ALUMINUM X COPPER IN SWITCHGEAR DESIGN
(With an idea for a new concept)

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Keywords: Substations, Optimization, Switchgear , design, reduction of costs, validation, High Power , Testing, Laboratory, Simulations, Calculations, IEC Standards, Busbar systems, Internal Arcs, Overpressures, Temperature rise, Electrodynamical stresses, Short time currents, Magnetic Fields

1) INTRODUCTION

The 3 most expensive requirements to attend in the design of switchgear, bus-bar systems and other equipment for substations are:

- the temperatures which shall not be over passed during normal operation to avoid premature ageing,
- The supportability to the overpressures caused by internal arcs with risks to persons and installations.
- The supportability to the forces on insulators and conductors produced by short circuit currents.

For example, the effects of electrodynamical forces depend on the distances between phases (D1 – Fig.1) and between supports (D2). A smaller D2 makes the system mechanically stronger but more onerous due to higher expenses with supports and mounting. Using a bus bar with a bigger cross section brings higher supportability but also higher expenses with copper or aluminum. The designer goal is to find the optimum point considering the objective to reach (cheaper, safer,.., etc…).

To find the optimal design is not an easy task because several technical and economic variables shall be considered. When manufacturers develop a product they know that, at least at the end of the process, they will need to do onerous and time consuming high power tests at a testing laboratory. Manufacturers frequently over dimension the design to avoid the risk of failures in the tests. Big international manufacturers have their own labs and repeat tests up to finding the optimal point. This cannot be done by small and medium sized manufacturers but they use each time more virtual testing simulations [1-7].

An IEC technical standard systematizing the use of simulations to replace some tests is missing. It would enable worldwide cheaper products. Most of the participants in the IEC working groups preparing IEC standards are the big manufacturers having their own laboratories. By this reason the way for the creation of this technical standard is a hard one.

The countries which would be more benefited with this standard are the ones which are not in the "developed" team. The average profile is that they do do not have solid technical standardization organizations or, the ones they have, are still focused in translating IEC standards to their languages. When they publish the translation, 4 years later, the IEC standard which originated it is not anymore updated. In despite of this, intelligent initiatives are running. One of them is in a country without testing laboratories which permitted in a formal government document the use of calculations and simulations to replace some tests. Another example is the use of simulation tools to support formal certification activities occurring in some other countries.

The objective of this paper, mainly addressed to small and medium switchgear manufacturers, is to show ideas about the of aluminum and how simulations can be used to obtain optimized products using less aluminum or copper, fewer insulators, less tests and maintaining the quality.

A test case explores a comparison between the use of aluminum or copper to attend the requirements of a specific switchgear project. The switchgear dimensions used in the test case (Figures 1 and 2) were intentionally chosen to represent a small size product. This was done to enable to asses in a small lab, if the results obtained by simulations are reliable or not if compared with the laboratory test results. Another reason for the small size model is that it emphasizes the aspects of temperature rise, electrodynamical forces and internal arc overpressures. These effects are more severe if the enclosure volume is smaller.

Within this test case an innovative solution using aluminum profile IWBC is presented and compared with the conventional solutions. In addition, Annex 2 contains test results made in a laboratory to validate simulation methods. In the next paper to be published soon we present an example of development of a new optimized aluminum LV switchgear 100 kA $_{rms}$ just using simulations.

All the calculations were done using a software tool developed by COGNITOR (download of a demo and a free book here http://www.cognitor.com.br/InfoSoftEN.pdf). Along the last 10 years, this tool is used to calculate many MV and LV switchgear already successfully submitted to laboratory type tests.

The abbreviations HV, MV and LV used here mean high voltage, medium voltage and low voltage.

2) "CASE STUDY" FOR A LV SWITCHGEAR

The objective to be reached is to find the best technical economical compromise, passing on the tests, for the design of a switchgear with a rated current 630A or up to 1000 kA, short circuit current (65 kA $_{rms}$) and an internal arc capability (65 kA $_{rms}$ during 0,3 s) taking into account the following:

- The number of insulators or supports of the busbar system (electrodynamical forces)
- Type of busbar profiles (temperature rise test and electrodynamical forces)
- To use or not ventilation openings with a certain area (temperature rise test)
- The pressure relief area and the net internal volume (internal arc test)
- The thickness of the enclosure plate (supportability to overpressures and burnthrough)
- It does not matter if the busbars are made of copper or aluminum.

The costs of parts used to do the economical comparison (Table 1) vary considerably from country to country and should be adapted in each case. The economic analysis which was done in this text is simplified but if a reader want to do a complete and professional economic assessment can use the free software tool developed by Cognitor available to download in the front page of http://www.cognitor.com.br/en_home.htm .

To create some design restraints, which are common in the daily life, we considered the following:

- The enclosure has dimensions 1400 x 700 x 220 mm (Figure 1)
- The busbars dimensions to be used are only the ones in Table 3.
- The phase to phase distance shall remain in the range 40 to 60 mm.

- Temperature rise: the maximum permissible value at any point is 65K. There is some power dissipation inside the enclosure (150W) in addition to the power losses originated by the circulation of the current in the busbars, circuit breaker. They are related to some internal losses including the connections between busbars and others. The circuit breaker (CB) has an electrical resistance 20 μΩ per phase, as seen from the terminals.

- Electrodynamical short circuit forces: the maximum acceptable mechanical stress is Q x σ 0.2 as used in in IEC 61117 – A method for assessing the short circuit withstand strength of partially type tested assemblies (PTTA) and IEC 60865-1 - Short-circuit currents . The value used for $\sigma_{0.2}$ is 250N/mm2 (copper) or 120N/mm2 (aluminum)
- Internal arc overpressures: the enclosure is made of a steel plate with a defined thickness and the construction is such that the maximum overpressure acceptable, without failing in the test, is 100% (1,0 bar) above the atmospheric pressure. The test criteria is the one from the IEC document IEC TR 61641(2008) – Enclosed Low Voltage Switchgear Assemblies – Guide for testing under Conditions of Arcing due to Internal Fault.

