SOME CONCEPTS FOR THE DESIGN and SPECIFICATION of SUBSTATIONS (interruption of short circuits, electrodynamical forces and temperature rise).

Author name: Affiliation:
Sergio Feitoza Costa COGNITOR – Consultancy, Research and Training Ltd.

Email: sergiofeitoza@cognitor.com.br Site : www.cognitor.com.br

Keywords: IEC, CIGRÈ Simulations, High Power Tests, Switchgear, Switchboards, Bus-bar systems, Testing Laboratory, Internal Arcs, Overpressure, Temperature rise, Electrodynamic forces, stresses, Short time currents, EMC, Magnetic fields, Electric Fields, Substations, certification.

1 SOME TERMS AND DEFINITIONS

An electrical power system is formed by generators, transmission lines and the loads supplied by the distribution system. In the example of Figure 1, just to show the relationship between each part, we show a generator that produces a rms voltage of $\sqrt{2}$ V . The impedance of the system is $\sqrt{2}$ Ω (reactance 1 Ω plus resistance 1 Ω). So, dividing the voltage by the impedance we would have an electrical current of 1 A.

The transmission line is composed of a large reactance and a small resistance of the cables. The phase angle between the reactance and the resistance of the line is near to 90°, for example 87 °. To meet the requirements of the power utilities, the load must have a phase angle close to zero (eg power factor> 0.92). In the load, the consumer must, if necessary, place capacitors in parallel with the inductances of motors, etc, so that the reactance becomes sufficient to attend the minimum power factor value prescribed. In the transmission line, the power utility shall assure that the losses are minimum to enable the power produced in the generator to arrive, almost all, in the load.

We use the terms rms voltage and current (eg 138 kV_{rms} and 40 kA_{rms}) and the term instantaneous current (eg 2.5 x 40 kA_{rms} = 100 kA_{crest} on the first crest of a short-circuit current) as shown in Figure 2.

Figure 1 – Simplified electrical power system

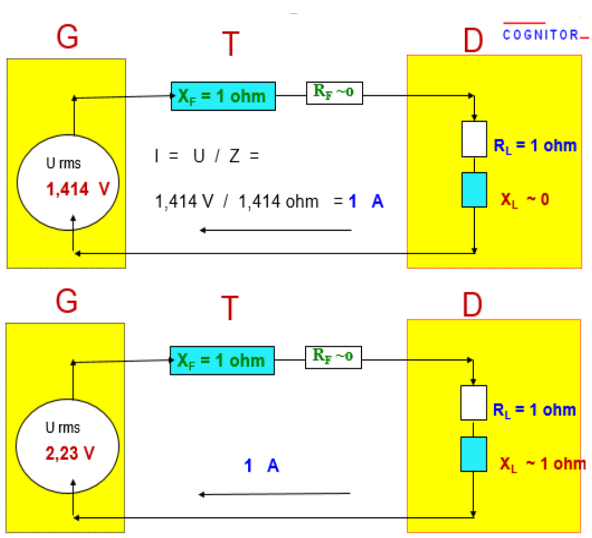
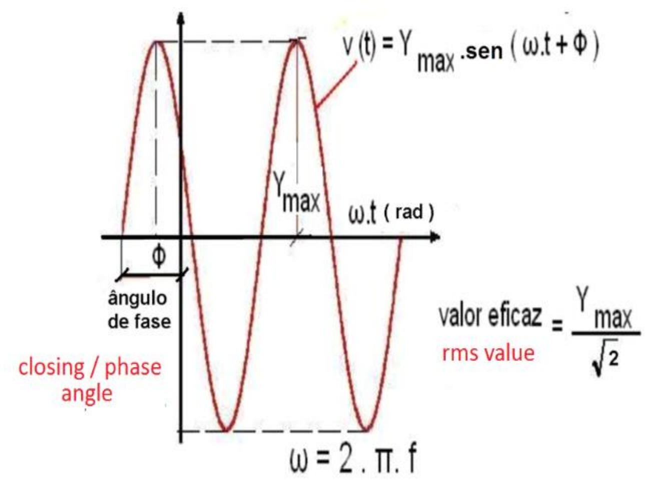


Figure 2 – Short circuit closing angle



A typical situation in a substation is presented in Figure 3. In normal mode, a current less than or equal to the rated normal current (I_N) arrives to the loads (X_L and R_L where $X_L << R_L$). When there is a short circuit near the substation, the voltage of the source will pass only in the reactance and resistance of the source (X_f and R_f where $X_f >> R_f$). So, the current will increase very much. A typical short circuit current is between 4 to 25 times the value of the normal current.

