VALIDATION OF SIMULATIONS OF ELECTRODYNAMICAL FORCES, TEMPERATURE-RISE AND INTERNAL ARC TESTS IN SWITCHGEAR
(and main parts of a code to do them)

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Power Transformers

1) INTRODUCTION:

Power transformers requirements are specified in IEC 60076-5. In section 4.2 of the standard it is written the following about to sustain without damage the effects of short circuits "… If required by the purchaser, the ability to withstand the dynamic effects of short circuit shall be demonstrated either by tests, or by calculation and design considerations. The choice of method of demonstration to be used shall be subject to agreement between the purchaser and the manufacturer prior to placing the order ...." To calculate electrodynamical forces on transformers is a complex task and practically impossible to validate even by a simple comparison with another already tested transformer.

From the paper "Test Experiences with Short-Circuit Withstand Capability of Large Power Transformers" (KEMA authors R. Smeets, L. Paske, P. Leufkens – April 2008) we understand that few transformers are tested and 30% of the ones tested fail initially in the IEC short-circuit tests.

So, within the scope of widely used IEC standards there are relevant openings to replace expensive laboratory tests by simulations or calculations. To do this in a wider scale, for other types of equipment means to provide industry and users with economies of design. To achieve this it is necessary to fix some rules. Someone should do the start up with an IEC New Work Item proposal.

A first step could be to create openings to replace temperature rise tests on medium voltage switchgear, busbar systems and fuses by simulations. For these last ones it is very easy to prove that the results of real tests are almost equal to simulation results. For a temperature rise test there is nothing that could happen in a real test which could not be considered in a simulation.

Nevertheless, there is a hidden barrier for a wider use of simulations to replace tests. In a first moment, the parties which would be benefited would be the users, by cheaper equipment, and the small and medium sized manufacturers. These last ones would become more competitive in front of the bigger size ones which have their own laboratories. Small and medium size manufacturers generate many job positions all over the World but have low ($) access to testing labs and do not participate regularly in IEC working groups.

So, who could take the initiative to propose a new work item within the IEC work to make the replacement of some tests by simulations? IEC advisory and management committees could analyze this.

Let's go now to the validation subject.

Electrical equipment testing simulation techniques can be used to foreseen testing results at low cost. This is particularly true when the simulation results are analyzed by people which know, by previous practical experience, without calculations, the results to expect. Due to the big number of input variables involved it is frequently difficult to identify whether the simulation results are valid.

The author of this paper is an electrical engineer with experience in high power testing, equipment and substations design and with IEC technical standardization management. After many years working at a high power laboratory he developed (by lack of funds to invest in a real lab) a home-made software tool to simulate of equipment performance under high power tests. The objective was just to reduce the risk of failures during the expensive real laboratory tests.

The objective of this paper is to show that simulation results can be very near to the laboratory test results and can contribute to reduce the price of electricity. We present results useful for the validation of simulation tools. The focus is on the following tests, whose principles are detailed in the Annex:

- Internal arc tests (overpressures during arc faults)
- Short-time withstand current and peak withstand current (electrodynamical forces and stresses)
- Temperature rise test.

The main parts of the home-made Delphi code developed by the author are available in the Internet links http://www.cognitor.com.br/ElectrodynamicalForces_code.pdf and http://www.cognitor.com.br/InternalArc_code.pdf

Simulation results within minus or plus 5 to 10% of the actual results obtained in the laboratory tests are sufficient for design purposes. This range is lower than the errors obtained when doing laboratory measurements of overpressures, electrodynamical forces or the temperature of the air in different points inside switchgear or a fuse or a transformer.

As the costs of high power tests are high it is a common practice for manufacturers to use safety factors in a range higher than 30 to 40%. They do this to avoid the risk of failures in the test. So, the possibilities for the optimization of the equipment design though simulations are considerable. An example is to reduce in 40% the number of epoxy insulators needed to resist to the electrodynamical forces in the construction of a bus duct for 4000A rated current and 50 kA short circuit..

2) THE DIFFICULTIES TO OBTAIN ACTUAL TEST RESULTS TO DO THE VALIDATION

The first step for the validation was to obtain test reports with results and input data which could be compared with the simulations. Even having in hands many different test reports issued all over the World people experienced in high power tests will have the perception on how not reproducible are such tests. In practically all the cases the equipment is not properly identified by photos, drawings and contact resistance measurements. It is usual to find in laboratory test reports – no reasonable identification drawings – but, instead, sentences more or less like

> *"The test results apply only to the specific piece of apparatus tested … the responsibility for conformity of any product having the same designation with that tested rests with the manufacturer"*

> *"The manufacturer has guaranteed that test object submitted for tests has been*

manufactured in accordance with the presented drawings. “

It is common to find, when validating temperature rise tests, reports which do not inform even the dimensions of the bus bar used in the equipment. The user has to pay attention, when buying a certain product, if the test report presented is not of another different product.

The main reason for the “non-reproducibility” of the tests is that our international technical standards do not give guidelines on how to do, properly, the identification of the tested equipment by drawings and photos. For example, in temperature rise tests it should be explicit in the test report the physical ventilation area, the temperature rise of the air inside the switchgear and the electrical contact resistance of the main equipment as circuit-breakers (and not only the total resistance per phase).

The inclusion of the measurements and specifications which make the test reproducible do not imply any significant cost to the test. In the 2010 revision of the Brazilian standard corresponding to IEC 60282-2, by the first time, something was done in this direction.

In another recent paper entitled ” Switchgear, busbar systems and its built-in components: something is missing in IEC standards and user specifications” which can be freely downloaded at the site www.cognitor.com.br there are details about this and suggestions to IEC on how to create the rules for the use of simulations to replace some laboratory tests.

The test reports available for the validation were not good enough to do a 100% reliable comparison between simulation results and test results in a reliable basis. Here are some comments on this:

a) Temperature rise tests

None of the test reports available showed simultaneously the electrical resistances, the ventilation areas, detailed drawings and temperatures of the air inside and parts inside. IEC TR 60890 Ed. 1.0 b: 1987, A method of temperature-rise assessment by extrapolation for partially type-tested assemblies (PTTA) of low-voltage switchgear and controlgear shows clearly why this information is necessary.
Two test cases made in 3rd part testing laboratories were used. The first one is a test made by a bus bar system manufacturer in which almost all the input relevant data for electrical resistance, ventilation openings, etc. is available. The second one was a test made on 15 kV switchgear.

b) Internal arc test

The test case used is a successful test made by a manufacturer in a 15 KV – 31.5 kA – 1s switchgear according to IEC 62271-1. The lab measured the internal pressure without any extra-cost. The pressure is the decisive agent for the good or bad test result. So, this measurement should be mandatory to be registered in the test report but our technical standards simply do not require this measurement. The reachness of the particles and hot gasses is also decisive and most of the failures during switchgear tests are due to this reason. Nevertheless the reachness is very difficult to assess to enable an acceptable comparison between test and simulation.
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c) Short-time withstand current and peak withstand current (electrodynamical forces and stresses)

The validation of simulations of this test is difficult to do. High power laboratories do not measure the forces during testing because this is complicated and expensive to do. What is to be verified is just the physical state of the equipment after test and if there are no damages.

The reason for the good acceptance of calculations, even not proved by tests, is because the calculation methods for parallel conductors are published in several engineering manuals and are considered “proved by the daily life” for decades.

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In IEC 61117 – A method for assessing the short circuit withstand strength of partially type tested assemblies (PTTA), there are guidelines on how to do it but only for parallel conductors. If you join such method with the equations valid for any geometry, in the Annex, (from the author’s M.Sc. thesis) you can prepare an useful calculation tool.

In IEC TR 60865-2 - Short-circuit currents – Calculation of effects – Part 2: Examples of calculation there are some useful examples for checking the methodology results. By lack of alternatives the comparison to be done here is the test case showed in pages 19 to 27 of IEC 60865-2 (1994).

The calculation in this paper was done using the same input data showed in the IEC document but using the code developed by the author. This code was used, 30 years ago, to help in the design of a high power laboratory with currents up to 300 kA rms / 750 kA crest. The lab is still there in normal operation.

Looking carefully and increasing the size of the figures of the Annex it is possible to see all the relevant data used in the simulations here presented.

3) VALIDATION OF TEMPERATURE RISE TESTS SIMULATION

3.1) Test case 1 - Bus-bar 4000 A (480 V) – 3 x (150x10) mm – copper – horizontal – no ventilation

The detailed input data is showed in the figures A-1 and A-2 of the Annex. The obtained results are showed in the Figure A-3 of the Annex and in the table 3-1. To identify the position of the conductors and the connections mentioned in the table below, see Figure A-1.

Table 3-1 – Comparison between the temperature rises in K for the actual test results and for the simulation results at Phase B (reference Report 67131 March 2009)..