Figure 1a – The test case of “small” switchgear

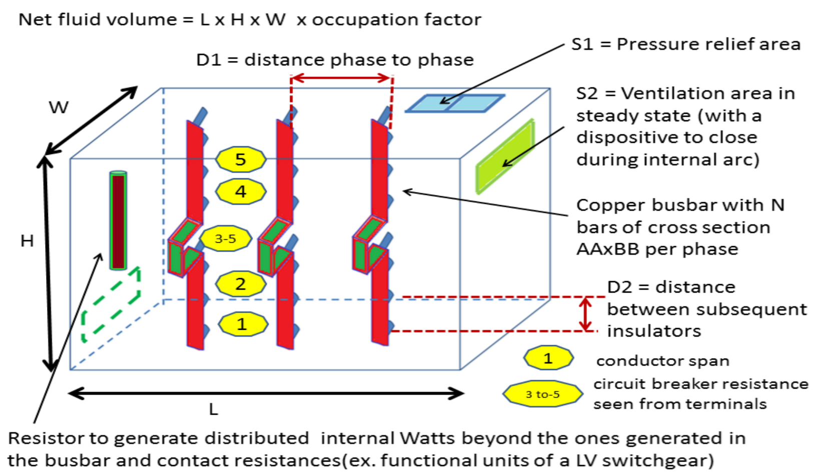
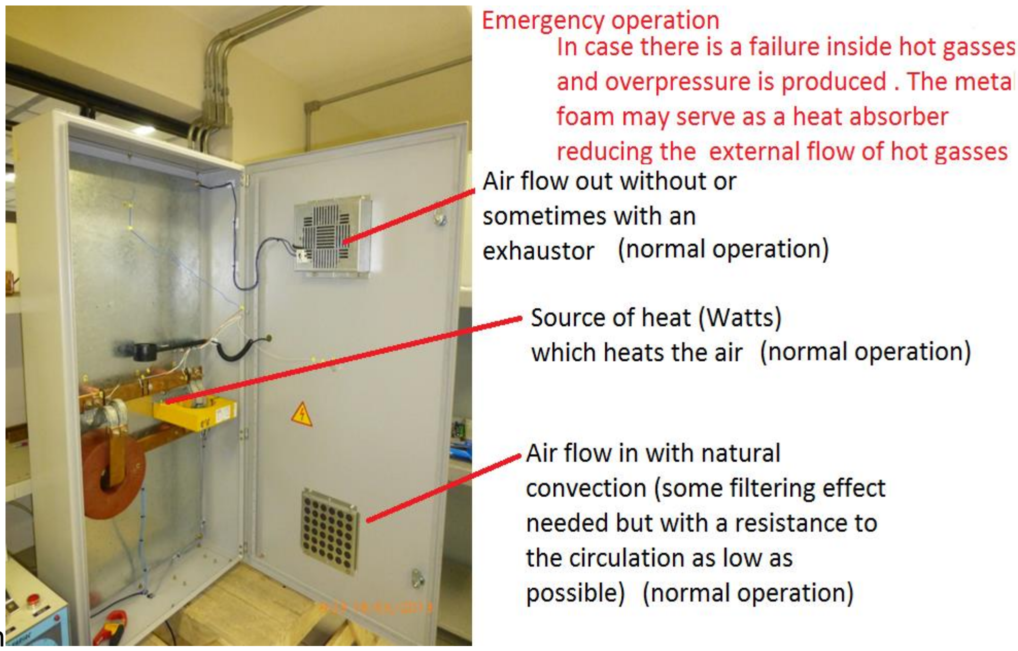


Figure 1b – The enclosure used in the test case 1400 x 700 x 220 mm



mm

Figure 2a – The test case - *Configuration for the temperature rise tests simulation*

(main heat source is the circuit breaker)

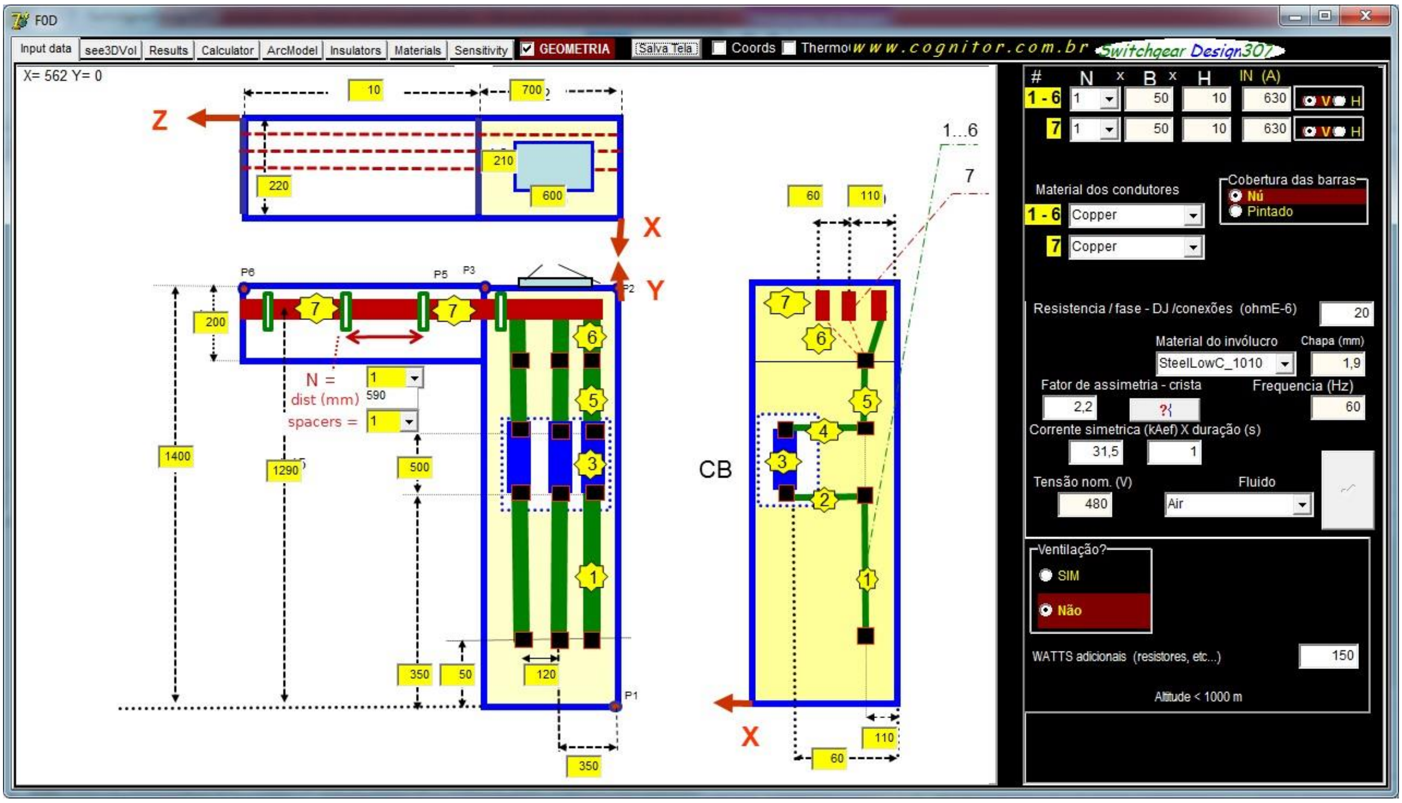


Figure 2a – Configuration used for the short circuit test (smaller distances phase-phase = higher forces)

