SHORT CIRCUIT ELECTRODYNAMIC FORCES & STRESSES. Switchgear example on how to save insulators.

Author: Eng. Sergio Feitoza Costa, M. Sc http://www.cognitor.com.br/trainingweek4.pdf

1. Short circuit forces and their increasing importance in the cost of switchgear
2. The calculation of electrodynamics forces in switchgear and other busbars
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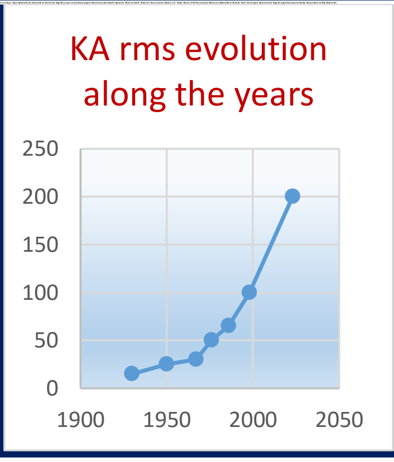
4. Advanced topic: propulsion using magnetohydrodynamics (MHD)
5. Final comments



1. SHORT CIRCUIT FORCES AND THEIR INCREASING IMPORTANCE IN THE COST OF SWITCHGEAR

The magnitude of short-circuit currents has been increasing over the past few decades, as shown in the chart above. As there is a desire to make medium-voltage (MV) and low-voltage (LV) electrical panels and busways smaller and smaller, this means that they are increasingly subject to higher short-circuit forces as well as higher overpressures and temperatures. This is because smaller distances between busbars cause higher short-circuit forces, and smaller air volumes imply higher normal temperatures and overpressures for the internal arc.

For example, by the end of the 70's, when I was younger and we designed the CEPEL's High Current Testing Lab in Brazil, we were looking decades ahead and dimensioned it for reaching 300kArms /750kAcr (and 50kA continuous). There are cases of such short circuit levels in 2025, some 40 years later.

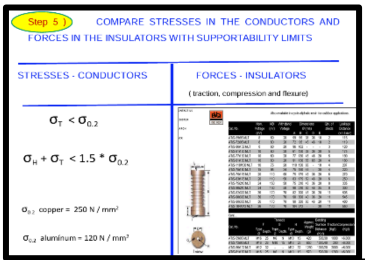
The electrodynamic forces acting on busbars and supports, are proportional to the square of the currents and the inverse of the distances between busbars. So, smaller equipment mean higher forces and mechanical stresses during short circuits. More accurate calculations enable to use less insulators and lower safety factors than if you use the equations of our well-known switchgear manuals which are based on equations valid only for parallel conductors.

The "optimal design objectives" for a lower cost switchgear using a minimum number of insulators are:

(a) **to maintain the short-circuit forces slightly below the relevant supportability of the insulators** (flexure or compression or tension). The flexure supportability is usually the lower one.

(b) **To maintain the mechanical stress of conductors lower than the materials strength limit** to avoid a visible deformation. E.g. mmaximum values for not having a permanent deformation > 0,2 % of the conductor length (up to this is not perceptible to the naked eye) are:

- Aluminum conductors:120-160 N / mm^2
- Copper conductors: 200 to 250 N / mm2



For example, the withstanding values of epoxy insulators may be like :

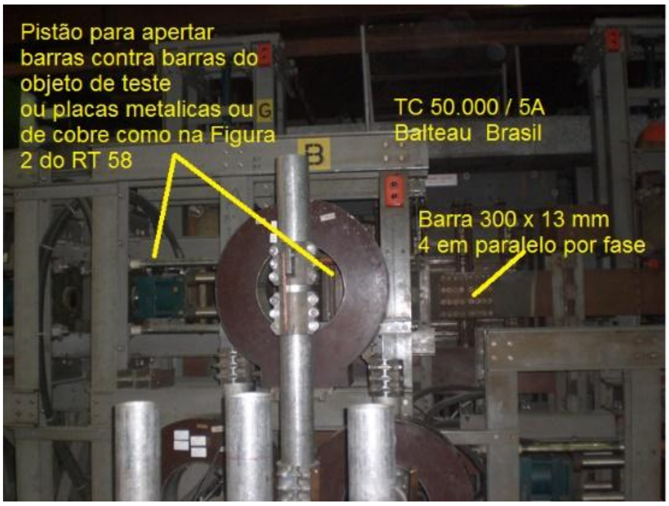
Insulator reference	Rated voltage (kV)	**Flexure (kgf) /** distance to face (mm)	**Traction (kgf)**	**Compression (kgf)**
AT/S-59/95 MLT	8	500 / 30	1000	>6.000
AT/S-72/95 MLT	8	1000 / 40	200	>6.000
AT/S-118/130 MLT	10	1960 / 50	2000	>6.000
AT/S-75/150 MLT	15	500/30	1400	>6.000
PI120 05	4,16 kV	2000 lb	ni	ni