Point of the measurement at central phase B	Test result (K)	Simulation result (K)
Connection at the start conductor # 2	72,4	75
Bus-bar at conductor # 3	84,0	82
Connection at the center conductor # 4	83,5	84
Connection at the end conductor # 7 (short circuit point)	66,6	74
Enclosure side at 50% height	30,2	30
Fluid inside near top	not measured	54
Fluid inside middle height	not measured	47
Total resistance per phase = joints + bars (μΩ)	not indicated	31 + 3x7
Joints per phase resistance (μΩ)	not indicated	3 x 7
Ventilation	No	
Bus bar	Copper 3 x (150x10) mm Horizontal	

3.2) Test case 2 – Medium voltage switchgear with 2500 A (15 kV)

The detailed input data is showed in the figures A-4 and A-5 of the Annex. The obtained results are showed in the Figure A-6 of the Annex and in the table 3-2. To identify the position of the conductors and the connections mentioned in the table below, see Figure A-4.

Table 3-2 – Comparison between the temperature rises in K for the actual test results and for the simulation results (ref. Test Report 67735).

Point of the measurement	Test result (K)	Simulation result (K)
Connection at conductor # 1 (short circuit point)	47	32
Connection at the end of conductor # 3 (circuit breaker - low)	57	54
Connection at the end of conductor # 4 (circuit breaker-low)	64	66
Connection at the end of conductor # 5 (circuit breaker-high)	64	65
Connection at the end of conductor # 6 (circuit breaker-high)	52	53
Connection at end of conductor # 7 (top horizontal)	32	28
Enclosure door circuit breaker	5	
Fluid 50% height - cables compartment	not measured	13
Fluid 50% height - circuit breaker compartment	not measured	9
Fluid 50% height – bus-bars compartment	15	15
Total resistance per phase (μΩ)	66 (without 2x7)	80 (with 2x7)
Circuit breaker resistance per phase (μΩ)	Not measured	33
Ventilation	natural	Inlet 150 cm2
Bus bar (main)	3 x (100x10) mm	
Bus bar (derivation)	2 x (100x10) mm	

4) VALIDATION OF INTERNAL ARC TEST SIMULATION

The detailed input data is showed in figure C-2 of the Annex. The obtained results are showed in the Figures C-3 to C-5 of the Annex and in the table 4-1.

Table 4-1 – Comparison between performance indicators for the actual test results and for the simulation results for a 15 kV switchgear tested for internal arc with 31,5 kA during 1s. (IAC AFLR) (Reference report 08-050 – oscilogram ROZV 050U – May 08).

Parameters	Test result	Simulation result
Current kA rms and duration (s) prospective	31,5 – 1s	
Symmetric or Asymmetric current	Asymmetric	
Frequency (Hz)	50	
Arc compartment volume (m^3) x occupation factor	1,026 x 0,53 = 0,54	
Pressure relief area in the tested compartment (m^2) + grid	0,66 x 0,31 = 0,20	
Arc voltage (V rms)	530	567
Maximum overpressure above 1 bar ΔP (%)	52	52
Overpressure duration (ms)	42	45
Integral Pressure curve along the time (bar*s*1000)	to calculate	13
Time to 100% ΔP (ms)	18	21
Time to 50% ΔP (ms)	24~26	36
Ventilation	No	
Absorbers or parts like grids working as absorbers	Yes	
Bus bar	Copper 1 x (100x10)mm	

Virtual arcs number = 3   Virtual arc diameter = 0,5 mm   Hertz = 50

5) VALIDATION OF ELECTRODYNANICAL FORCES AND STRESSES SIMULATION (SHORT-TIME and PEAK WITHSTAND CURRENTS)

The detailed input data is showed in the figure B-2 of the Annex. The obtained results are showed in the Figure B-3 and B-4 of the Annex and in the table 5-1.

To identify the position of the conductors and the connections mentioned in the table below, see Figure B-2. In the Figures B-6 of the Annex there are other results for a 15 kV switchgear characterized in Figure B-5 and Table 5-2.

Table 5-1 – Comparison between forces and stresses for the actual test results and for the simulation results (ref. IEC 60865-2 – pages 19 to 27- 1994) in a bus-bar system 16 kA rms – 30,6 kAcr)

Parameter	Test result	Simulation result
Max. Mechanical stress σH (N/mm2)	24,7	25
Max. Mechanical stress σT (N/mm2)	16,1	17
Toa max. mechanical stress σH + σT (N/mm2)	40,8	42
Max. Force on the insulator in compression or tension (N)	Not considered	15
Max. Force on the insulator in flexion (N)	1606	1610

Table 5-2 –Comparison between forces and stresses for the actual test results and for the simulation results in a 15 kV switchgear 31,5 kA rms – 79,0 kA crest

	Test result	Simulation result
Max. Mechanical stress σH (N/mm2)	(*)	94
Max. Mechanical stress σT (N/mm2)	(*)	18
Max. mechanical stress σH + σT (N/mm2)	(*)	111
Max. Force on the insulator in compression or tension (N)	(*)	8918
Max. Force on the insulator in flexion (N)	(*)	5711

(*) the equipment was approved in the short time and crest current tests in a official laboratory.

6) FINAL COMMENTS.

The objective of this paper is to present a contribution to experts involved with the use of simulations of high power tests. There is a lack of information in this area because most of our international technical standards are still prepared under the old vision of “test everything”.

Another two texts will be published in the next months. The first one is related to a model to calculate the internal temperatures of power transformers under overload. Standards consider that the average temperature of windings and the hot spot point of a 55K transformer are lower than 10 K but may be much greater depending on the design. The second one is related to high voltage expulsion type fuses breaking tests (IEC60282-2)

A remark to present is that a real possibility for the use of simulations to replace real tests in switchgear, busbar systems, fuses and transformers (medium voltage and low voltage) is within certification institutes in countries where there is low availability of laboratories.

The author welcomes to receive testing results or simulation / calculation which may be useful to improve the validation of these results. A typical "Test Simulation Report" can be downloaded in ithis link http://www.cognitor.com.br/TR_000_10_ENG_Standard.pdf

The author of this paper is Mr. Sergio Feitoza Costa. Sergio is an electrical engineer, M.Sc in Power Systems and director of COGNITOR. The detailed CV may be read in the link http://www.cognitor.com.br/cv_english.htm (*)

Sergio has a 30 years experience in high power, high voltage and materials testing, R&D services, electrical equipment and power systems specification, simulation and operation. For many years he was the manager of the main high power and high voltage testing laboratories in Brazil.

His experience includes international technical standardization management (former chairman of IEC Technical Committee 32 - Fuses). Sergio is member of the CIGRÈ International Working-Group CIGRE WG A3. 24 - Tools for Simulating Internal Arc and Current Withstand Testing

He is coordinator of the Brazilian National Standardization Committee for High Voltage Fuses (equivalent to IEC SC32A) and coordinated some years ago the commission related to "Protection against Fire in Electrical Energy Generation, Transmission and Distribution Installations".

Sergio develops, for electrical equipment manufacturers, customized software for the calculation and simulation of internal arc tests, short-time withstand current and peak withstand current and temperature rise tests.

He also provides consultancy and training on "substations equipment and design" showed in the site. For more information write to sergiofeitoza@cognitor.com.br or call the phones indicated in the top of the page www.cognitor.com.br .

He can communicate in English, Spanish, Portuguese or French.

***Other recent publications in English*:**

1) *SIMULATION, IEC STANDARDS AND TESTING LABORATORIES: JOINING PIECES FOR HIGH QUALITY SUBSTATIONS*
http://www.cognitor.com.br/Artigo_Cigre_SergioFeitozaCosta_Cognitor.pdf

2) *CFD, IEC STANDARDS AND TESTING LABORATORIES: JOINING THE PIECES FOR HIGHER QUALITY HV EQUIPMENT.*
Paper published PS1-06 in the Cigrè International Technical Coloquium - Rio de Janeiro - September 2007

3) *SIMULATIONS AND CALCULATIONS AS VERIFICATION TOOLS FOR DESIGN AND PERFORMANCE OF HIGH-VOLTAGE EQUIPMENT*

Co-authors: M. Kriegel, X. Zhu, M. Glinkowski, A. Grund, H.K. Kim, P. Robin-Jouan, L. Van der Sluis, R.P.P. Smeets, T. Uchii, H. Digard, D. Yoshida, S. Feitoza Costa
CIGRE WG A3-20 publication A3-210 (2008) - Presented at the Congress Cigrè - Paris 2008

ANNEX – GENERAL INFORMATION ON HIGH POWER TESTS AND ITS SIMULATION

Annex A) TEMPERATURE RISE TESTS

Temperature rise tests are used from low to extra high-voltage equipment. The procedures for all are basically the same. The equipment shall be installed in a room free of air drafts and the rated current shall be applied during a time sufficient to have the temperatures of the measured points stabilized.

The final measured temperature rises of the parts shall not go beyond certain limits dictated by the properties of the insulating and conductive parts. These limits are showed in the relevant technical standard and, if they are exceeded, premature aging or even destruction of parts may occur along the equipment use. IEC TR 60943 explains very well the concepts.