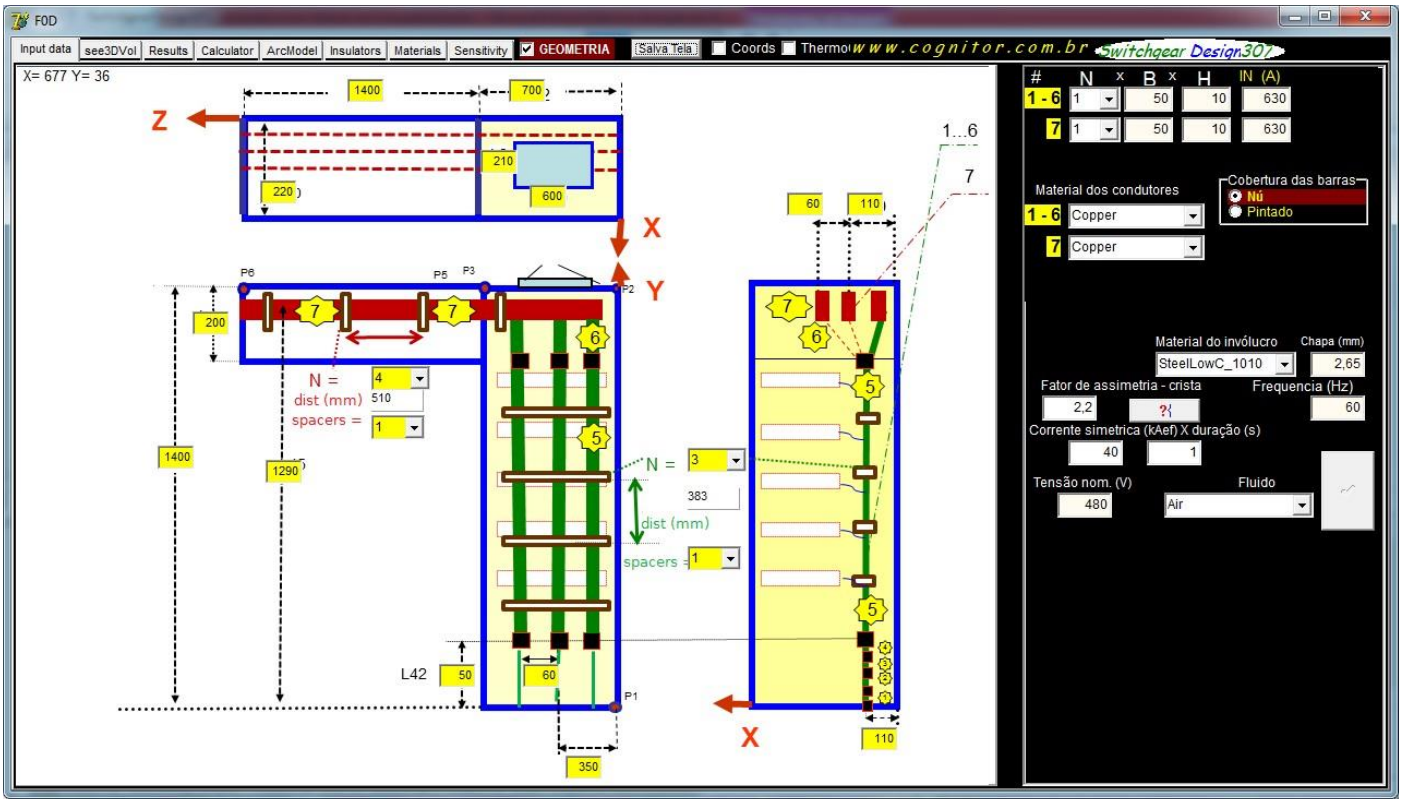


Table 1 - Input data and order of magnitude of the costs used for the economic comparison.

Item	Unit of the cost	Specification (dimensions AA x BB)	Order of magnitude in U$D per unit of cost	Typical figure
Copper Busbar (*)	U$ / KG (material)	50x5 mm or 50x10 mm	10 10	
Aluminum Busbar (*)	U$ / KG (material)	80x5 mm or 800 x 10 mm	2,5 2,5	
Insulators	U$ / piece	Epoxy type 15 kv	13	
Insulators	U$ / piece	Epoxy type 600V	2	
Busbar Supports	U$ / piece	Low voltage for high electrodynamical forces	3	
Enclosure	U$ / kg (mounted)	Plate 1,90 mm	2	
Pressure relief device	U$ / piece	Rupture disks	30	
Small fan + dispositive to close the vent opening	U$ / piece		150	Small fan to produce 0,5 m/s + dispositive
Mounting	U$ / piece (hours of work)	Low or medium voltage	250	Mounting excluding items covered above
Busbar painting	U$/ m^2		5	

(*) The values in 2013 are around 7 to 8 and 1,8 to 2 U$D/kg

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3. STRATEGIES TO REDUCE FAILURES IN THE TESTS WITHOUT OVERDIMENSIONING

It is a common practice to over dimension the design to avoid risk of failures in the lab tests. To consider this aspect in our test case we will compare how much the equipment would cost if it was designed to attend the recognized limits of the supportability for that test and how much it would cost if designed with a 25% safety margin (see Table 2). Many other strategies are possible depending on the degree of confidence assigned to the simulation method.

Table 2 – Limits of supportability and strategies to reduce the possibility of failures in the tests.