In next section we show how to calculate forces and mechanical stresses as a function of the relevant design parameters. For whom wants to go deeper I suggest reading references below. Calculations include determining electromagnetic forces between conductors and the mechanical stress that can cause damage to insulators and bend busbars. The calculation methods used in the SwitchgearDesign software, developed by me, are based in the following documents:

- IEC 61117, Method for assessing the short-circuit withstand strength of partially type-tested assemblies (PTTA)
- IEC 60865-1, Short-circuit currents – Calculation of effects – Part 1: Definitions and calculation methods.
- IEC TR 60865-2, Short-circuit currents – Calculation of effects – Part 2: Examples of calculation.
- M.Sc. Thesis by Sergio Feitoza Costa -M.Sc. Thesis - 1979: Electromechanical stresses in electrical equipment, especially switchgear created to support the design of CEPEL's High Power and High Current Test laboratories.
- IEC TR 62271-307 - High-voltage switchgear and controlgear - Part 307: Guidance for the extension of validity of type tests of AC metal and solid-insulation enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV. I suggest reading the article "IEC 62271-307 – Extension of the validity of type tests to avoid tests repetitions" in this link https://www.cognitor.com.br/IEC62271307ENG.pdf

A good way to start understanding what is relevant to calculating short circuit forces is to look for the performance criteria regarding thermal and electrodynamic short-circuit stresses of Table 5 of IEC 62271-307.
I, Sergio Feitoza Costa, am co-author of this IEC document published in 2015.

Item	Design parameter	Acceptance criterion	Condition	Criteria attended?
(1)	(2)	(3)	(4)	
1	Centre distance between phases	≥		
2	Electro-dynamic forces due to current path	≤	The conductors have the same physical arrangement.	
3	Mechanical strength of insulating conductor supports	≥		
4	Length of unsupported sections of conductors	≤		
5	Cross-section of conductors	≥	Connections of the conductors are scaled and have the same or greater clamping force and contact area.	
6	Material of conductors	same		
7	Temperature class of insulating material in contact with conductors	≥		
8	Mechanical strength of the enclosure /partitions/ bushings	≥		
9	Contacts of removable part	same	Consider complete design of contact sub-assembly and the fixing / mounting of the removable part.	



2. THE CALCULATION OF ELECTRODYNAMICS FORCES IN SWITCHGEAR AND OTHER BUSBARS

The concepts on how to calculate electrodynamic forces and stresses which occur during short circuits are a must in the design of switchgear, busbar systems and even complete substations arrangements. The objective is to determine forces and their consequences to design the structures, size of the busbar conductors, number of insulators and supports, etc. From the thermal point of view, is important to define minimum cross sections of grounding busbars,

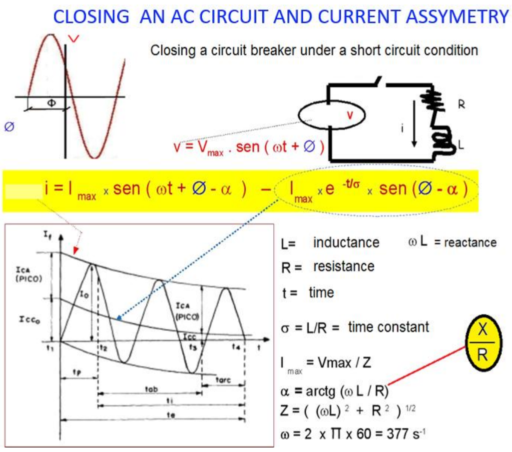
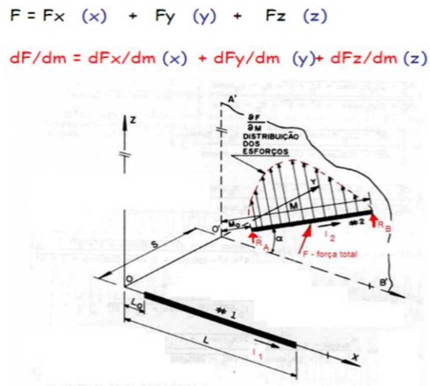


Figure 1 – Forces created in two neighbor conductors circulated by short circuit conductors.