During a short circuit caused, eg by a branch of a tree touching one of the cables, the voltage wave (Figure 4) may be passing through any point of the voltage wave (closing angle Ø). Some devices called synchronizers allow certain operations to close and open substation circuit breakers at a controlled angle.

Controlling closing or opening angles may force the overvoltages or overcurrents in a particular switching operation to be lower than would occur without control. The synchronizers add a certain cost to the circuit breaker but produce far greater benefits. In substations with voltages higher than 245 kV they are widely used. In high voltage networks of 138 kV, 69 kV and less they are little used due to the incorrect view that they make the circuit breaker more expensive.

Figure 3 – Typical substation, normal and short-circuit currents

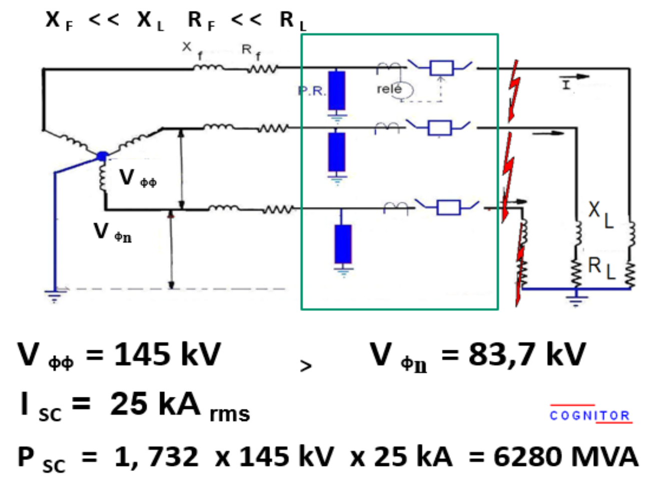
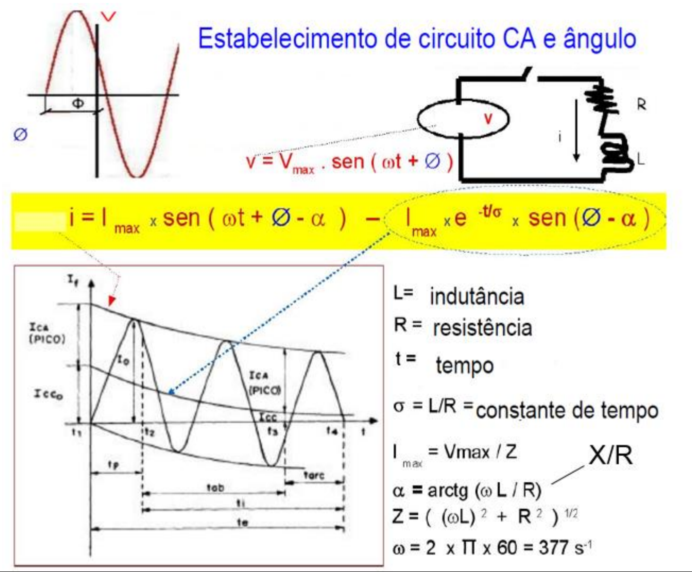


Figure 4 – Closing angle and short-circuit instantaneous current



The closing angle on the voltage wave affects the value of the first crest current. The values of reactance and resistance shown in the equation of Figure 4 are in such relation that cause the first crest of current to be around 2.6 times the effective current value, when we are not very close to generators. As an example, it is common to see, for a 145 kV_{rms} circuit breaker, the specification of a symmetric 40 kA_{rms} short circuit current and the first crest of the current 2.5 × 40 = 100 $kA_{crest.}$ These values are used to calculate the supportability to the thermal effects of the short circuit current (40 kA_{rms}) and the electrodynamic effects (100 kA_{crest})

When the short circuit occurs near generators the so-called asymmetry factor may have values higher than 2.6 (Figure 5), for example 3 or more. This occurs because in the initial moments of the short circuit the transient and sub transient reactances are much smaller than will be some 2 electric cycles after.