The data affecting the test and the simulations results are the circulating electric current, the materials involved, and the contact resistances, the ambient air or other fluid temperature, the fluid velocity and the geometry of conductors and compartment components. The contact resistances are usually a known variable but they can also be estimated as function of the contact force, materials and coatings.

The validation of this type of test simulation should be easy because the proof is just the measurement of temperature done in the laboratory test. If you do a temperature rise test and, before it, you measure the resistances of the components and the geometry then you need only to compare test results with simulation results. The problem is that the technical standards do not request the registration of certain important parameters in the test reports.
In the lines at the end of the part C of this Annex I present the basic sequence for the development of simulation software for the calculation of temperature rises and also for the internal arc test.

Figure A1 – Input data for a test on a bus bar system with 4000 A

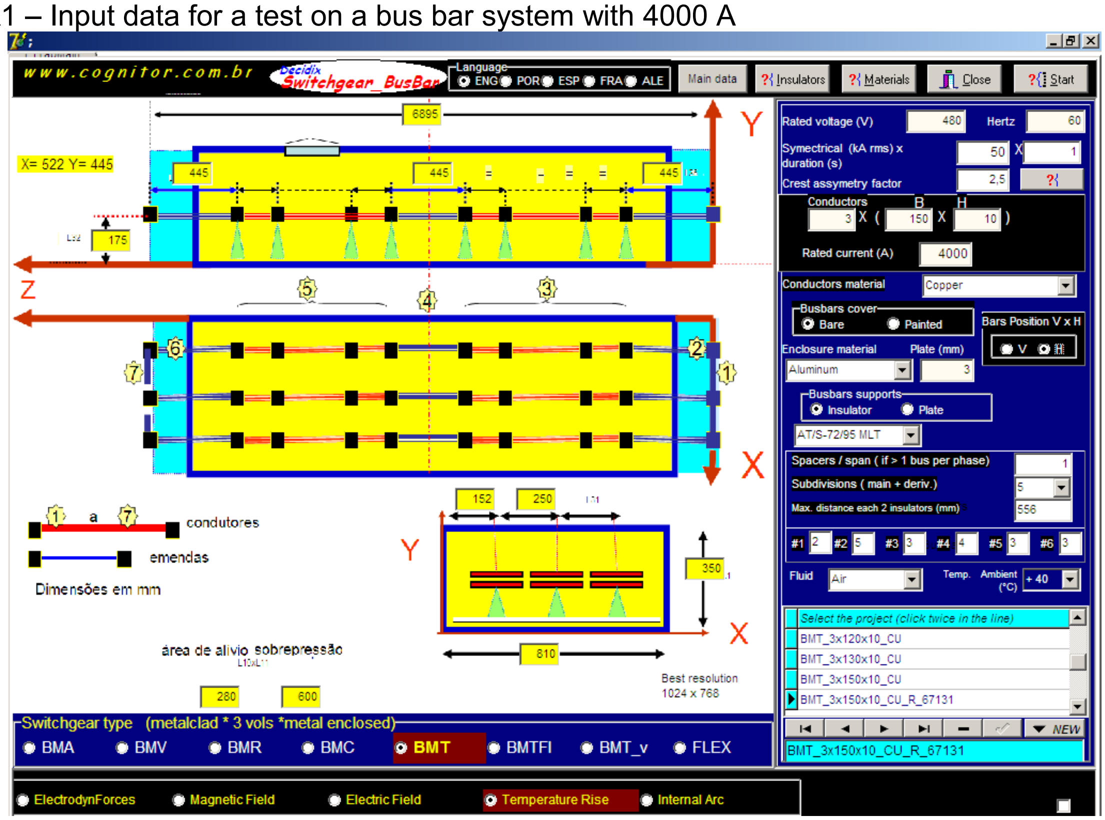


Figure A2 – Additional Input data for a test on a bus bar system 4000 A

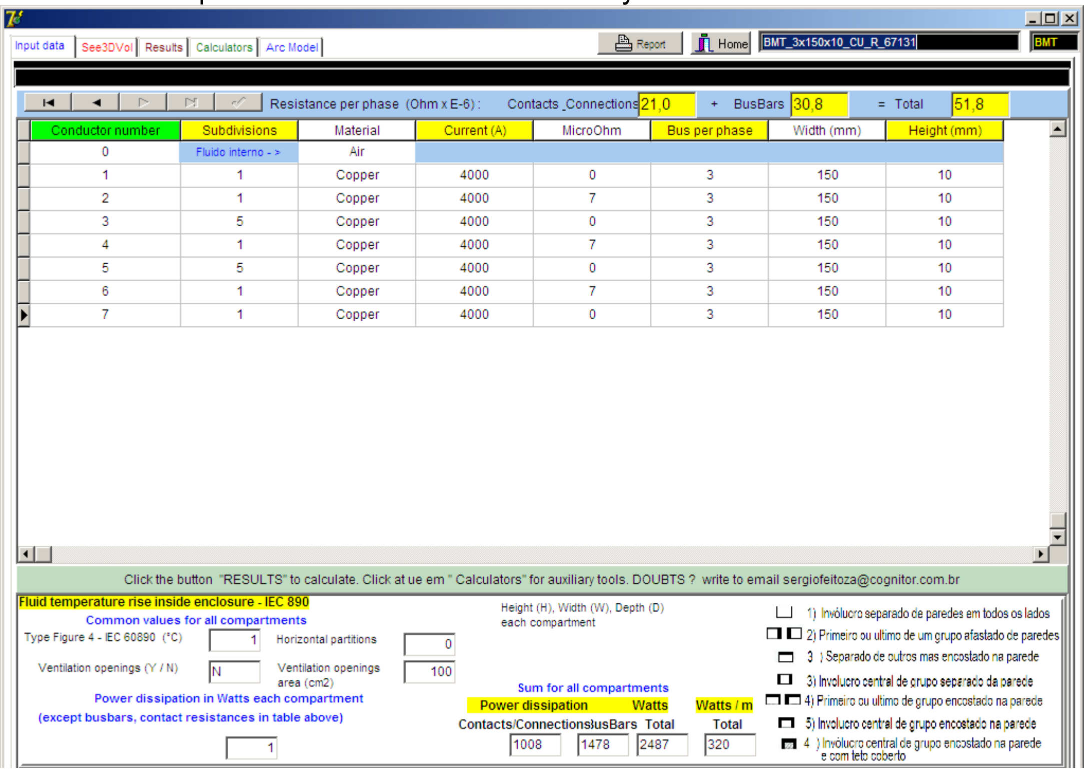


Figure A3 – Test Results for a temperature rise test on a bus bar system 4000 A

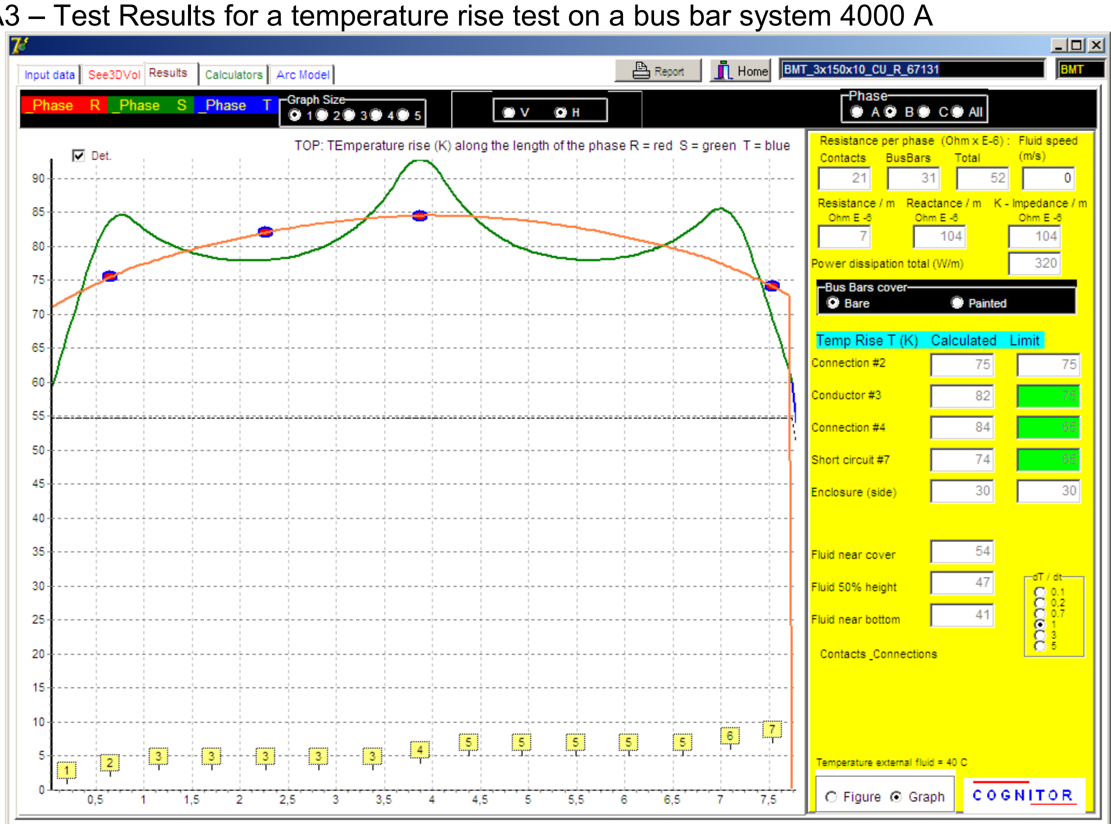


Figure A4 – Input data for a test on a 15 kV switchgear

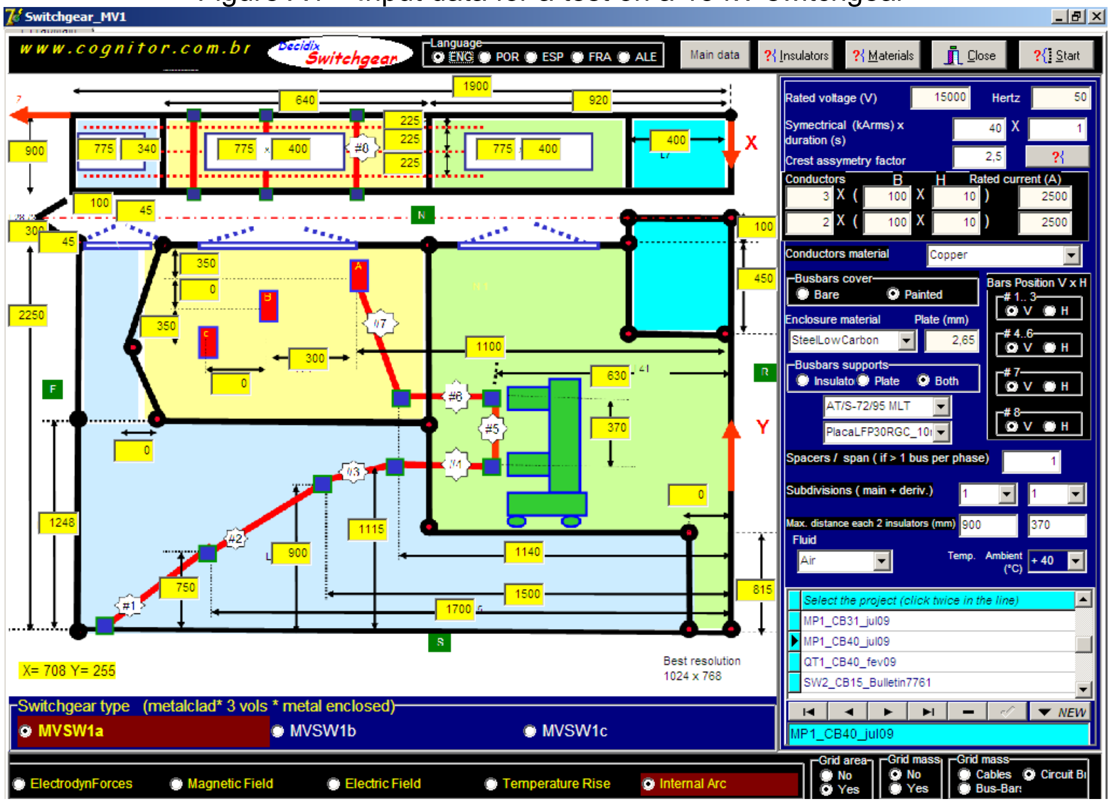
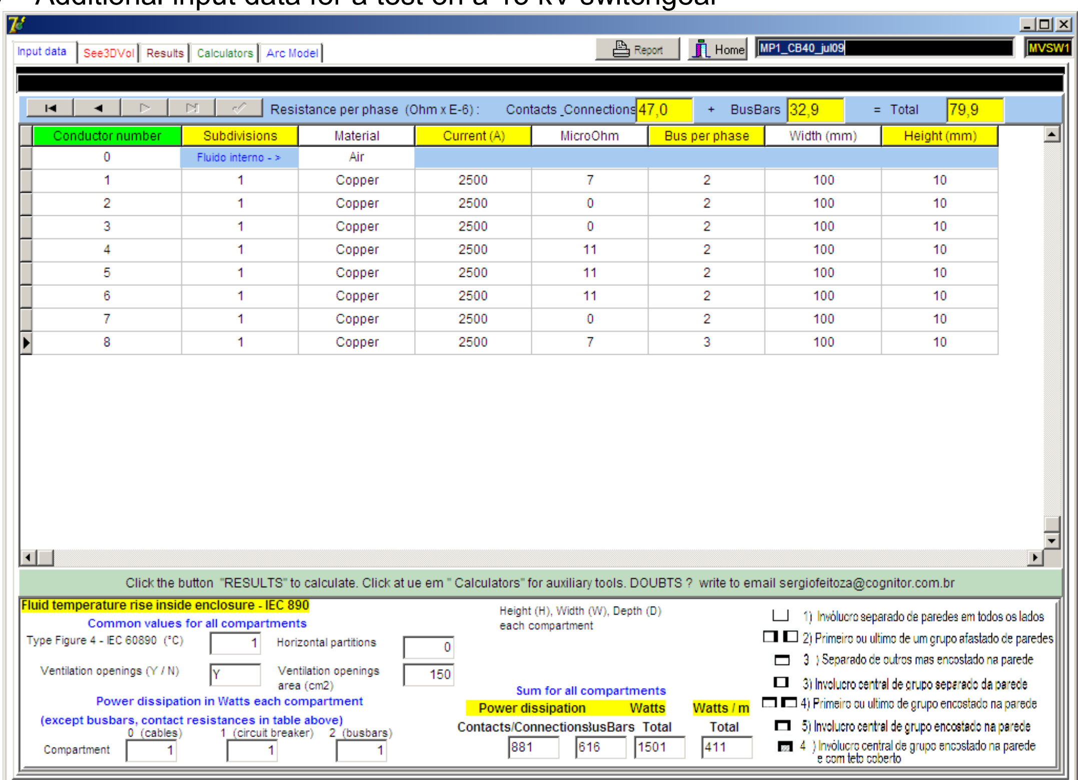
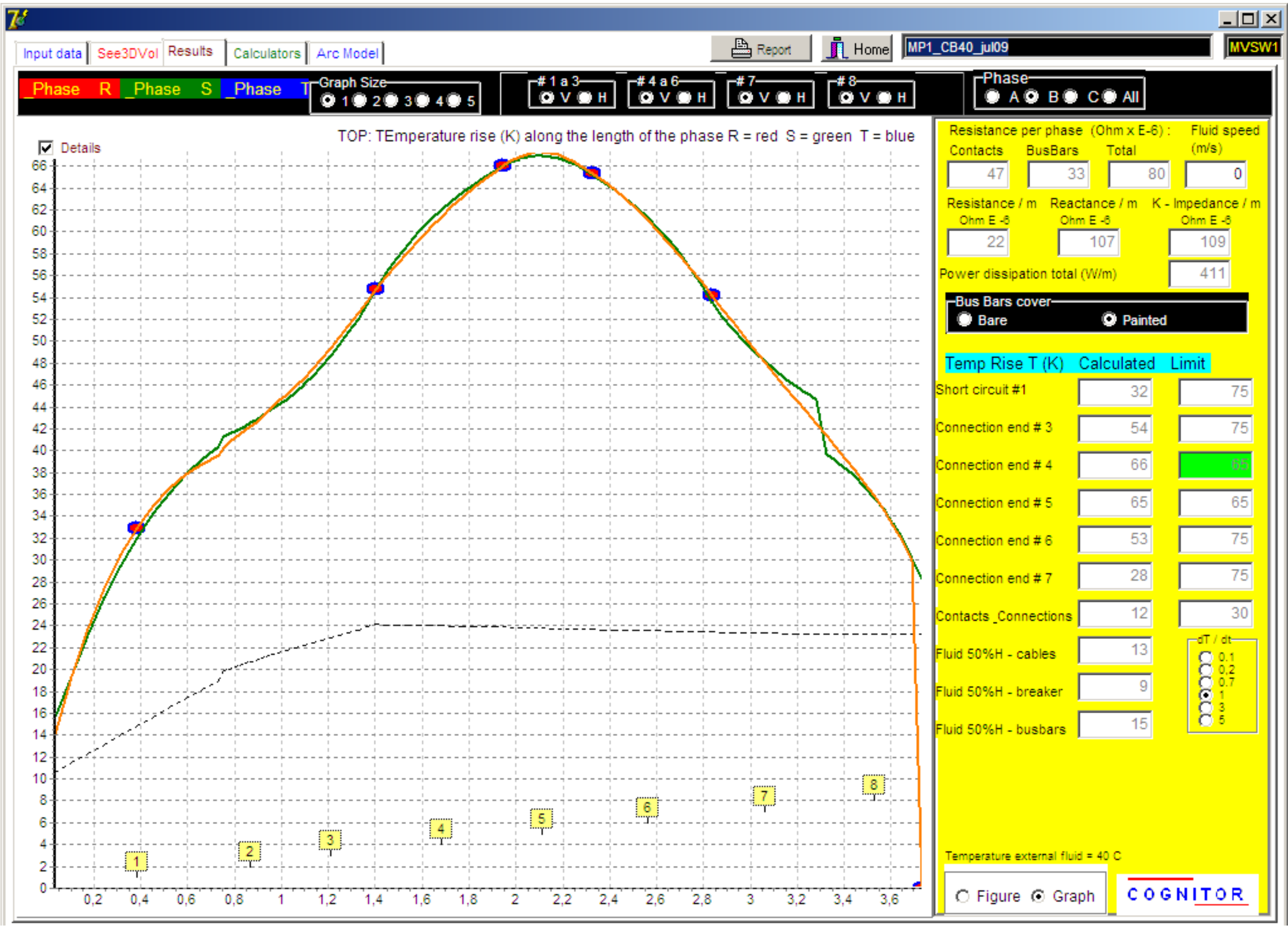