If you do calculations on a MV or LV switchgear we will conclude that at short circuit levels higher than, let's say 31,5 kA you may get forces in the range of tons. The shape of the short circuit currents can be understood in the Figure1 The equations to calculate forces and stresses in two neighbor conductors circulated by short circuit currents are like the ones showed below, extracted from my 1979 M.Sc. Thesis.

What we do in software like SwitchgearDesign is to calculate, for each one conductor, the forces produced in it by all the other conductors of the switchgear busbar system. We use the maximum instantaneous values (I1 and I2) in the equations considering each phase. These forces depend on the currents, asymmetries, phase angles, geometry, distances, materials used, etc..... Inside a switchgear there are dozens of conductors, each one influencing the other.

So, to calculate the forces in conductors and in the supports and insulators it is necessary to use a computer program like SwitchgearDesign, just entering the values of currents, distances and asymmetry factors (example in Figure 3).

When using these exact equations, you do not need to use uncertainty safety factors over dimensioning the system. When calculating with the approximate equations of switchgear manuals, to avoid failing in the expensive type tests in testing laboratories, the designer tends to use high "safety" factors. So, the project becomes over dimensioned with a higher weight of copper and aluminum and a much higher number of supports and insulators than necessary.

Figure 2

$$\frac{\partial F_x}{\partial m} = (\mu_0 I_1 I_2/4\pi).\mathrm{sen}^2\alpha.m\left\{\left[1/\left(\sqrt{m^2-2L_0\cos\alpha\, m+L_0^2+S^2}\;\left(\sqrt{m^2-2L_0\cos\alpha\, m+L_0^2+S^2}+L_0-m\cos\alpha\right)\right)\right]-\left[1/\left(\sqrt{m^2-2L\cos\alpha\, m+L^2+S^2}\;\left(\sqrt{m^2-2L\cos\alpha m+L^2+S^2}+L-m\cos\alpha\right)\right)\right]\right\} \quad (3.1)$$

$$\frac{\partial F_y}{\partial m} = -(\mu_0 I_1 I_2/4\pi).\cos\alpha.S\left\{\left[1/\left(\sqrt{m^2-2L_0\cos\alpha m+L_0^2+S^2}\;\left(\sqrt{m^2-2L_0\cos\alpha m+L_0^2+S^2}+L_0-m\cos\alpha\right)\right)\right]-\left[1/\left(\sqrt{m^2-2L\cos\alpha m+L^2+S^2}\;\left(\sqrt{m^2-2L\cos\alpha m+L^2+S^2}+L-m\cos\alpha\right)\right)\right]\right\} \quad (3.2)$$

$$\frac{\partial F_z}{\partial m} = -(\mu_0 I_1 I_2/4\pi).\cos\alpha.\mathrm{sen}\alpha.m\left\{\left[1/\left(\sqrt{m^2-2L_0\cos\alpha m+L_0^2+S^2}\;.\left(\sqrt{m^2-2L_0\cos\alpha m+L_0^2+S^2}+L_0-m\cos\alpha\right)\right)\right]-\left[1/\left(\sqrt{m^2-2L\cos\alpha m+L^2+S^2}\;.\left(\sqrt{m^2-2L\cos\alpha m+L^2+S^2}+L-m\cos\alpha\right)\right)\right]\right\} \quad (3.3)$$

In the reports in References [2,3] below we present complete explanations for the calculations as well as comparisons of real test results with simulation / calculation results

Figure 2a – Input data for calculation of forces and stresses in MV switchgear (extracted from References [2,3] – links below) Report 071/2014: Validation of Software Switchgeardesign_307 for Simulation Of High Power Tests (Temperature Rise, Short Time and Crest Current Tests – Electro Dynamical Forces / Stresses and Overpressures from Internal Arc)

MV switchgear in which considerable savings in the number of insulators

are not usually possible

because the position of the insulators is practically determined by the enclosure geometry

