \cdot 121 \cdot 10^6 \cdot \sqrt{1} = 24200\ A = 24{,}2\ kA > 7{,}5\ kA \quad T \text{ (condition fulfilled)}$$

Project's Chapters

It is required to design & determine the main parameters for a tripolar, medium voltage disconnector with earthing switch with the following rated parameters:

→ rated working voltage: u_n [kV]
→ rated thermal current: i_n [A]
→ rated short time current (for 1s): i_{t1s} [kA]
→ rated dynamic current: i_d [kA] = 38 kA
→ dielectric withstand test between earth switch & fixed contact at 50Hz: u_1 [kV]
→ dielectric withstand test between poles at 50 Hz: u_2 [kV]
→ lighting impulse voltage test between earth switch & fixed contact at 50Hz: u_3 [kV]
→ lighting impulse voltage test between poles: u_4 [kV]

V) Computation of electrodynamic forces on bus bars:

Def: forces which appear between 2 close conductors when current passes through them.

If the current has the same direction, then the force will be one of attraction, otherwise, there will appear a repulsive one. Also F depends on i^2 so if the current will ↗ 10 times, the force will ↗ 100 times. The longer the distance between the bus bars a[m], the smaller the force becomes.

The electrodynamic force exerted between 2 bus bars with rectangular section has the following expression:

$$\boxed{F_{eldin} = \frac{\mu_0}{2\pi} i_1 i_2 \frac{l}{a} \varphi(f)} \quad [N]$$

$\mu_0 = 4\pi \cdot 10^{-7}$ H/m = absolute vacuum permeability
i_1, i_2 [A] = electric current flowing through the busbars
l [m] = length between busbars
a [m] = distance between busbars
$\varphi(f)$ = correction factor which is dependent on the shape of the bus bars & has the following formula:

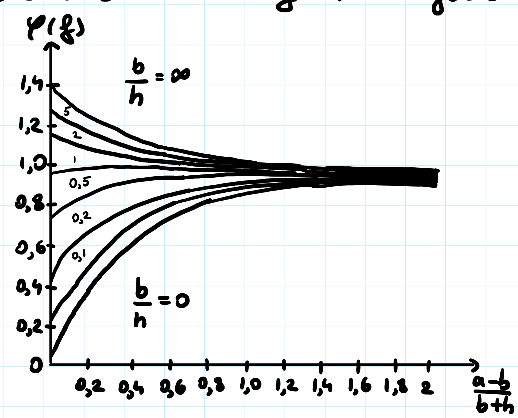
$$\boxed{\varphi(f) = \frac{a^2}{h^2}\left(\frac{2h}{a}\operatorname{arctg}\frac{h}{a} - \ln\left(a + \frac{h^2}{a^2}\right)\right)}$$

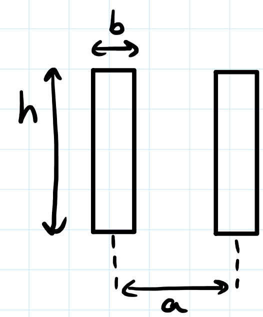
f = variable of the function & it depends on the distance between the busbars (a) & the geometric dimensions of the bus bars (x_c & y_c).

The graphical representation of the correction's function can be seen in the following figure. The correction factor can be chosen using Dwight's curves considering the 2 following notions:

$\frac{b}{h}$ which varies between 0 & ∞

$\frac{a-b}{b+h}$ which varies between 0 & 2





The electrodynamic force exerted between 2 bus bars with rectangular section has the following expression:

$$\boxed{F_{eldin} = \frac{\mu_0}{2\pi} \cdot \left(\frac{i_d}{2}\right)^2 \frac{l}{a} \varphi(f)} \quad [N]$$

i_d [A] = rated dynamic current
a [m] = distance between 2 bus bars on a single pole
l [m] = length of bus bars

The air distance in open position between the fixed & moving contact computed in the first chapter is $a_1 = 12{,}6$ cm & the length of the bus bar can be determined the following way:

If we consider the maximum relative angle between the moving contact & the fixed contact in open position to be 45°, the length of the bus bar is:

$$\boxed{\sin 45^\circ = \frac{a_1}{l}} \Rightarrow \frac{\sqrt{2}}{2} = \frac{a_1}{l} \Rightarrow l = \frac{2\cdot a_1}{\sqrt{2}} = \frac{2\cdot 12{,}6}{\sqrt{2}} = 17{,}97\ cm = 0{,}1797\ m$$

The distance between 2 bus bars (mobile contact) is:

$$\boxed{a = h + \frac{2\cdot b}{2}} \quad b = 10\ mm,\ h = 20\ mm \;\Big|\; \Rightarrow a = 20 + \frac{2\cdot 10}{2} = 30\ mm$$

Because $b = x_c$ (width of bus bars)
$h = y_c$ (height of bus bars)

$$\frac{b}{h} = \frac{10}{20} = 0{,}5$$

$$\frac{a-b}{b+h} = \frac{30-10}{10+20} = \frac{20}{30} = \frac{2}{3} = 0{,}66$$

$\Rightarrow \varphi(f) = 0{,}95$

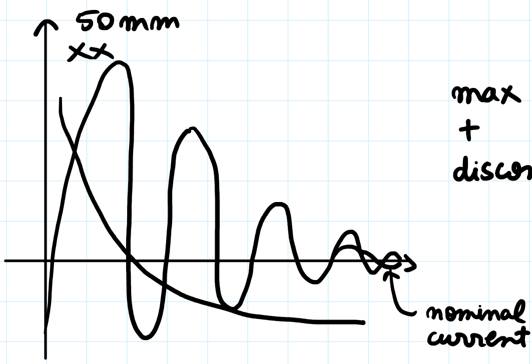
Considering the previous values, the electrodynamic force exerted between 2 bus bars (mobile contact) on a single pole is:

$$F_{eldinc} = \frac{\cancel{4\pi}^{2}\cdot 10^{-7}}{\cancel{2\pi}}\cdot\left(\frac{38\cdot 10^3}{2}\right)^2\cdot\frac{0{,}1797}{0{,}03}\cdot 0{,}9 = 2\cdot 10^{-7}\cdot\frac{1444\cdot 10^6}{4}\cdot 5{,}99\cdot 0{,}9 = 3892{,}302\cdot 10^{-1} \simeq 389{,}23\ N$$

The electrodynamic force exerted between 2 poles can be computed using the following formula:

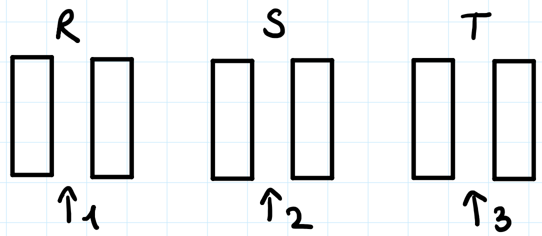
$$\boxed{F_{eldin\_p} = 1{,}615\cdot c_1\cdot i^2 = 1{,}615\cdot\frac{\mu_0}{2\pi}\cdot\frac{l}{a}\left(\frac{i_d}{\sqrt{2}}\right)^2}\quad [N] = 1{,}615\cdot\frac{\cancel{4\pi}^{2}\cdot 10^{-7}}{\cancel{2\pi}}\cdot\frac{0{,}1797}{0{,}03}\cdot\left(\frac{38\cdot 10^3}{\sqrt{2}}\right)^2 =$$