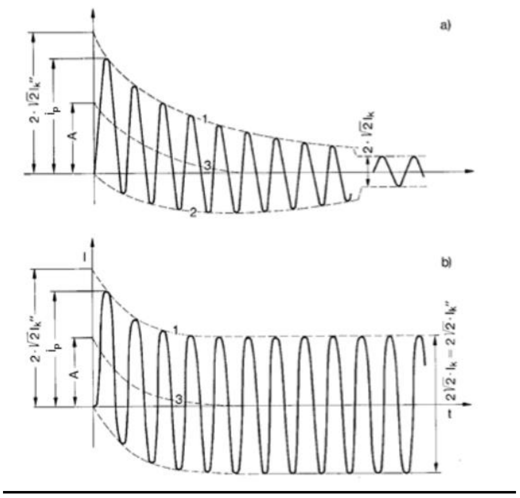
A critical factor in specifying interrupting devices such as circuit breakers, reclosers, and fuses is the transient recovery voltage (TRV). When there is a short circuit in the network, which may even lead to a blackout, we have a dispute between the circuit breaker trying to open the circuit as fast as possible and the TRV, which is a reaction caused by the inductances, capacitances and resistances of the system trying to keep the previous situation. The process is shown in Figure 6. The red line is the withstandability of the circuit breaker to the TRV wave in the period just after the current zero, when the breaker is trying to do the interruption. The more time passes and the contacts move away, the greater the dielectric withstandability becomes until the end of the course of opening distance is reached and the line is horizontal. The black oscillating line is the TRV that depends on the electrical characteristics of the system and (almost) does not depend on the circuit breaker unless it has special resistors or capacitors that add up to the values of the network to facilitate the interruption. If the black line becomes above the red line the circuit breaker can no longer isolate the fault and a re-ignition occurs, restoring the short-circuit current.

The wave shape of the maximum TRVs that can be produced by the system is described in technical standards like IEC 62271-100 produced by IEC - International Electrotechnical Commission. These values are established by the IEC mainly based in surveys done in the working groups of CIGRÈ - International Council on Large Electric Systems. Countries around the world are consulted in these surveys. The values showed in the IEC standards represent something like the 98% more common cases occurring all over the World.

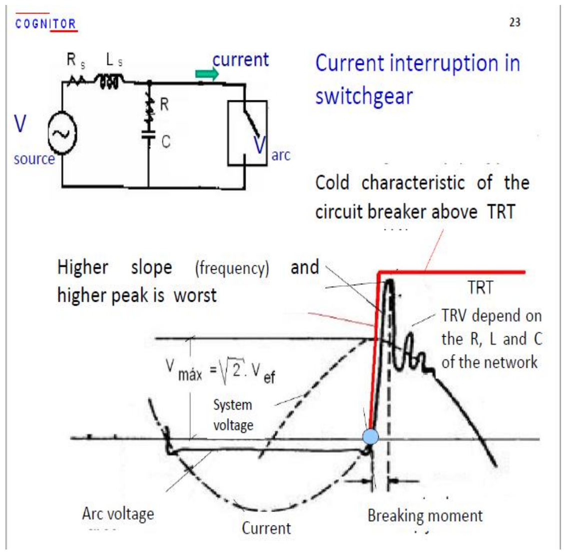
Here there is an interesting point. There are worldwide efforts in the direction of providing effective solutions for low cost substations for electrification of rural and remote areas in developing countries, where electricity supply is non-existent or unreliable (see work of Cigré WG B3-43). Implementation of low cost technologies is directly associated with the high costs of testing equipment in testing labs. Other factors are the education & training and having technical standards and power utilities specifications with proper requirements (not necessarily the same used for developed countries). An IEC standard which is used to assure a good quality of energy in a city of Europe maybe is not the proper one to assure the existence of a minimum electricity service in a poor region of Africa, Asia or South America. The experts which produce the IEC and Cigré documents are mostly from the developed countries. They invest in participating in these activities to defend the particularities of their systems.