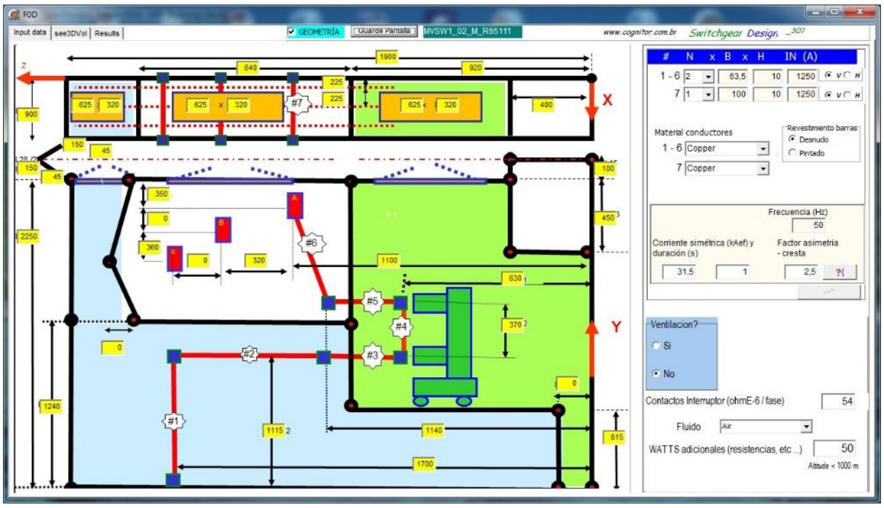
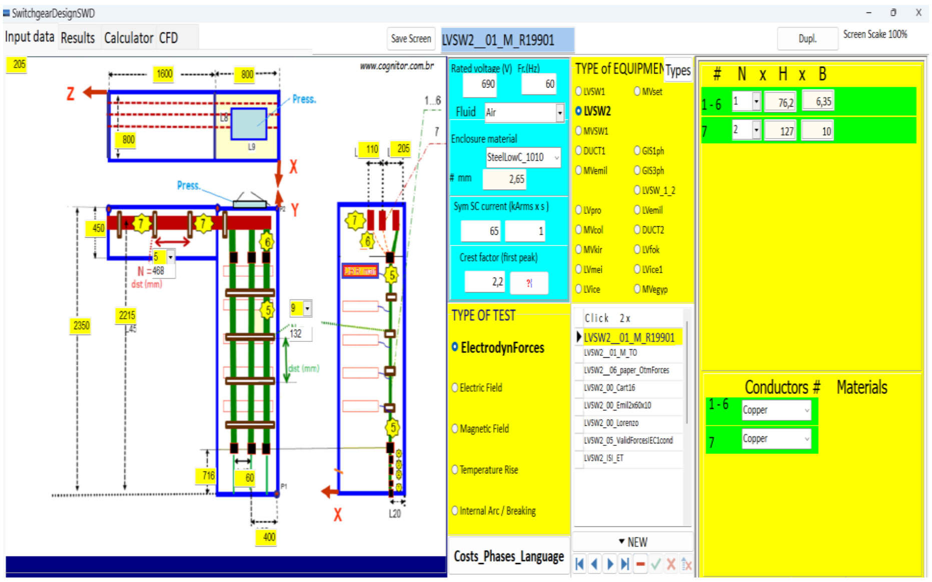


Figure 2b – Input data for calculation of forces and stresses in LV switchgear (References [2,3] – links below)

LV switchgear ttypes in which considerable savings in the number of supports

are frequently possible

because the vertical bars are very near (and close) and the short circuit levels are the same as the (large) horizontal bars



It is impressive to see the number of possibilities of optimizations and reduction of materials in the existing designs of some MV and many LV switchgear. A lot of money and resources are thrown away due to over-dimensioned designs. In many cases gains of 20 to 30% are easily achieved by a more precise calculation. This occurs not only in the aspect of mechanical forces but also with temperature rise aspects.