Test	Effect and critical point considered	Strategy to reduce the possibility of failures in the tests (Note 1)	Limit commonly used (100%)	Over dimensioning Limit with ~25% safety margin
Short time current withstand test	Stress in the busbar conductor	Reduce distance between subsequent insulators maintaining phase to phase distance	Q x 250 N/mm^2 for copper busbars Q x 120 N/mm^2 for aluminum	Q x 0.75 * 250 =qx187 N/mm^2 or 0.75 * 120 =90 N/mm^2
Short time current withstand test	Highest forces in flexure in any of the insulators	The same as above	10000 N in flexure, tension or compression	7500 N
Temperature rise test	Temperature rise in a silvered connection of the switching device.	Increase the busbar section. or paint the bar or increase ventilation.	65 K	50 K
Internal arc tests	Overpressure bend the plate creating an opening from where hot gasses scape	To reduce the distance between fixing points or to increase the plate thickness. To enlarge the size of pressure relief devices	2 mm 90% of overpressure peak (not considering integral of overpressure curve)	1,5 mm

Note: O factor for the electrodynamical stresses is $q \times \sigma_{0.2}$ in IEC 60865

4. OPTIMIZING THE DESIGN FOR THE TEMPERATURE RISE TEST

The initial step is to estimate the size of the bare copper or aluminum bars to use. Searching in some busbar table published in engineering handbooks we find the current which can be applied in free air to have a temperature rise of 35 K above the air ambient temperature of 35^{0}C. As the temperature of the air inside the switchgear is higher than the external one these tables serve only to provide an order of magnitude. The additional losses caused by the contact resistances and other power losses will bring to the need for a larger busbar.

Initially we calculate the temperature rise of the air inside the enclosure ($\Delta T_{internal\ air}$) as a function of the total internal Watts, the dimensions and the area of the ventilation openings considering resources like fans. The method is the one in IEC TR 60890 (A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear) with some additions for the fans which are not covered there. Knowing $\Delta Ti_{internal\_air}$ we use, in addition, a finite volume method to calculate the temperature rise of the conductors and their contacts above this internal air temperature ($\Delta T_{conductor\_parts}$)

The final temperature rise to be compared with the laboratory test results is

$$\Delta T_{\text{simulation}} = \Delta T_{\text{internal air}} + \Delta T_{\text{conductor parts.}}$$

To check the impact of the different design alternatives we simulated a temperature rise test finding the value of current which would produce the temperature rise of 65K and also 75% of 65K (~ 50K) in the hot spot point (connection of the circuit breaker to the bus bar). The values are showed in Table 3.

For simplicity we will consider the optimum design as the one with lowest cost per transmitted power. The transmitted power was considered TP = 1,732* rated voltage phase to phase * current in Table 3.

Table 3 – Design alternatives X costs for a temperature rise of the hot spot 65K (without a safety margin) or 50K (with margin). CB resistance 20 µΩ plus a 150 W resistor. Ventilation area = none or 100 cm^2

Case #	Busbar dimensions (mm)	Bare or painted (Note 1)	Air speed (m/s) (Note 2)	Ventilation opening area (cm2)	Current (A) for **65K** Temp. rise	Cost / transmitted power 65K (USD / KVA)	Current (A) for **50K** Temp. rise	Cost / transmitted power 50K (USD / KVA)
1	1 x (50 x10) Copper	bare	0 (no vents)	No vents	630	1,5	450	2,1
1	2 x (50 x 5) Copper	bare	0 (no vents)	No vents	690	1,4	500	1,9
2	1 x (50 x10) Copper	Painted	0 (no vents)	No vents	680	1,4	510	1,8
2	2 x (50 x 5) Copper	painted	0 (no vents)	No vents	710	1,3	535	1,8
3	1 x (50 x10) Copper	bare	< 0,1 (vent/no fan)	100	830	1,2	670	1,4
3	2 x (50 x 5) Copper	bare	< 0,1 (vent/no fan)	100	1000	1,0	780	1,2
4	1 x (50 x10) Copper	bare	0,55 (vent + fan)	100	1175	0,9	1000	1,1
4	2 x (50 x 5) Copper	bare	0,55 (vent + fan)	100	1350	0,8	1100	1,0
8	2 x (80 x 5) Aluminum	bare	0 (no vents)	No vents	745	0,9	530	1,2
9	Web channel 100xx4	bare	0 (no vents)	No vents	1000	0,7	745	0,9

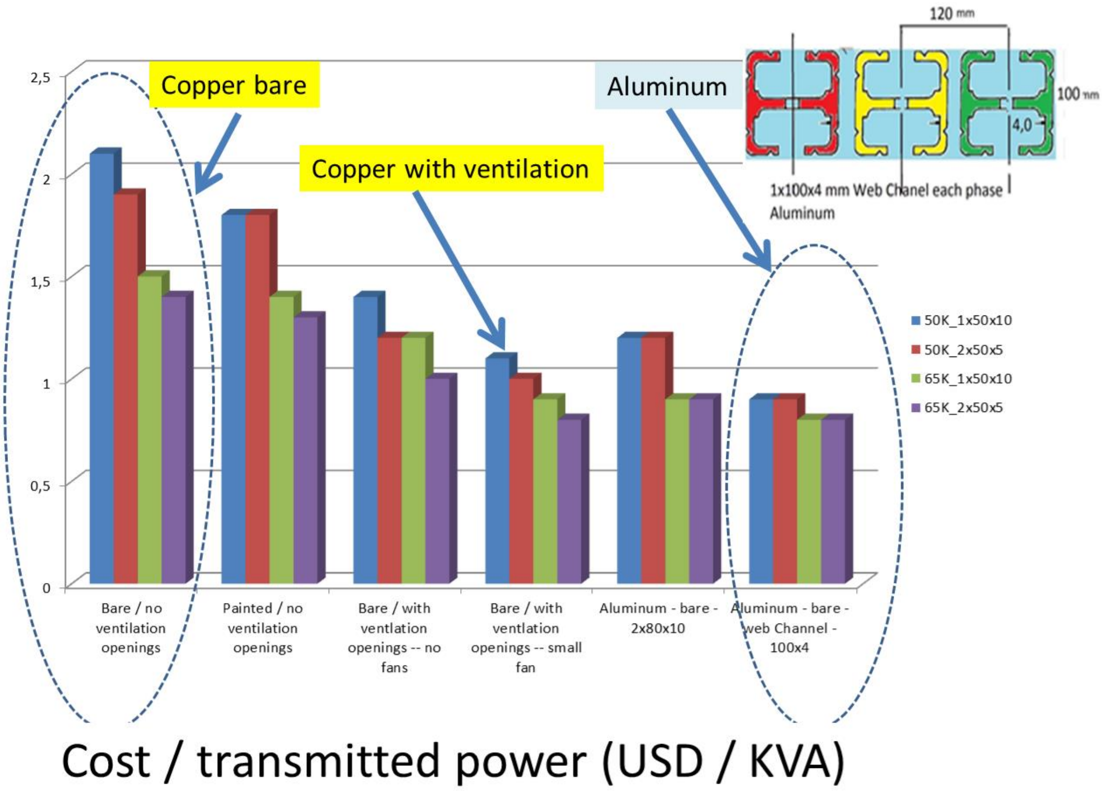
Note 1 - Painted or using a thermo plastic cover

Note 2 - No vents = sealed ****** Vent + no fan = there is a ventilation opening 100 cm^2 without a filter and without forced ventilation ******* Vent + fan = there is a ventilation opening 100 cm^2 with a filter and with forced ventilation through an exhauster.