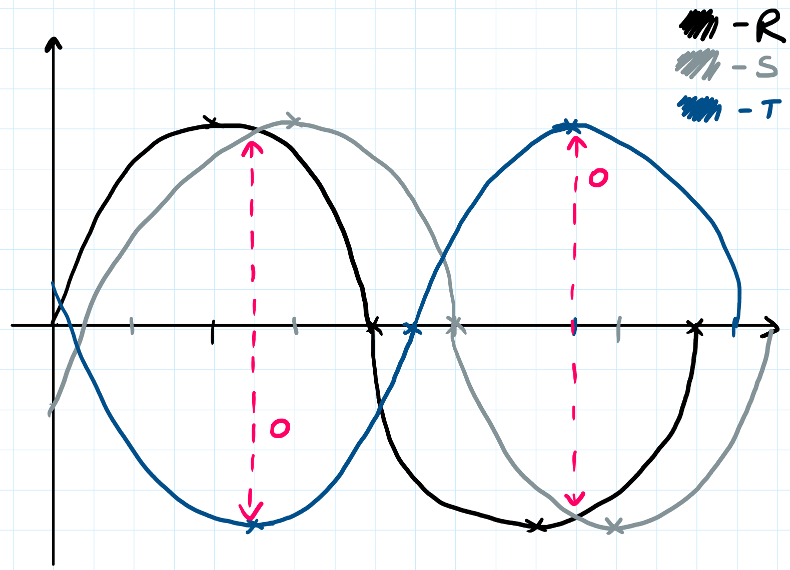
$$= 3{,}23\cdot 10^{-7}\cdot 5{,}99\cdot 722\cdot 10^6 = 13969{,}0394\cdot 10^{-1} \simeq 1396{,}9\ N$$



max value at short circuit = strike current
+
disconnector

$\Rightarrow F \nearrow\nearrow 50^2 \Rightarrow$ bus bar deformation





if R, T = negative ⇒ repulsive force

S would be the less affected set of bars because it is pushed & pulled simultaneously by R & T, but the other 2 have a larger risk of breaking because, if both R & S push T, the 3rd one will break, as the force will be greater than what it can sustain.

Considering the fact that the distance between the first & second poles is equal to the distance between the second & the third poles, the attraction & repulsion forces can be computed:

$F_a = 0{,}115 \cdot C_1 \cdot i^2$ = attraction force between marginal busbars

$$= 0{,}115 \cdot \frac{4\pi \cdot 10^{-7}}{2\pi} \cdot \frac{0{,}1797}{0{,}03} \cdot$$

$F_r = -1{,}615 \cdot C_1 \cdot i^2$ = repulsion force excerted between marginal bus bars

$$= -1{,}615 \cdot \frac{4\pi \cdot 10^{-7}}{2\pi} \cdot \frac{0{,}1797}{0{,}03} \cdot$$

The repulsion force has a higher value than the attraction force & has a maximum value:

$$F_{eldin\_p} = 1{,}615 \cdot C_1 \cdot i^2 = 1{,}615 \cdot \frac{\mu_0}{2\pi} \cdot \frac{l}{a} \cdot \left(\frac{i_d}{\sqrt{2}}\right)^2$$

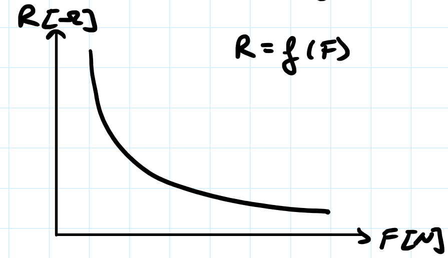
(VI) Verification of the electric contacts in short circuit functioning of the disconnectors

(a) verification of the electric contacts in short circuit functioning of the disconnector

During a short circuit, the electrodynamic force exerted between mobile contact's bus bars increase the pressure force excerted between contacts. During a short circuit, the current increases tens of times & the electrodynamic force exerted between the bus bars increases hundreds of times. Considering this, the force pressure force exerted between contacts. During a short circuit, the current increases tens of times & the electrodynamic force exerted between the bus bars increases hundreds of times. Considering this, the force exerted between contacts increases & the electrical resistance of contacts decreases. The electrical resistance of the contact can be computed using the following expression:

$$\boxed{R = c \cdot F^{-m}} \quad \text{where} \quad \boxed{F = F_1 + \frac{F_{eldin\,c}}{2} + \frac{F_{eldin\,p}}{4}}$$

the previous expression conducts approximative results because Feldin c & Feldin p are peak values of vectors with phase shifts.