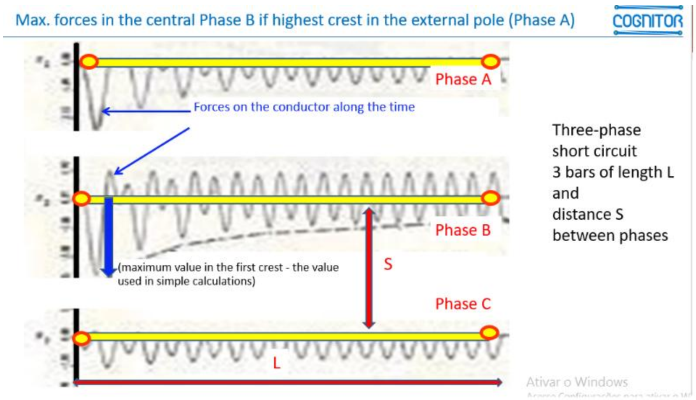
To assess the withstand ability of insulators and conductors the main steps to follow are:

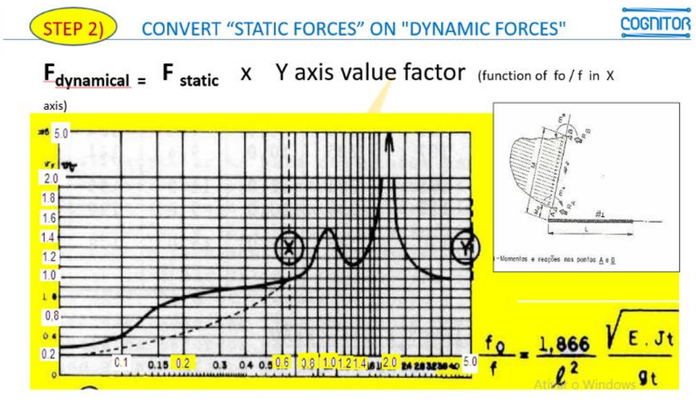
- Calculate the static forces distributions (equations above).
- Convert static forces in "dynamic" forces (figure below)
- Calculate forces on insulators, shear forces and bending moment diagram.
- Calculate mechanical stresses on the conductors = bending moment / resistant moment
- Compare stresses in conductors and forces in insulators with permissible limits.

The determining design parameters are:

- Geometry and distances between phases
- Materials
- Short circuit currents and its asymmetry
- Supportability (tensile, compression and bending) and distance between insulators.

Aspects of resonance and types of short circuit shall be considered properly to arrive at the final values of forces and in the assessment of the supportability **(Figure 3).**

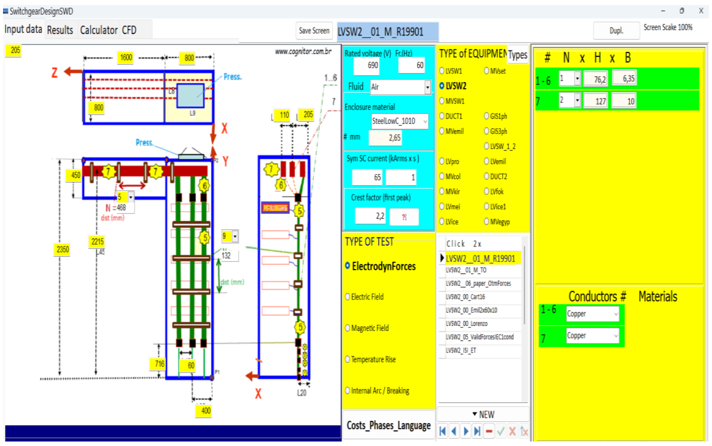


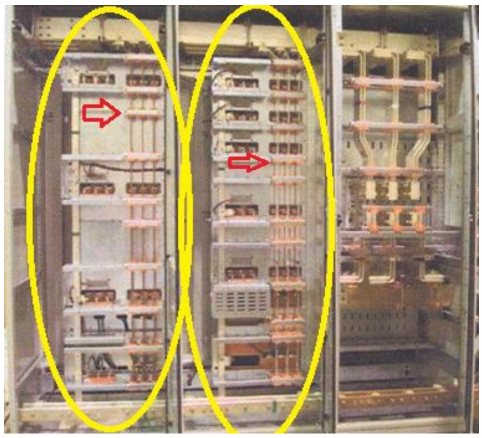


3. SIMULATING SHORT TIME CURRENT & CREST TESTS (AN EXAMPLE OF SAVING INSULATORS in Fig. 2b)

In this video – part of the article - we show a simulation made with the software SwitchgearDesign on a LV switchgear with asset of horizontal "strong" bars (2x127x10mm) and a set of vertical "thin" busbars (1x76,2x6,35mm).