Note 3 - bar 1x50x10 mm copper – Catalog rated current for 35 K = 852 A

Note 4 - bar 2x80x5 mm aluminum – Catalog rated current for 35 K = 1150 A

Figure 2 – Comparison of the cousts / transmitted power (USD / kVA) (TEMPERATURE RISE)



5. OPTIMIZING THE DESIGN FOR THE SHORT TIME CURRENT TEST (ELECTRODYNAMICAL FORCES)

To optimize the switchgear design for the electrodynamical forces we do:

- The reduction of the number of insulators or supports in the busbars.
- the reduction of the cross section of the busbar, maintaining the mechanical stiffness and attending the temperature rise requirements
- Changing the phase to phase distance not impacting the dielectric supportability or significant increase in the voltage drop.

In MV cubicles, most of the times, the number of insulators is determined by reasons which do not give margin for optimizations. By the other side, in busways and in LV panels there are excellent possibilities.

To change the distance between phases may be interesting because:

- Using bigger distances we reduce the forces and enable a bigger distance between spacers. For LV switchgear we have, in addition, a favorable impact in the reduction of the internal arc current. For lower voltages the arc resistance has an important impact to reduce the arc current. An interesting solution is to create an "intrinsic safety" product using big distances that will make the arc to auto-extinguish in a small time. The focus on reducing the size of equipment frequently is an error of design strategy. Inside offshore oil platform, to reduce size and weight is very important. On the contrary, to reduce 100mm in the width of switchgear installed in a room 20x10 meters, in a land big industry is just a source of problems due to higher heating, overpressures and electrodynamical forces.
- If the distance between phases is smaller the impedance is smaller. For a LV motor control center (MCC) this is not very relevant but for a bus way going through a 40 floors building to reduce the voltage drop is a very welcome result.

In our test case we considered , as an objective, that the value of the short circuit current is fixed and searched the maximum possible distance between the supports of the vertical busbar without passing the maximum acceptable mechanical stress in the busbar ($q \times \sigma_{0.2}$ in IEC 60865) . This maximum distance means the minimum number of supports. A stress higher than this would produce visible deformations after the test which is not permitted by the technical standard. The idea is to economize supports and we are considering that the supports are good enough to support the resulting compression, tension and flexion forces. To show the impact of the different design alternatives we simulated the alternatives showed in Table 3. There are two different phase to phase to show the impacts..

Table 3 – Design alternatives /costs for optimization to electrodynamical forces (65 kA rms x 143 kAcr).

Case #	Busbar dimensions (mm)	Distance between centers of phases (mm)	Maximum distance between supports (mm) for q x 250 N/mm2	Cost / transmitted power q x 250N/mm2 (USD / KVA)	Maximum distance between supports (mm) for q x 187 N/mm2	Cost / transmitted power q x 187N/mm2 (USD / KVA)
1	1 x (50 x10) Copper	60	~260	1,07	230	1,10
2	2 x (50 x 5) Copper	60	210	1,21	144	1,31
3	Web channel 100xx4	60	Note 1	Note 1	Note 1	Note 1
1	1 x (50 x10) Copper	120	~380	1,04	290	1,07
2	2 x (50 x 5) Copper	120	210	1,21	192	1,24
3	Web channel 100xx4	120	900	0,72	1100	0,68

Note 1: Not possible due to the necessary space of ~120mm phase to phase as the external cross section of the profile is 100x100 mm

6. FINDING THE SOLUTION FOR THE INTERNAL ARC TEST

It is relatively easy to construct switchgear using the “arc free” concept but there is a certain resistance from designers which are focused in the paradigm “small is better”. Let´s show the difference between projects where the arc with or without self-extinction.

The overpressure is the key parameter. It depends on the voltage applied and the arc current, the pressurized volume and the area and speed of the pressure relief device. The process is that the arc starts at a certain place and moves in the opposite direction of the voltage source. Along its duration there are three effects that may cause impacts to the panel and people standing near it.

The first effect is the overpressure caused by the vaporization of the conductor material. It may damage the enclosure doors or cause deformation of the walls. The mechanical withstand of the enclosure increases with the thickness of the wall. If the distance between the bolts joining the plates is smaller the deformation of plates will be smaller for a given pressure.

<u>The second effect</u> is the so called "burnthrough". When the arc is moving it can eventually stop at a bolt or an arc barrier. If it stops, the metallic material at the point where the arc is playing is melted and vaporized by high temperatures. The greater is the plate thickness more time is needed to create a hole from which the pressurized hot gases could flow out of the housing. When the arc is moving it causes less damage, because less material is extracted at a specific point. <u>The third effect</u> is the ejection of the hot gases and particles through the pressure relief devices which depend on the values and duration of the overpressure.