The TRV waveforms have different frequencies and amplitudes depending on the greater or lesser value of the interrupted current (Figure 7). If the short circuit occurs closer to or farther from the circuit breaker, capacitances and inductances are different and these affect the value of the current and waveform of the TRV.

Figure 5 - Short circuit current near or far from generators



Figurea 6 – Transient recovery voltage



In standards, the TRV waveforms are represented by two parameters (Figure 8) or by 4 parameters depending on the system voltage level. The 4-parameter representation is used for circuit breakers above the 245 kV range and is a more refined representation of the 2 parameters one. Another factor required in the specification is the first pole to clear factor (Figure 9). This factor is related to the fact that the short circuit currents in each of the 3 phases are 120 degrees out of phase. Therefore, the interruption in one of the phases happens before the simultaneous interruption in the other two phases. It can be shown by calculation that the voltage in the first phase to be interrupted is somewhere on the order of 1.4 to 1.6 times that in the next two.

For higher power circuit breakers, say over some 10.000 MVA (near 145 kV - 40 kAef) even the largest testing laboratories in the world cannot test all three phases simultaneously. The test is done on only one pole with the full short-circuit current applied and a voltage at the interruption equal to the phase to rated ground voltage times the first pole to clear factor.

Figure 7 – Interruption of low and high currents

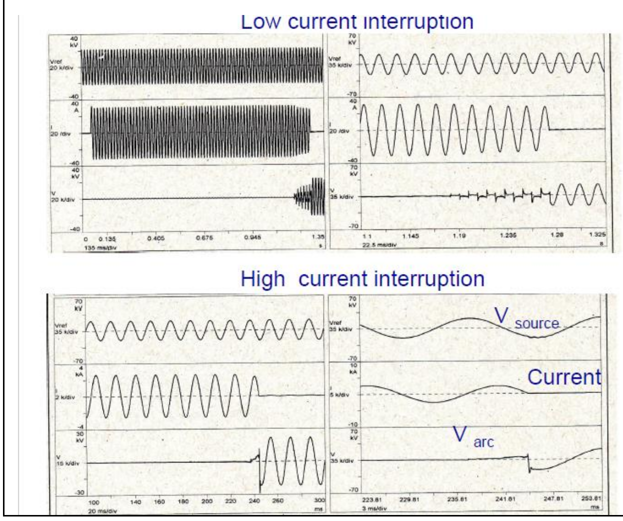
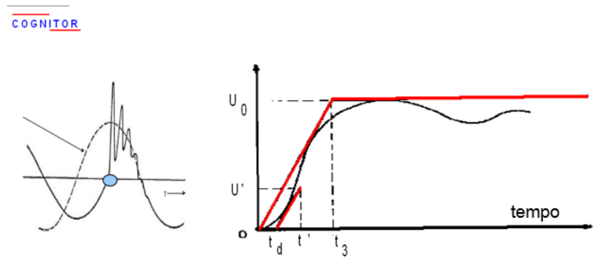


Figure 8- TRV representation – 2 parameters



	Tensão Nominal U_r (kV)	Tipo da interrupção	Fator de primeiro polo k_{pp} (p.u.)	Fator de amplitude k_{af} (p.u.)	Valor de pico da TRT u_c (kV)	Tempo t_3 (μs)	Tempo de retardo t_d (μs)	Tensão u' (kV)	Tempo t' (μs)	TCTR[b] ** u_c/t_3 (kV/μs)
	4,76[c]	Falta terminal	1,5	1,4	8,2	51	8	2,7	24	0,16
		Discordância de fases	2,5	1,25	12,1	101	15	4,0	48	0,12
	72,5[a]	Falta terminal	1,5	1,4	124	165	8	41	63	0,75
		Falta quilométrica	1	1,4	83	166	8	28	64	0,50
		Discordância de fases	2,5	1,25	185	336	50	62	163	0,55

Related to the substation equipment's ability to conduct normal currents (ampacities), the main factor to consider are the temperatures of certain parts of the equipment that cannot be exceeded under the risk of causing premature aging or immediate damage. The temperature of conductive or insulating parts cannot go beyond the limits of the supportability of materials. These limits are specified in the technical standards for use in temperature rise tests. These limits apply to contacts, terminals, connections, welding and insulation.