In the vertical thin bars, there are several supports to avoid a visible permanent bending of the busbars after a short-circuit current of 65kArns / 143kAcr during 1s. It is like the drawers column in the photo.





The objective is to use only the minimum possible number of insulators by reaching, in the limits, the "optimal design objectives" which are:

- Forces acting in the insulators <= insulators limits for flexure. Compression and tension.
- Mechanical (normalized) strength in the conductors <= 1 to avoid a visible permanent bending.

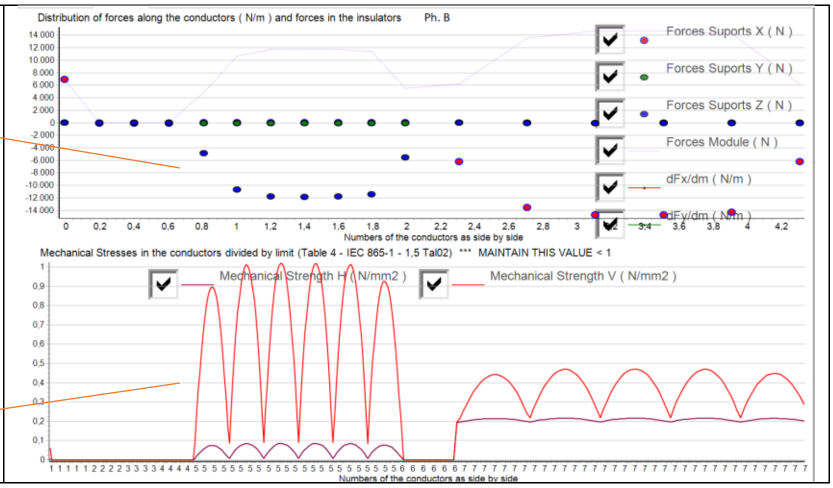


Figure 4a – Results by approximate method from manuals

Maximum force in supports < 14.000 N
Maximum normalized mechanical strength = 0,45 (< limit)
Distance between supports = 132mm **(9 supports)**

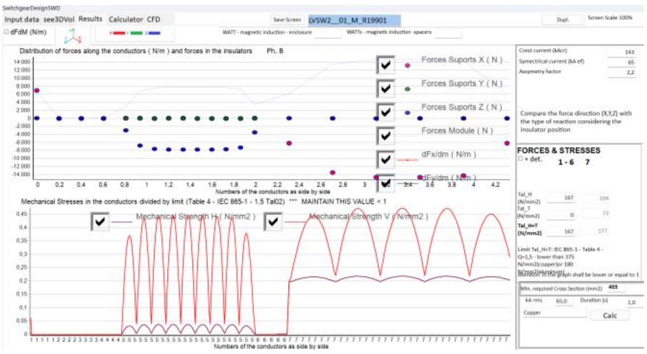
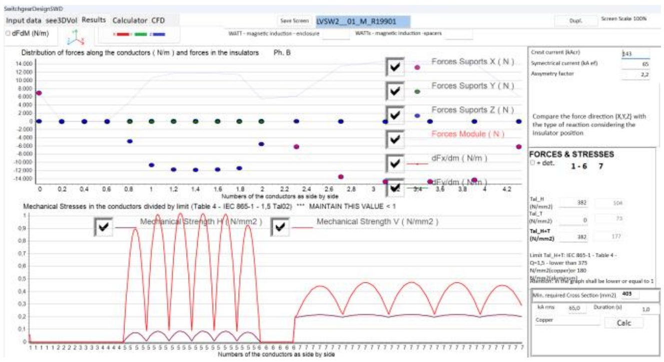


Figure 4b - Using the complete equations of SwitchgearDesign

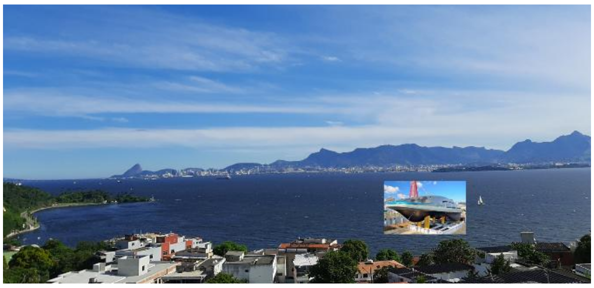
Maximum force in supports < 14.000 N
Maximum normalized mechanical strength = 1,00 (= limit)
Distance between supports = 1197mm **(6 supports)**



Click here to see the movie https://www.cognitor.com.br/forces.mp4

4. ADVANCED TOPIC: PROPULSION USING MAGNETOHYDRODYNAMICS (MHD)

There are modern applications of electrodynamic forces that go far beyond switchgear and substations busbars. Here is some general information about MHD (Magneto Hydrodynamics) propulsion. You may find much information in the Web.