An interesting strategy, which may bring intrinsic safety, is to increase the phase to phase distance to provoke the auto extinction of the arc during the test or in the real life. In practice this is useful only to LV switchgear because the distances involved are small. On the other side there is also the possibility of using quite reduced phase to phase distances. Nevertheless if this is positive from the of view of the internal arc it is more difficult from the point of view of the electrodynamical forces

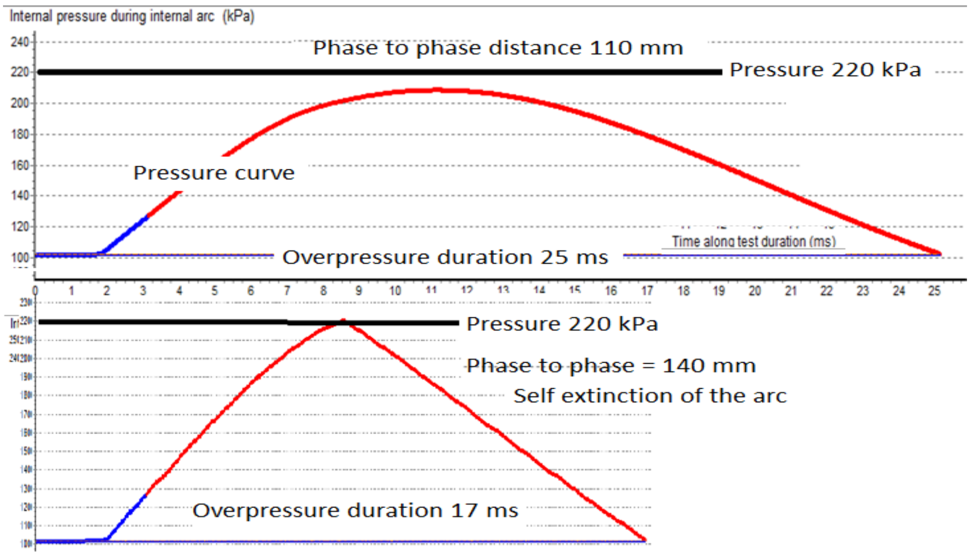
Suppose that our design objectives are to maintain the "Integral of the overpressure curve" below 20 and pressure peak below 2,2 bar for a 65 kA current during 0,3 s. We will consider the area of the pressure relief flap as 90% of the top face (630x200 mm). Three different distances between centers of the phases were used to show the impacts in the arc current and overpressure. See results in Table 4.

It is possible to see that forcing the self-extinction may be a quite interesting strategy

Table 4 – Internal arc test. Pressure relief area = 630x200 mm Volume occupation factor = 80%

LVSW1_1x50x10bare_noV

Case #	Distance between centers of phases (mm)	Short circuit current presumed value (kA rms)	Actual short circuit current due to arc resistance (kA rms)	Overpressure duration (ms)	Maximum overpressure peak (%)	Integral of the overpressure curve along the time (% bar x S)
1	60	65	55,4	20	56	12
2	110	65	49,6	25	106	31
3	140	65	20,0	16	118	17



7. CONCLUSIONS ABOUT THE OPTIMUM DESIGN

Depending on the costs attributed to each switchgear component as materials, labor work, mounting, etc and the objectives to reach (safety, minimum fabrication cost, durability,…) different design strategies may be followed to reach the optimum design .

If, in our test case, we look only to the parameter “Cost / Transmitted power - USD / KVA)” there is an obvious conclusion which is the big potential for the use of aluminum busbar profiles mechanically more resistant (Web Profile or 2 x U).

Many designers do not understand well the difference between using just aluminum (aluminum with aluminum connections) and aluminum + copper connections. Only the last one may have premature ageing and not the first one. So, the use of aluminum for switchgear has a potential which is not reflected in the commercial market. Here is a good opportunity for small and medium manufacturers.

There is more information in this book written by Sergio Feitoza
http://www.bookess.com/read/15214-reference-text-for-the-courses-switchgear-busways-isolators-substations-equipment/ .

This book is used in the trainings showed in http://www.cognitor.com.br/en_home.htm . In the switchgear course the software described in Section 7 of the book is made available complete free to the participants

Without the use of simulations this paper could not be done due to the number of laboratory tests which would be necessary and the associated costs.

The authors emphasize the need of a new IEC standard creating basic rules for the use of simulations to extrapolate the results of laboratory tests or even to replace some tests.

A complete draft proposal is available since 2010 in the link
http://www.cognitor.com.br/GUIDE_Simulations_v0_October2010.pdf

A forum about the theme is at
http://www.linkedin.com/groups/Switchgear-Proposal-IEC-Guide-on-4219744?trk=myg_ugrp_ovr

ANNEX 1 – REFERENCES

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Draft text for the Guide http://www.cognitor.com.br/GUIDE_Simulations_v0_October2010.pdf

ANNEX 2 – SOME INFORMATION USEFUL TO VALIDATE TEMPERATURE RISE SOFTWARE CALCULATIONS

In the tables and figures to follow we show the results of a series of experiences done in a laboratory just to validate the results obtained in the calculations using the software developed by Cognitor.

The tests were performed by Macro Painel using the configurations showed in a box with dimensions 1400x 700 x 220 mm as in the figures below. In these tests we used bus bars 50x10 mm We used possibilities from without any ventilation to forced ventilation with or without filters. The obtained values are showed in the Table below . Several measurements were done including the speed of the air in key locations. We used as input data the information showed in the 3 figures below the table including a sum of the internal connections 24 μΩ

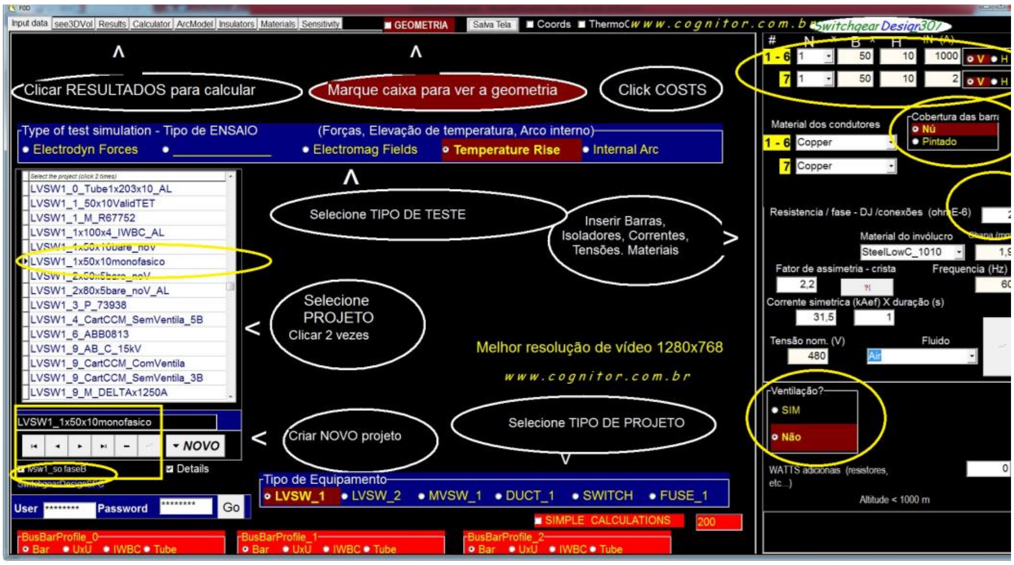
Table A-1 - Temperature rise measured and calculated with several configurations and using a 50x10 mm copper bar installed in the “vertical” position inside a 1400x 700 x 220 mm enclosure with or without ventilation openings and forced ventilation. The current is 1000 A . The values P1 to P6 are the temperature rises above the temperature of the external air