As an example, the temperature rise of a silver connection measured in the test cannot exceed 75K. Imagining that the ambient air temperature surrounding this connection was 40°C, what the standard value means is that the average working temperature over long periods cannot exceed 40 + 75 = 115°C. The calculation methods shown in document IEC 60943 make it possible to estimate that if a contact operates at a temperature of 10°C above the limit, its lifetime will be reduced by 67%. For example, over a period of 10 years three contacts would have to be purchased instead of just one (see page 113 of the Reference [1]

The main villains provoking high temperatures are the unavoidable contacts and electrical connections. Imagine we had a 10-meter-long copper bar and no joints or connections. When passing a current of 1800 A, the temperature rise at all its points would be of the order of 30K above ambient air. However, if we sawed the bar and made a bolted union, at the cut-off point, the temperature rise in the connection would be of the order of 40K. (Pages 107 and 108 of Reference [1])

Figure 9- First pole to clear factor during interruption

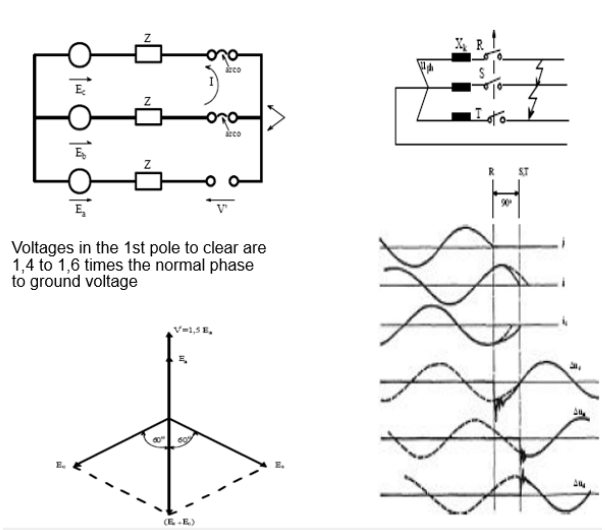
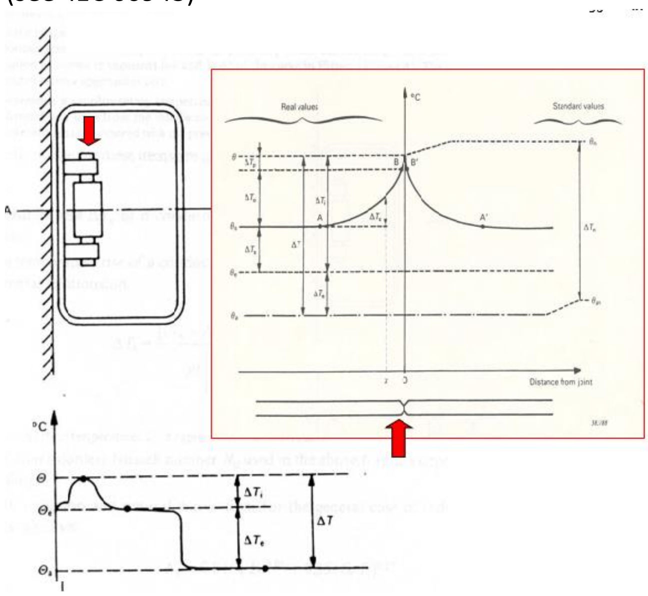


Figure 10 - Temperature rise near na electrical contact (see IEC 60943)



Severiano da Fonseca, 68 / 203 *** Rio de Janeiro – RJ – Brazil - CEP 21931-220
Phone: 55-21-2465 3689 *** 55-21-33934600 *** Cell phone. 55-21-9 88874600
E-mail: sergiofeitoza@cognitor.com.br Site: http://www.cognitor.com.br

The contact resistances of busbar connections can be calculated from expressions such as shown in Figure 11. IEC60943 (Ref. [2]) shows many particularities on this subject. For transformers, the concepts are of the same nature and the limits of temperature rise follow similar principles. The focus in this case is that temperatures are not exceeded which would cause accelerated aging of the insulation paper or which could initiate a process of deterioration and bubble formation in the insulating oil. This applies particularly in the peak hours overloads.