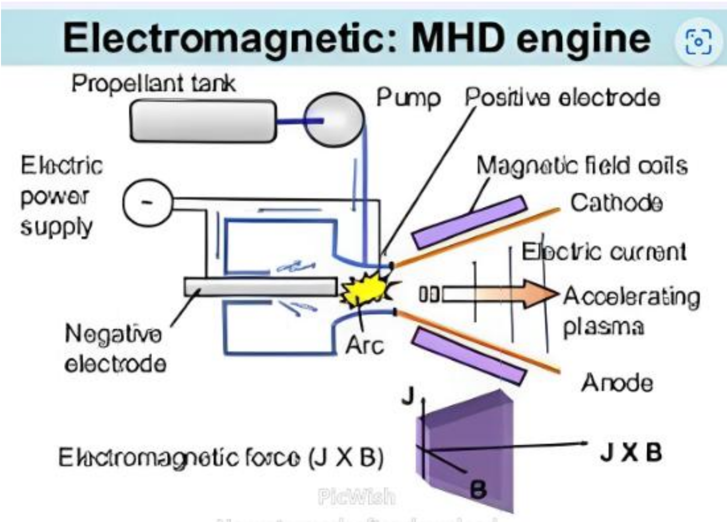


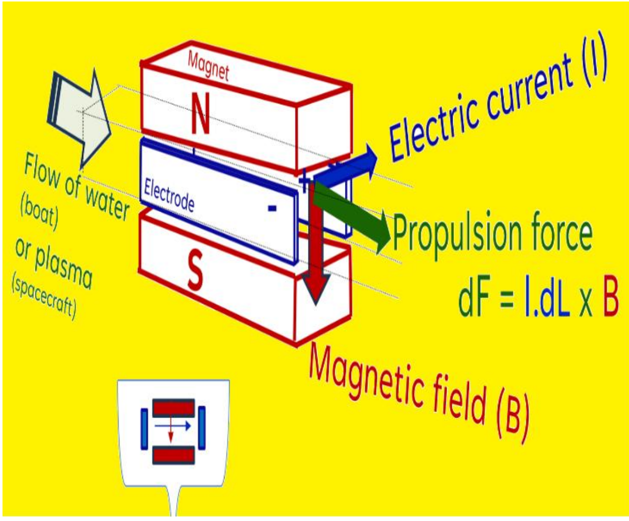
As in Wikipedia

https://en.wikipedia.org/wiki/Electromagnetic_propulsion#mw-head electromagnetic propulsion (EMP) is the principle of accelerating an object using the interaction between magnetic fields over conductors made of metals, water or plasma. It is the same principle of two electric busbars of a busway circulated by high currents. The current in one of them create a magnetic field that will reach the neighbour conductor creating mechanical (Lorentz) forces.

If you mind that one of the conductors is made of water or even plasma you can use the forces for the propulsion in a system designed to take advantage of the phenomenon. First you use something to create a strong magnetic field. After, a fluid (liquid or gas) is employed as the conductor that will be moved by the forces. It is sometimes named as magnetohydrodynamic drive. In electric motors the forces are used to produce rotational energy

The science of electromagnetic propulsion has application in many different fields. The thought of using magnets for propulsion has been dreamed of since at least 1897 when John Munro published his fictional story "A Trip to Venus".[1] The easier applications are in maglev trains, ships, and submarines. Check the fundaments in the figure.