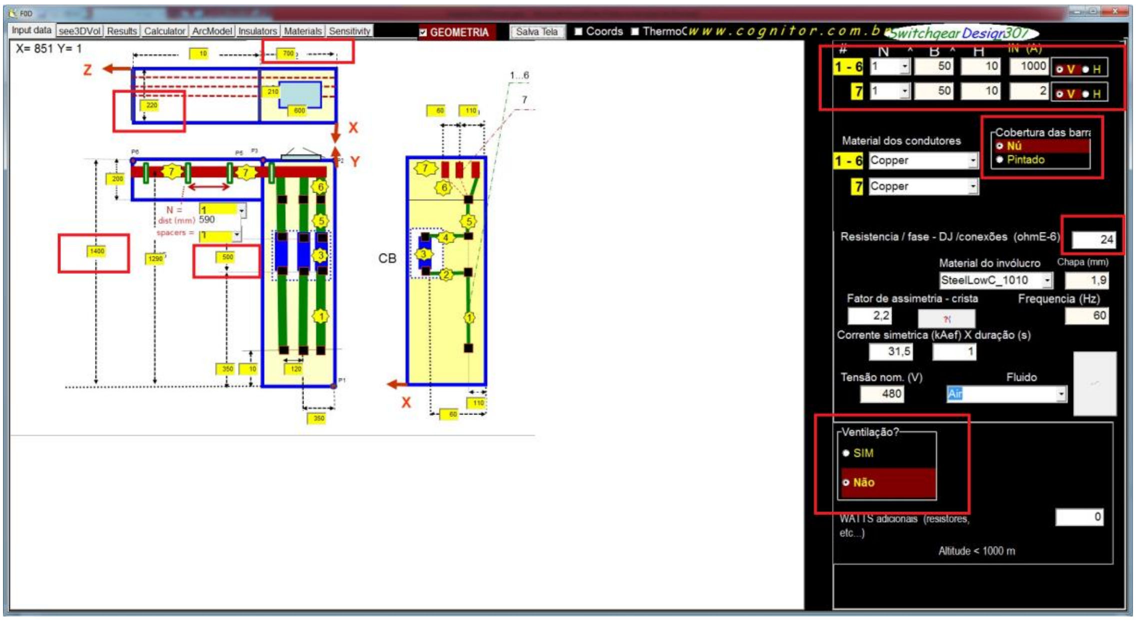
Ventilation condition	Sealed (no ventilation openings)	With ventilation openings and no forced ventilation (using filter)	With exhauster in the top without filter plus filter in lower part	With exhauster but no filters in the upper and lower openings	Sealed (no ventilation openings)	With ventilation openings and no forced ventilation (using filter)	With exhauster in the top without filter plus filter in lower part	With exhauster but no filters in the upper and lower openings
Air velocity (m/s)	0	0	0,55	0,87	0	0	0,55	0,78
With or without covering in the busbar	Bare	Bare	Bare	Bare	Thermo	Thermo	Thermo	Thermo
Left side connection (P1)	73	57	34	24	44,2	56,1	21,1	16,6
Center of bar (P3)	70	55	33	23	43,2	55,1	21,1	16,6
Right side connection (P2)	73	58	36	25	41,2	55,1	21,1	16,6
Internal air near the top (P5)	19	8	3	2	13,7	7,5	2,4	2,6
Enclosure plate (P6)	21	11	6	4	13,2	7,1	4,1	1,6
Door center (P4)	10	4	2	1	7,2	3,1	2,1	1,6

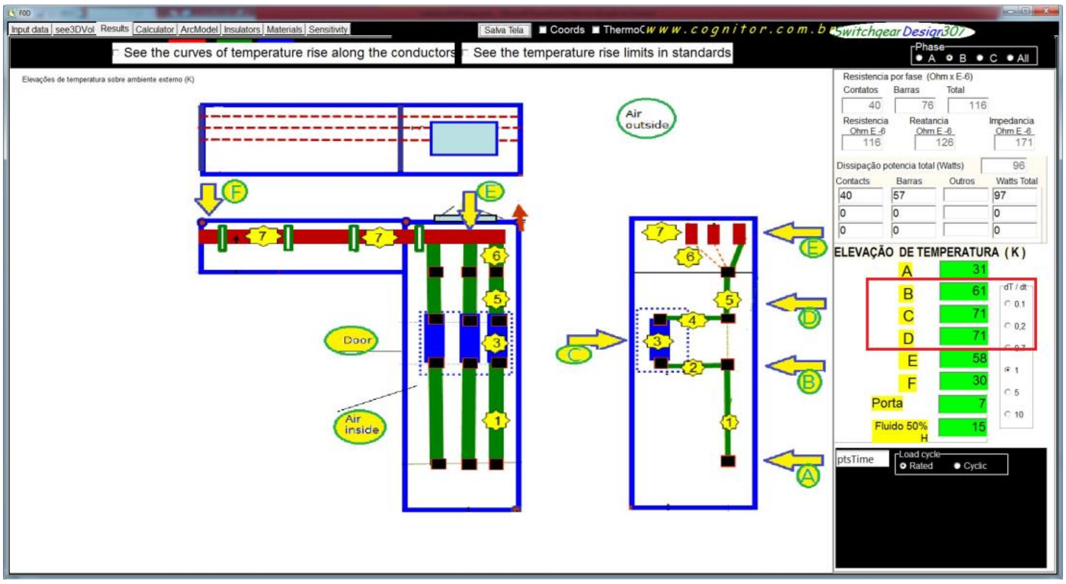
COMPARISON BETWEEN MEASURED VALUES AND VALUES OBTAINED IN THE SIMULATIONS WITH COGNITOR SOFTWARE (POINT P3 – center of the bar)

Ventilation condition	Sealed (no ventilation openings)	With ventilation openings and no forced ventilation (using filter)	With exhauster in the top without filter plus filter in lower part	With exhauster but no filters in the upper and lower openings	Sealed (no ventilation openings)	With ventilation openings and no forced ventilation (using filter)	With exhauster in the top without filter plus filter in lower part	With exhauster but no filters in the upper and lower openings
Measured values in Table above	70	55	33	23	43,2	?	21,1	16,6
Calculated with Cognitor software	71	52..63	28..35	23..30	40..47	32..40	22..29	19..25