The main parameters that affect the result of the temperature rise tests are:
• The contact and connection resistances (not only the total resistance per phase)
• Fluid velocity, type and area of ventilation
• Cross section and geometric position of bars (vertical, horizontal)
• Materials of bars and their coatings
• Fluid interconnections between compartments

The IEC standards do not address the relationship between the temperature rise and internal arc tests and do not make explicit what should be recorded in the test reports. The recent IEC 62271-307 is good for understanding these aspects. Medium and low voltage panel standards should ask - but do not ask - to record these resistances in the test report.

Figure 11 - Calculation of the contact resistance (see IEC60943)

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$$R_c = \frac{\rho}{2.\eta.a} + \frac{\sigma_0}{\eta.\pi.a^2}$$

$$a = \sqrt{\frac{100}{18.\pi.(0.45).(5.5x10^8)}} = 85x10^{-6} m$$

$$n = 2.5x10^{-5}\ x(5.5x10^8)^{0.625}\ x100^{0.2} = 18.2 = 18$$

$\rho = 1.78 \times 10^{-8}\ \Omega.m$
$\sigma_0 = 5 \times 10^{-12}\ \Omega.m^2$

$R_c = 6 + 12 = 18\ \mu\Omega$

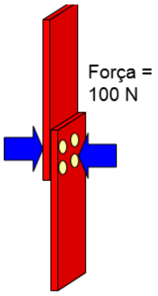
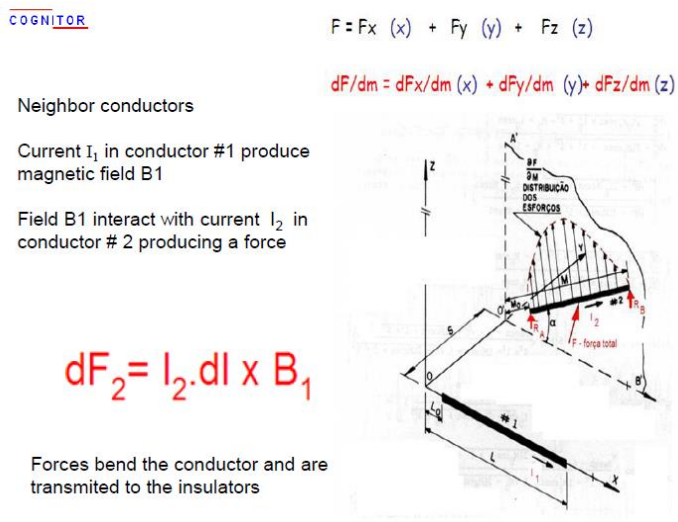