Figure A5 – Additional input data for a test on a 15 kV switchgear



. Paper "Validation of simulations of electrodynamical forces, temperature-rise and internal arc tests in switchgear" by Sergio Feitoza Costa. sergiofeitoza@cognitor.com.br

Figure A6 – Test Results for a temperature rise test on a 15 kV switchgear



Annex B) SHORT-TIME WITHSTAND CURRENT AND PEAK WITHSTAND CURRENT

When a short circuit occur in electrical equipment considerable mechanical forces may be applied to isolators and conductors. Also considerable temperature rises occur because there is no time to dissipate the high amounts of heat produced by Joule effect.

The forces are calculated using expressions like the ones in Figure B1. I deduce these expressions more than 30 years ago when doing my M.Sc. thesis. At that time we were designing the Brazilian high power laboratories busbar systems for currents up to 300 kA rms sym / 750 kAcr. The busbar and the lab are still there in good operation.

After calculating the “electrical forces” it is necessary to do calculate shear forces, bending moments and to take into account resonances and other effects.

This kind of simulation have as objective to get the total vibratory forces acting in the insulators (compression, traction and bending) and also the mechanical stresses acting in the conductors.

The forces on the isolators shall be below the limits specified by the insulator manufacturer otherwise the insulator can be destroyed. The mechanical stresses on the conductors shall be maintained below certain limits (for example 200 N/mm2 for copper) otherwise the busbar will suffer a permanent and visible bending.

The data affecting the test and the simulations results are the short circuit circulating electric current, the materials involved, and the geometry of conductors and insulators.

Figure B1 – Forces produced by currents circulating in two neighbour conductors

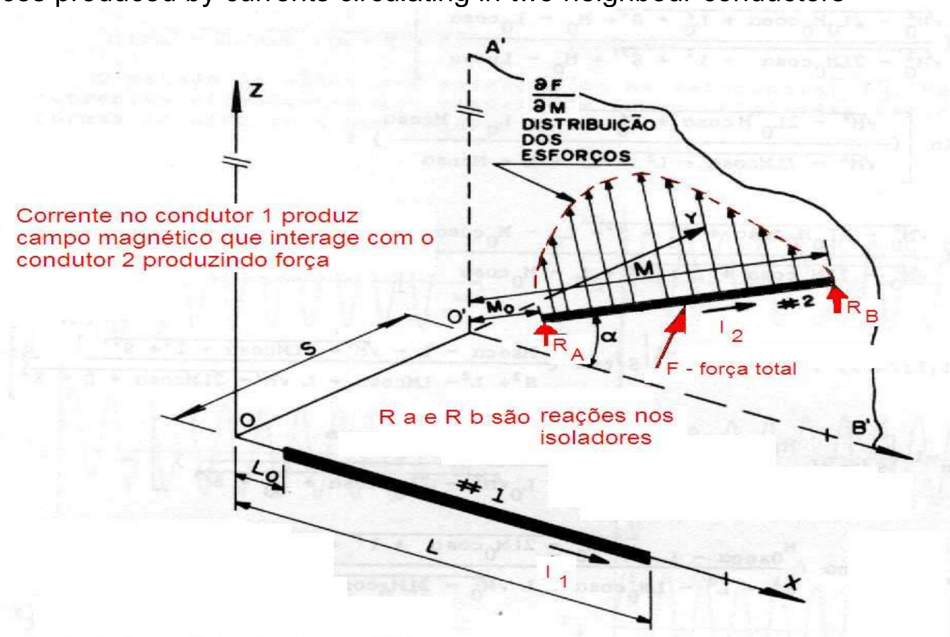


Figure B1 (cont.) – Forces produced by currents circulating in two neighbour conductors

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

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

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

Figure B2 – Input data for a test on a bus bar system

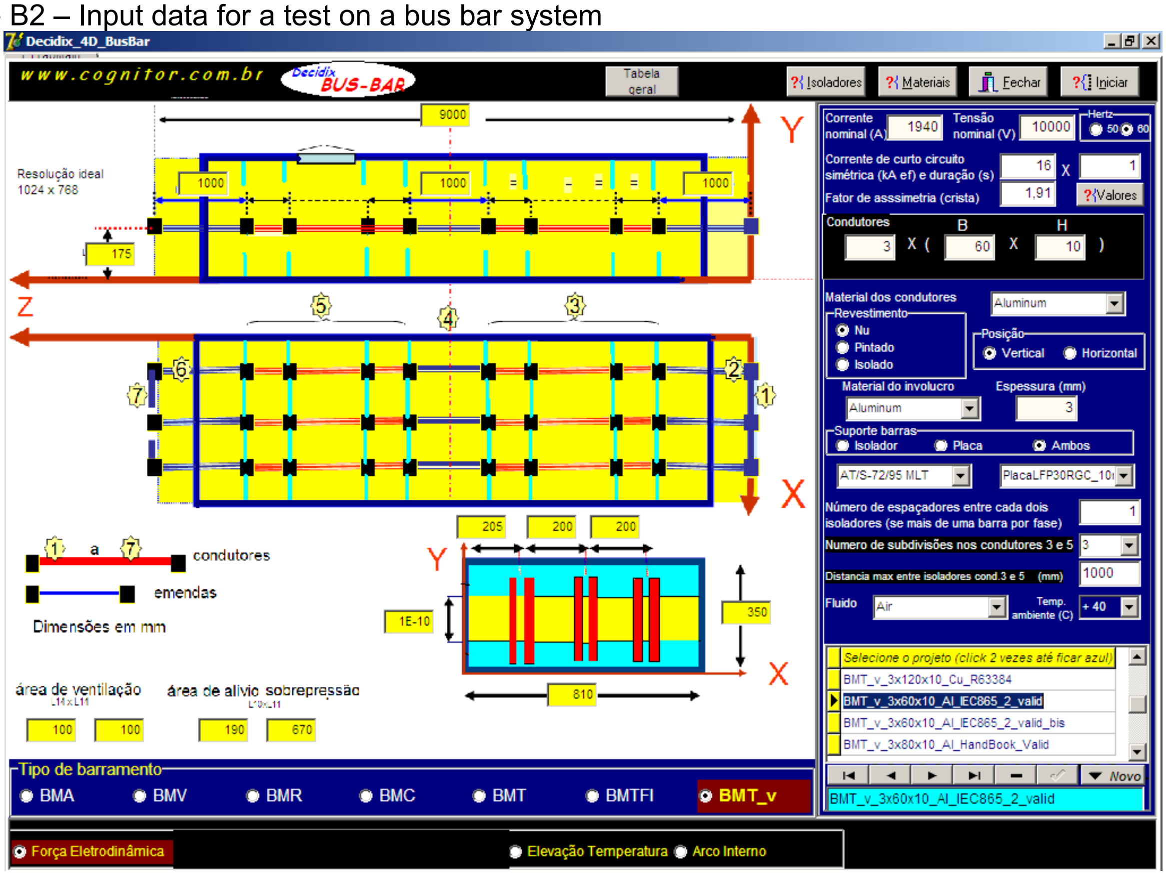


Figure B3 – Results data for the electrodynanical forces on a bus bar system (validated)