For some other validation values see the paper in
http://www.cognitor.com.br/Validation_Simulations_English.pdf and Section 7 of the book in
http://www.cognitor.com.br/Book_SE_SW_2013_ENG.pdf







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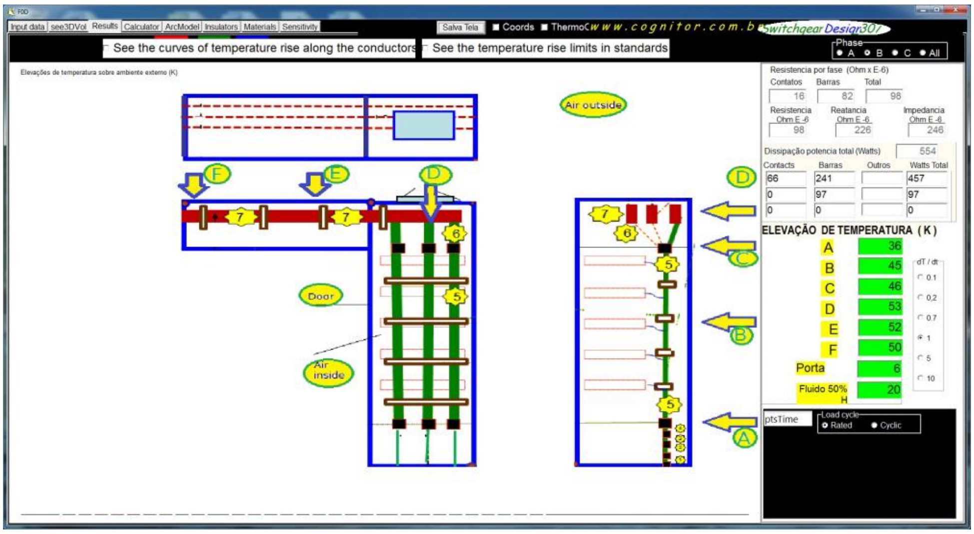
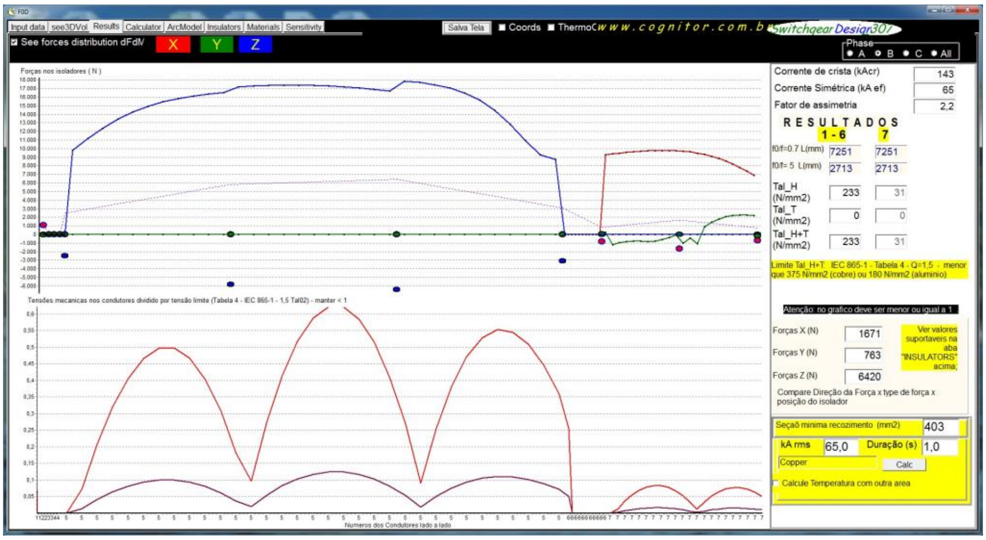
ANNEX 3 – SOME SIMULATION RESULTS

TEMPERATURE RISE TEST



SHORT TIME CURRENT TEST



INTERNAL ARC TEST

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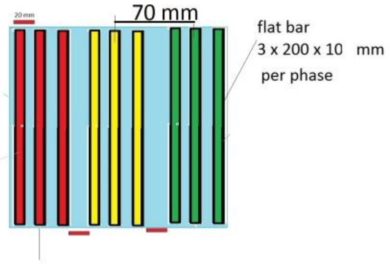
Annex 4 - **A DRAFT DESIGN OF AN OPTIMIZED LV SWITCHGEAR 4000A – 100 KA$_{RMS}$.**

To be presented in the next paper



Space occupied by the bus bar 190 mmx 200 mm

Weight per phase = 15,4 kg/m

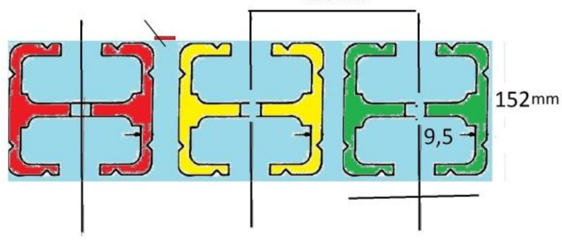
Moment of inertia = 165 cm^4

Section modullii = 66 cm^3

Cross section= 60 cm^2

Perimeter = 126 cm

1 x 152x9,5 mm Web Channel



Space occupied by the bus bar 490 mm x 152 mm

Weight per phase = 14,9 kg/m

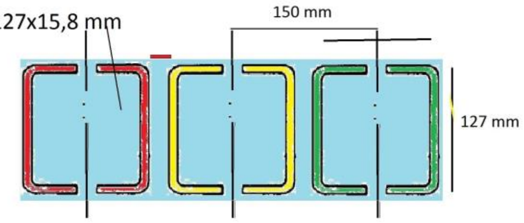
Moment of inertia = 1912 cm^4

Section modullii = 251 cm^3

Cross section= 55 cm^2

Perimeter = 118 cm

2x127x15,8 mm



SFC criteria = 20 mm between live parts phase - phase
for up to 1 kV rated voltage systems in air.

Space occupied by the bus bar 427 mm x 127 mm

Weight per phase = 16,8 kg/m

Moment of inertia = 1472 cm^4

Section modullii = 194 cm^3

Cross section= 62 cm^2

Perimeter = 95 cm

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