We consider: $c = 84 \cdot 10^{-6}$

$m = 1$ = material coefficient

By replacing the above mentioned values in the previous equation, we have:

$$F \simeq 308{,}7 + \frac{389{,}23}{2} + \frac{1396{,}9}{4} = 308{,}7 + 194{,}615 + 349{,}225 = 852{,}54\ N$$

which is the pressure force exerted between contacts during a short circuit.

$$R = 84 \cdot 10^{-6} \cdot 847{,}08^{-1} = \frac{84 \cdot 10^{-6}}{847{,}08} \simeq 0{,}1\ \mu\Omega$$

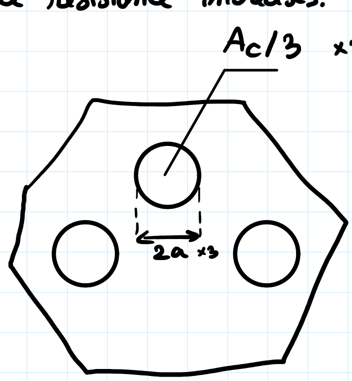
The number of microscopic spots is:

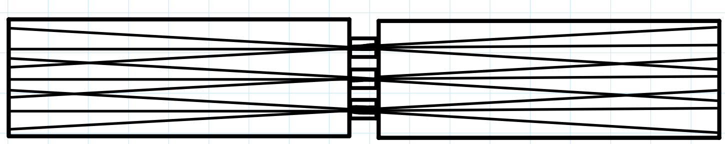
$$\boxed{m = 2 \cdot 10^{-5} \cdot H^{0{,}625} \cdot F^{0{,}2}} \quad \text{where: } H = 4500\ \frac{kgf}{cm^2} = 4{,}41 \cdot 10^{8}\ N/m^2 = \text{material hardness}$$

$F[N]$ = pressure force exerted between contacts

$$m = 2 \cdot 10^{-5} \cdot (4{,}41 \cdot 10^{8})^{0{,}625} \cdot (847{,}08)^{0{,}2} = 2 \cdot 10^{-5} \cdot 2{,}527 \cdot 10^{5} \cdot 3{,}851 = 19{,}46 \simeq 19$$ microscopic spots for the electrical contact

In the following figure, the electric contact is made of 3 microscopic spots. The number of microscopic spots depends on the material hardness & the pressure between the two contacts. If the pressure force exerted between contacts increases, the number of microscopic spots also increases & thus, the electrical resistance decreases. If the chosen material has a higher hardness, considering the same pressure force exerted between contacts, the number of microscopic spots of the contact decreases & thus, the electrical resistance increases.





$F \nearrow \Rightarrow m \nearrow \Rightarrow R \searrow$

$++$ hardness $\Rightarrow m \searrow \Rightarrow R \nearrow$

If the microscopic spots are circular, the radius can be computed with the following expression:

$$\boxed{a = \sqrt{\frac{F}{n \pi \xi H}}}$$

with $\xi = 0,6 =$ Prandl's coefficient
$H =$ material hardness $[N/m^2]$
$n =$ no. of microscopic spots

$$a = \sqrt{\frac{847,08}{19 \cdot \pi \cdot 2,6 \cdot 4,41 \cdot 10^8}} = \sqrt{\frac{847,08}{157,86 \cdot 10^8}} = 2,316 \cdot 10^{-4} \, m = 0,2316 \, mm$$

The area of 1 microscopic spot can be computed with the following expression:

$$\boxed{A_{pc} = \pi a^2} = 3,14(2,316 \cdot 10^{-4})^2 = 3,14 \cdot 5,3638 \cdot 10^{-8} = 16,85 \cdot 10^{-8} \, m^2 = 0,1685 \cdot 10^{-6} \, m^2$$

The area of the entire contact can be computed by summing the areas for every microscopic spots:

$$\boxed{A_c = n \cdot A_{pc}} = 19 \cdot 0,1685 \cdot 10^{-6} = 3,2015 \cdot 10^{-6} \, m^2 \simeq 3,2 \, mm^2$$

The apparent contact area equal the common surface between the mobile contact & fixed contact, which also depends on their geometrical dimensions. We can consider that the apparent surface equals the cross section are of the mobile contact:

$$A_{app} = 5 \cdot 20 = 100 \, mm^2$$

$$\boxed{R[x] = \frac{A_c}{A_{app}}} = \frac{3,2}{100} \cdot 100 = 3,2\%$$

Considering this, the effective area of the contact is approximatively 3,2% of the apparent area of the electric contact.