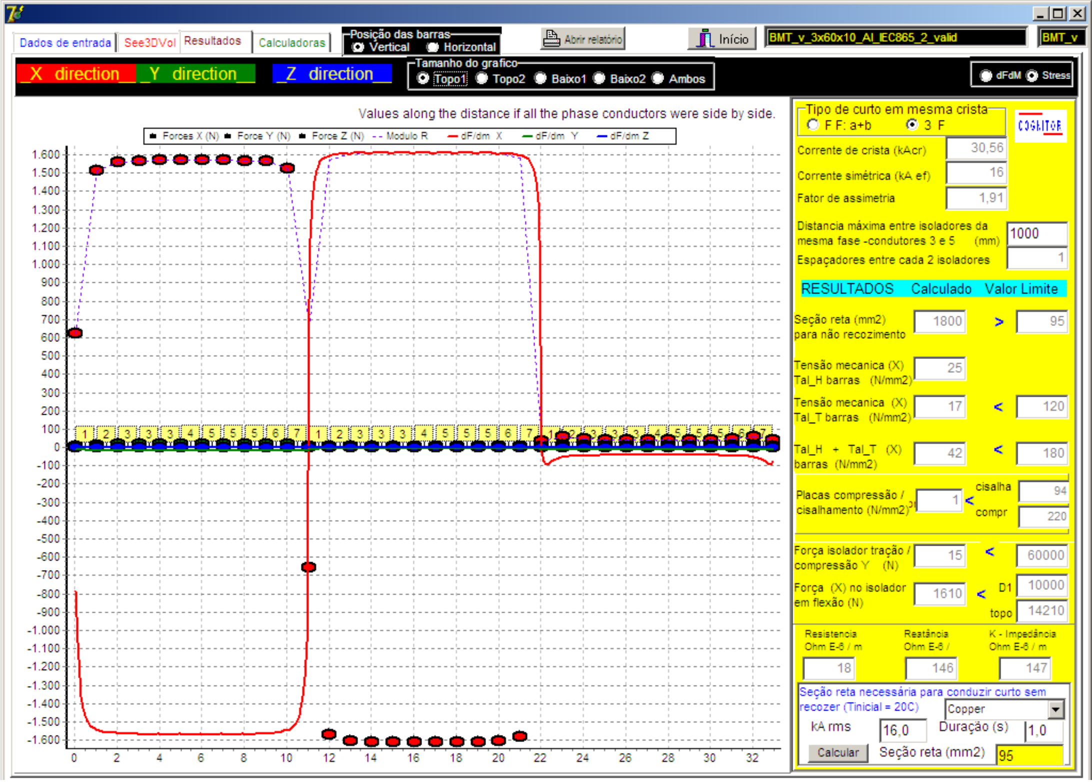


Figure B4 – Results data for the mechanical stresses on a bus bar system (validated)

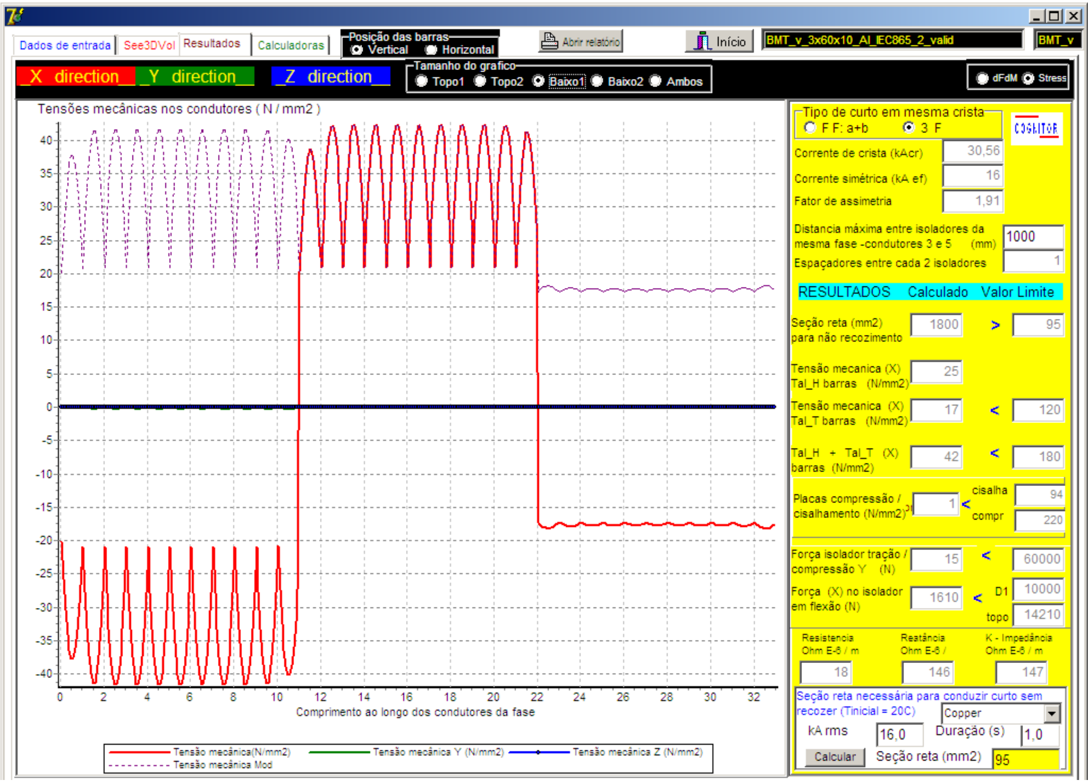


Figure B-5 – Input data for a test on a 15 kV switchgear

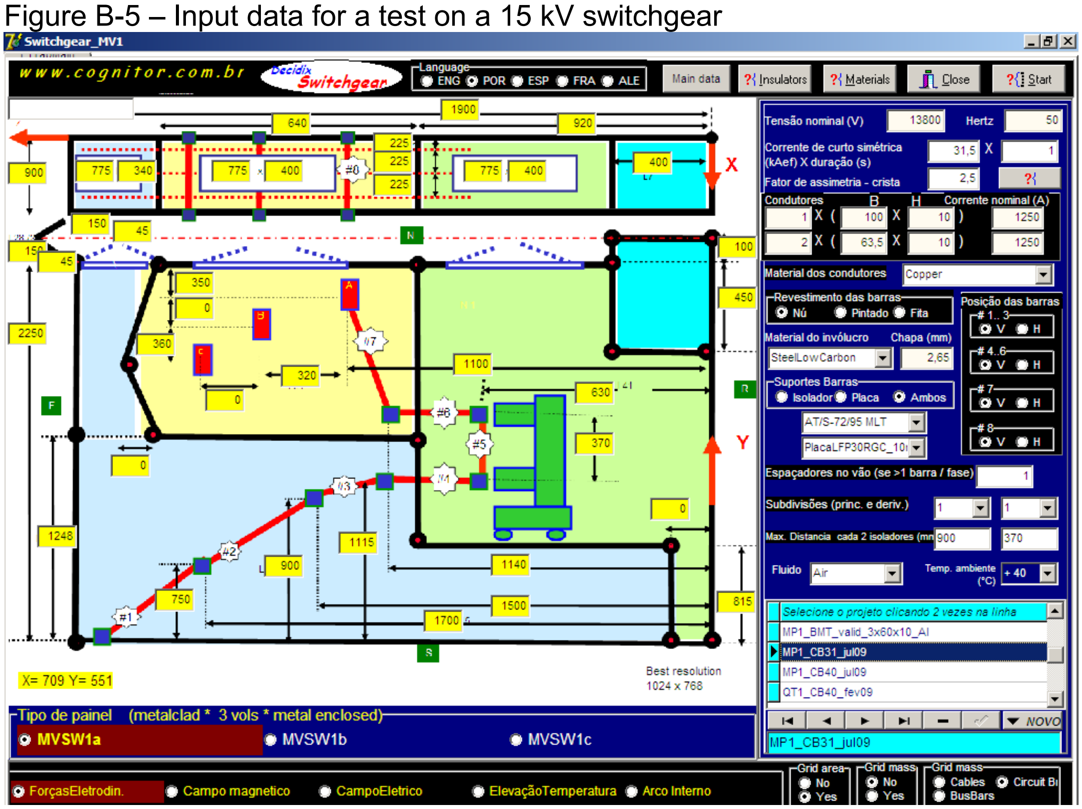
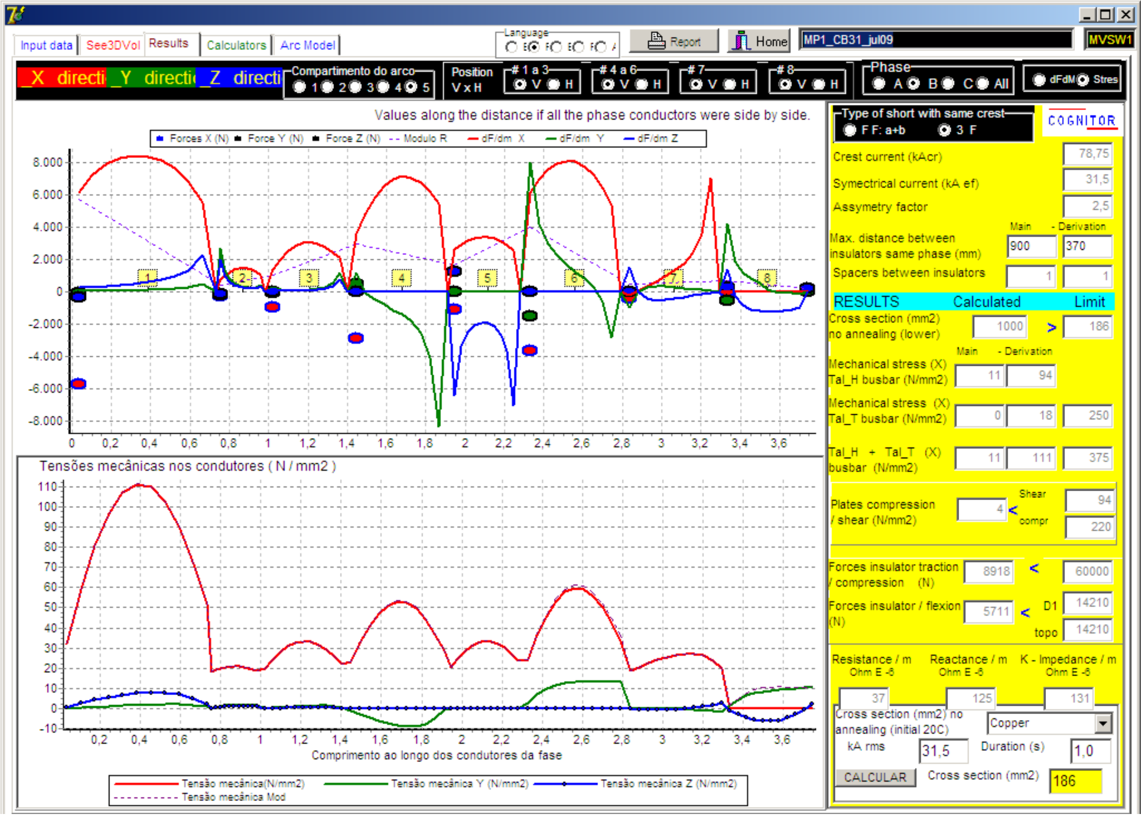