Figure 12 - Electrodynamic forces

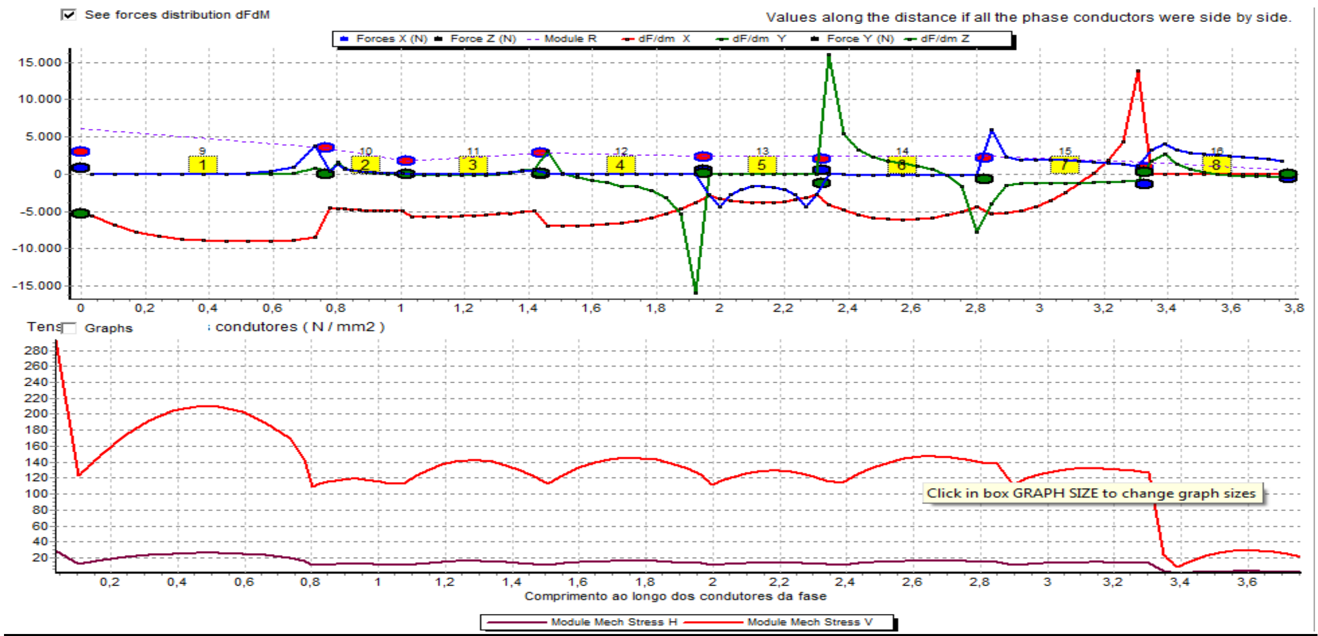


Regarding the electrodynamic forces and stresses that occur during a short circuit, in Figure 12 the main concepts are shown. When a current is circulated through a conductor, a magnetic field is produced that will act on the neighboring conductors producing forces in the conductors, tending to bend them (pages 124 to 138 of Reference [1].) These forces will be transmitted to insulators and supports.
In the IEC 61117 (Ref. [3]) is shown in detail a calculation method which consists of.
• Calculate static force distributions by equations
• Convert static forces into "dynamics"
• Calculate forces on the insulators, shear forces and bending moment diagram.
• Calculate mechanical stresses in the conductors (bending moment / resistant modulus)

The main parameters affecting the results of electrodynamic tests are:
• Geometry and distances between phases
• Materials used and their electrical and mechanical properties
• Values of short-circuit currents and their degree of asymmetry.
• Supportability to traction, compression and flexion as well as distance between insulators

Figure 13 shows the results of a typical electrodynamic stress analysis for the design of panel and busbar systems. At the top are the forces on the insulators that cannot exceed the limit values specified by the insulation manufacturer. At the bottom are the mechanical stresses which, for copper, should remain below around 250 N / mm2.

Figure 13 - Calculation of forces in insulators and mechanical stresses in conductors.



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The author of this article is Mr. Sergio Feitoza Costa. Sergio is an electrical engineer, M.Sc in Power Systems and director of COGNITOR. Sergio has 25 years of experience in design, operation and management of high power, high voltage and other testing laboratories. After activities in testing labs Sergio acquired 16 years of experience in the use of testing simulations, giving support and consultancy to manufacturers and certification companies.

Sergio is the author of the simulation software SwitchgearDesign. It enables simulations to predict the results of high power and high voltage tests. The reader may find Information in free training movies in the following link in YouTube (Item 1, Item 3 Item 7 in English . Others in Spanish and Portuguese.
https://www.youtube.com/channel/UCyQtdE7dQTvsZPHBw3ostMg/videos?view=0&sort=dd&shelf_id=0

Sergio is, in the last 3 years, involved in the implantation of a new set of big testing laboratories which are under construction in South America (High Power lab 2500 MVA, High Voltage testing up to class 550 kV and temperature rise up to 25.000A).

In these links, there are some videos and reference material, inclusive for validation of testing simulations:
Cognitor site and CV http://cognitor.com.br/en/site/index.php?sec=1

Articles and book by Sergio (free download) : http://www.cognitor.com.br/en/site/index.php?sec=5

Information on trainings http://www.cognitor.com.br/en/site/index.php?sec=3
More information on trainings, forum, etc..: http://www.cognitor.com.br/en/site/index.php?sec=6
LinkedIn posts : https://www.linkedin.com/today/author/0_0Qwvfip2RwUUnZw30ieO2m?trk=mp-reader-h
Trainings and consultancy are available in English, Spanish, Portuguese and (partially) in French.

Sergio Feitoza, in the vacant time, is musician (guitar), composer and singer. Here is part of a recent show https://www.youtube.com/watch?v=TYPnmY7_LYE