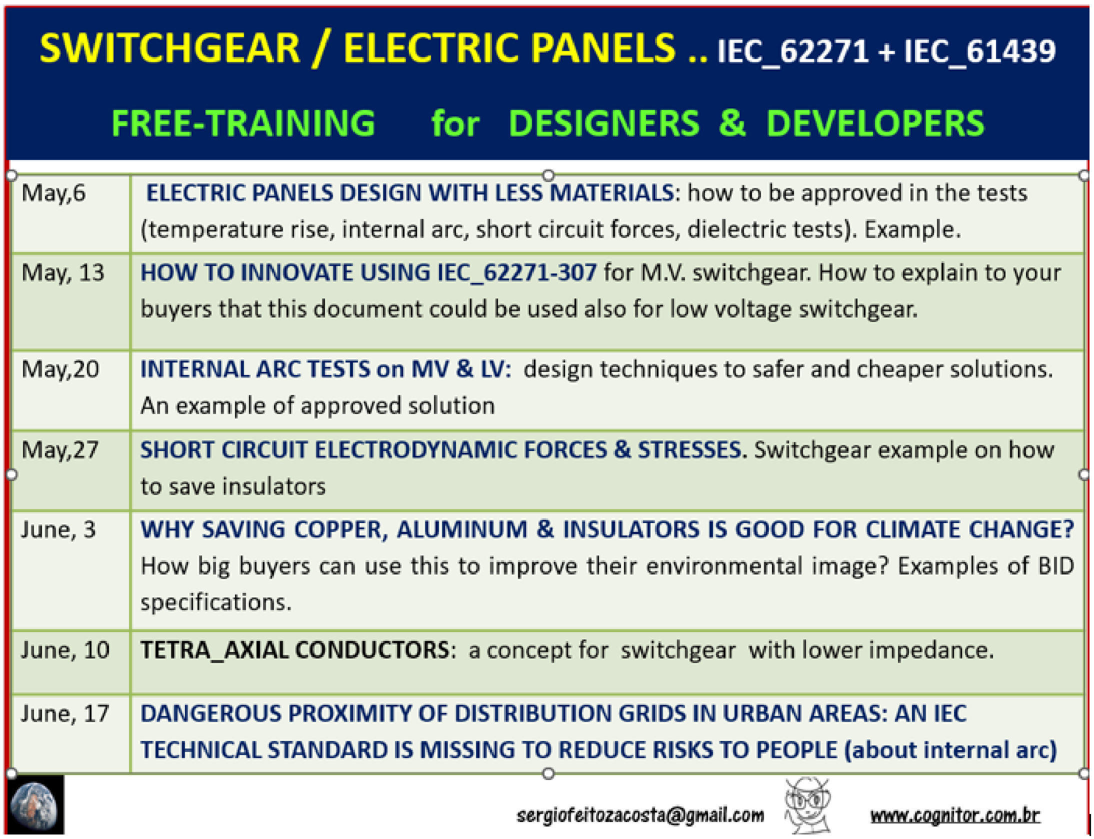


5. FINAL COMMENTS

The concepts and calculations of electrodynamic forces have been known for many decades, but there is still a lot of room for optimization in the design of switchgear, switchboards, busways, and busbar systems in general.

The potential of magnetohydrodynamics tends to be more explored at this time when the use of green hydrogen is being more explored. It is a good theme for R&D projects and master's or doctoral thesis. The use of hydrogen is now increasing on the Planet due to environmental issues. This will help bring more attention to the potential of MHD. When we do a simple search on the Web, we see that the number of experimental projects is significant, it is likely that developers are already seeing good medium-term opportunities.

This article is part of the free training I made available in the WEB. If you or your company need a presential training to go deeper in this theme, check this link https://www.cognitor.com.br/trainingENG.pdf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END OF THE ARTICLE

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Things I helped to do: https://www.cognitor.com.br/HelpedToDo.pdf

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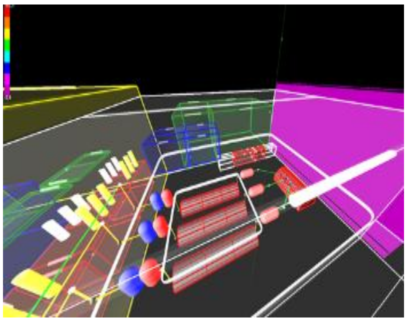

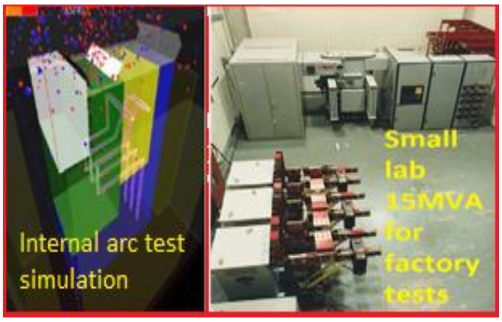

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