Figure B-6 – Results data for the electrodynanical forces and mechanical stresses on a 15 kV switchgear approved on tests with 31,5 kA during 1s – 79 kA cr



Annex C) **INTERNAL ARC TESTS.**

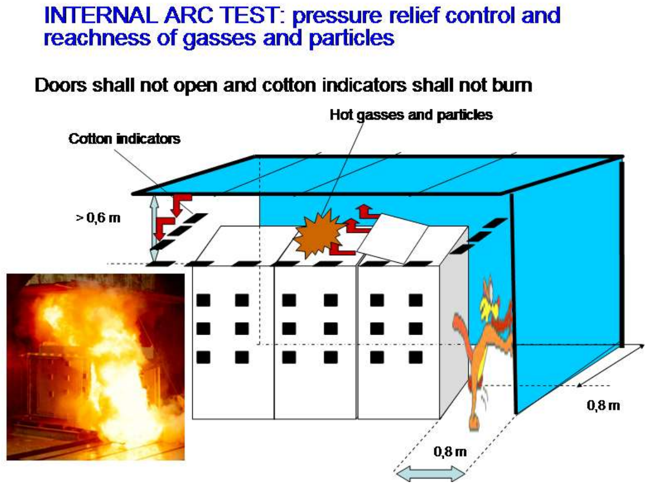
Internal arc testing of metal enclosed switchgear is intended to offer a tested level of protection to persons in the vicinity of switchgear in the event of an internal arc. These tests are applicable to high, medium and low voltage equipment.

For medium voltage the type test is defined in the IEC 62271-200. IEC 62271-200 define a classification (IAC, Internal Arc Classification) taking into account the types of accessibility (front, rear and sides) and the effects of the ejected gasses and particles. For this reason and because of the much easier public accessibility of medium voltage installations internal arc testing of metal enclosed medium voltage switchgear is very common. It is a quite expensive test.

In Figure C1 I give an idea of the test fundamentals. The approach is that the black cotton pieces representing person's skin are not burned by the effects of the overpressures and hot gasses.

This test is not yet a type test for low voltage switchgear. As the risks and energy involved in low voltage installations with short circuit levels higher than 40 KA rms are considerable it is a question of time that the internal arc test will become a type test for low voltage assemblies. The rules are in the IEC TR 61641 (2008) Enclosed Low Voltage Switchgear Assemblies – Guide for Testing under conditions of arcing due to internal fault.

Figure C1 – The internal arc test in switchgear



From the point of view of to compare test results with simulation results there are two main criteria for being approved in the tests:

(a) Doors shall not open or bend permitting hot gasses to go outside and

(b) The gasses ejected by the pressure relief parts shall not burn cotton pieces located near the accessible parts. These cotton pieces simulate the skin of persons in the vicinity and can be burnt by the reflection of thee gasses in walls and in the ceiling

.
Criteria **"doors shall not open"** means that the forces exerted in consequence of the pressure and the mechanical stresses on plates, bolts and others can not go above certain materials limits. For the steel plates this could mean that the yield strength ($\sigma_{0.2}$) should not be higher than 1270 N/mm^2 to avoid a deformation higher than 0.2%. With some work a model can be done to show the pressure evolution along the time. Certain values of pressure shall not be over passed.

Criteria **"not to burn cotton indicators"** means that the ejected particles can not arrive to the pieces and this is possible but difficult to simulate. There are some techniques which can be used to show if a certain type of technological solution lead to a higher or lower probability of burning the indicators.

To enable a practical use of internal arc simulations it is necessary to create comparison indicators not dependent on sophisticated techniques (like to calculate the flow lines of the particles ejected).

For my consultancy work for manufacturers I use in the software I developed, in the case of air insulated switchgear (15-36 kV) the parameters:

(a) The peak value of the overpressure ΔP (max. 70 up to 90 %)
(b) the time to the overpressure peak
(c) the time to 50% of the peak pressure (as done for impulse waves used in dielectric testing)
(d) the integral of curve overpressure x time ΔP x T (max. 20 to 40 bar x milliseconds)

The basic input data to do the calculations are the source voltage, the short circuit current,, resistances, inductances and capacitances of the external circuit (for the arc model), the conductor and fluid materials and the overall geometry of the compartment and pressure relief parts (without excessive details). The geometry includes the position of ceilings, walls and cotton indicators.

In the following lines we present the basic sequence for the development of simulation software for the calculation of temperature rises and also for the overpressures of the internal arc test.

It is only one code for both tests and not two different models. The only aspect to note is that in the internal arc test simulation when the temperature of a conductor (the arc conductor) reaches the vaporization temperature I transform the volume of that mass of “solid or liquid” from the “solid” volume” to the “gas volume”.

The fundamental is the following. The initial volume of a solid copper wire with a diameter 1mm and a length 300 mm can become something like 0.5 m^3. If you add 0.5 m^3 of gas to a 1 m^3 closed compartment originally at a pressure 1 atm the pressure goes to 1,5 atm.

To do this is not difficult and you need only to use the physical properties of the materials (specific heat, density, thermal conductivity and others) as a function of the temperature. When you are simulating a temperature rise test you can maintain these properties fixed because they do not vary very much. Nevertheless when you go beyond the melting and boiling temperatures they change a lot.

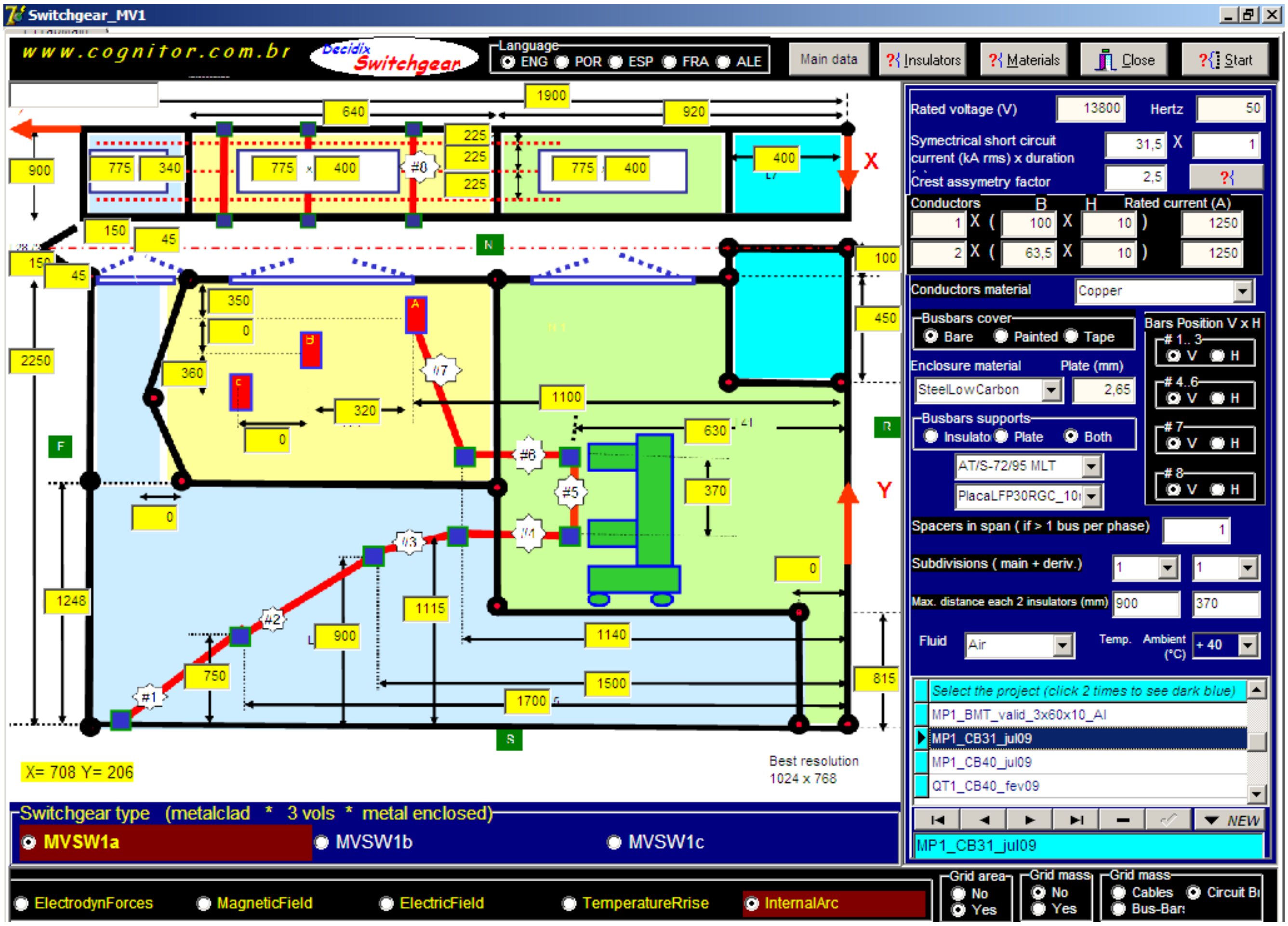
Another trick is that when you are simulating a “temperature rise test under arc conditions” you need to create a higher limit for the arc temperature. You can choose this limit as 4000 K, 8000 K, 12000 K, 20000K. In our case when I use a value around 12000 to 15000K the overpressure curve is very close to the one measured in the lab. <u>I do not use the KP factor mentioned in literature.</u>

This entire works well only if instead of fixing an “average value” for the arc voltage I use a simplified model to calculate the arc voltage (simplified Mayr or Cassie). The idea is just to do a “temperature rise test” from zero to the high arc temperature but forcing it does not go beyond for example 12000 K.

When the calculated internal pressure goes beyond, lets say 1.5 atm, the pressure relief part will open due to the effect of the force = pressure x area. Having the force inside and some basics of mechanics you can estimate the opening of the covers and the free open area in each instant. Having the internal and external pressures and the opening area you calculate the amount of mass which is leaving the hole and so the reduction of the internal pressure.

In my case I use only the equation of the balance of energy and a one dimension approach like calculating by finite volumes, the temperature along a cylinder or a rectangular bar. If you use the physical properties as a function of the temperatures the values of losses by radiation, conduction, convections will change accordingly. You may even make some correction on the radius of the conductor (arc conductor) as a function of the temperature.

Figure C-2 – Input data for a test on a 15 kV - 1250 A – 31,5 kA during 1 switchgear



Switchgear_MV1
www.cognitor.com.br
Switchgear
Language
ENG
POR
ESP
FRA
ALE
Main data
Insulators
Materials
Close
Start
Rated voltage (V)
13800
Hertz
50
Symectrical short circuit current (kA rms) x duration
31,5
1
Crest assymetry factor
2,5
Conductors
B
H
Rated current (A)
Conductors material
Copper
Busbars cover
Bare
Painted
Tape
Bars Position V x H
Enclosure material
Plate (mm)
SteelLowCarbon
2,65
Busbars supports
Plate
Both
AT/S-72/95 MLT
Spacers in span (if > 1 bus per phase)
Subdivisions (main + deriv.)
Max. distance each 2 insulators (mm)
900
370
Fluid
Air
Temp.
Ambient (°C)
+ 40
Select the project (click 2 times to see dark blue)
MP1_BMT_valid_3x60x10_Al
MP1_CB31_jul09
MP1_CB40_jul09
QT1_CB40_fev09
NEW
MP1_CB31_jul09
X= 708 Y= 206
Best resolution 1024 x 768
Switchgear type (metalclad * 3 vols * metal enclosed)
MVSW1a
MVSW1b
MVSW1c
ElectrodynForces
MagneticField
ElectricField
TemperatureRrise
InternalArc
Grid area
No
Yes
Grid mass
No
Yes
Grid mass
Cables
Bus-Bars

Figure C-3 – Simulation   Overpressure x duration (circuit breaker compartment)

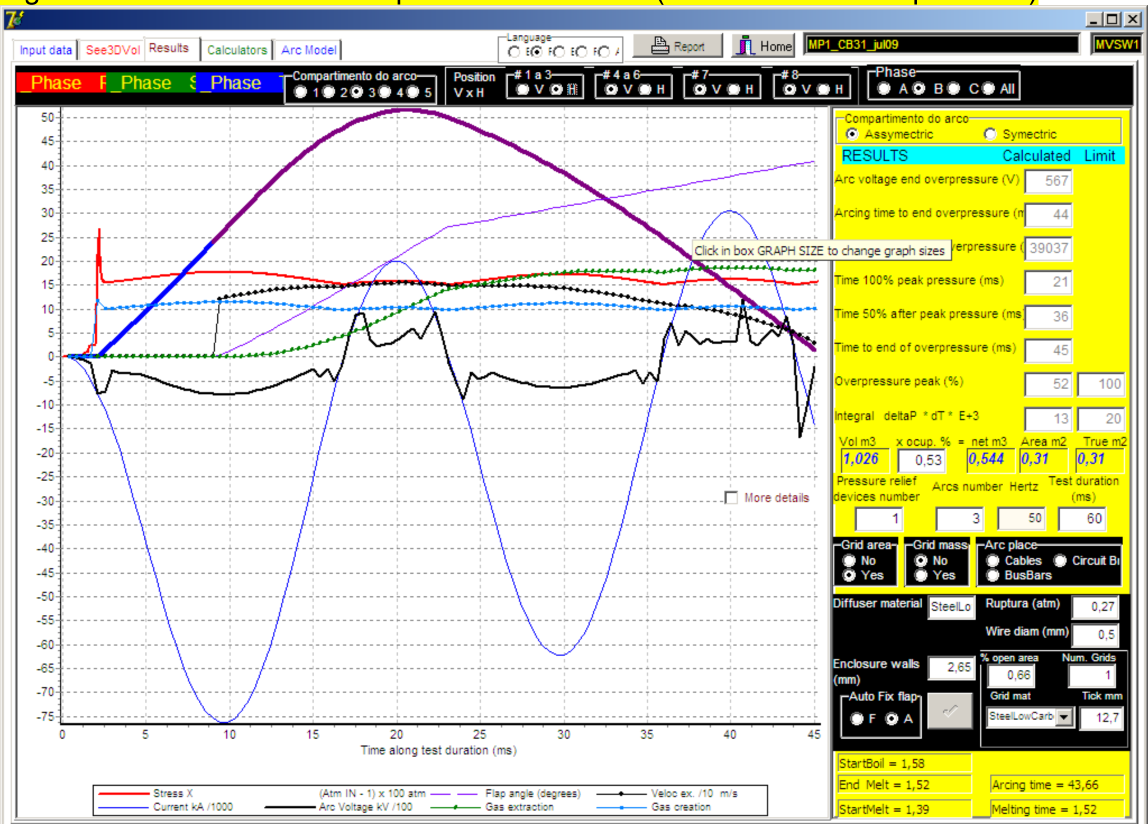


Figure C-4 - Overpressure x duration (simulation and test)

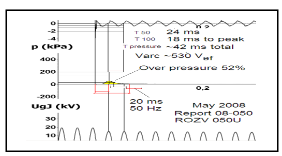
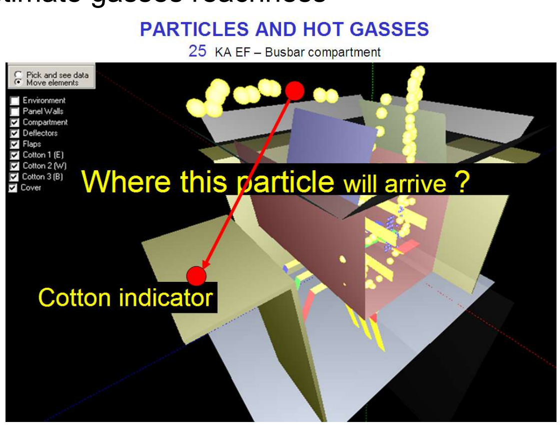


Figure C-5 – 3D method to estimate gasses reachness



Annex D) **SIMULATION OF POWER TRANSFORMERS, FUSES, SUPERCONDUCTING SPECIALS AND OTHERS**