# POWER TRANSFORMERS & REACTORS: TESTING SIMULATIONS OF ELECTROMECHANICAL FORCES & STRESSES, TEMPERATURE RISE and OVERPRESSURES OF INTERNAL ARC.

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

**Read also:**

- Explosion & Fires in power transformers (a new technical standard) : https://www.cognitor.com.br/transformersfiresexplosions.pdf
- Loading Transformer Limits Determination : https://www.researchgate.net/publication/264580683_Thermodynamic_models_and_three-dimensional_analysis_for_determination_of_Load_Limits_Transformers
- Electromechanical forces & stresses, temperature rise and overpressures of internal arc.: https://www.cognitor.com.br/PowerTranformersReactorsCalculation.pdf

## 1) INTRODUCTION

This text is for designers of power transformers. I was motivated to write it when helping to write the Brochure Cigrè 740 (2018): "Contemporary Design of Low-Cost Substations In Developing Countries" which is a "must" document for people acting in the power electric industry.

In general, the objective of the calculations is to estimate the performance for conditions like short circuit electromechanical forces & stresses, temperature rise under overloads and overpressures of internal arc. In the last case, the overpressure calculations can be used to design fast action pressure relief devices (Brazilian standard NBR8122). I will refer to the software SwitchgearDesign (see references at the end). However, I will not present results here as I did in a complete way in Ref. [8,9] for switchgear. The reason is easy to understand. I did not find any complete reliable data to compare with my calculations.

In the past I had a straight contact with calculations for power transformers, but I stopped by lack of interest by manufacturers. I still applied trainings on this for some years. Nowadays I am not updated about what happened after this. However, I included in my testing simulation software SwitchgearDesign a module to simulate tests in transformers. As no manufacturer asked me calculations, I could not validate them and removed the module. Simulations are helpful when are well validated as in Ref. [6,8] below. For power transformers this was not possible.

The figure to follow shows the calculation model of SwitchgearDesign. We represent the geometry of the 3-phase equipment by the parameters in Figure 1. For better visualization, only the central phase is represented. The other necessary input parameters are presented in the next sections.

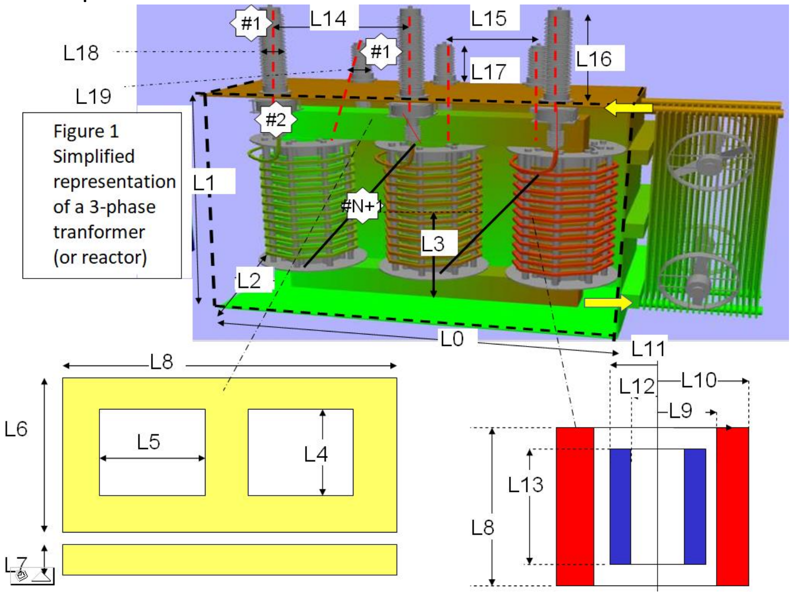



Figure 1 Simplified representation of a 3-phase tranformer (or reactor)

## 2) CALCULATION OF ELECTROMECHANICAL FORCES, STRESSES

Cell phone. 55-21-9 88874600 E-mail: sergiofeitozacosta@gmail.com Site: http://www.cognitor.com.br
CV http://www.cognitor.com.br/Curriculum.html Downloads: http://www.cognitor.com.br/downloads1.html Training: https://www.cognitor.com.br/trainingENG.pdf

The objective is to calculate de minimum number of rods and shims which are necessary to maintain the windings in good state after a short circuit. During the short circuits very, high forces vertical and horizontal (radial) forces are developed, and they should not damage the windings. In high power laboratory the verification is done, after the test, by visual inspection and by comparing the inductances of the windings before and after. The concept is that if important movements occur inside, they will be reflected in the value of the winding's inductance.

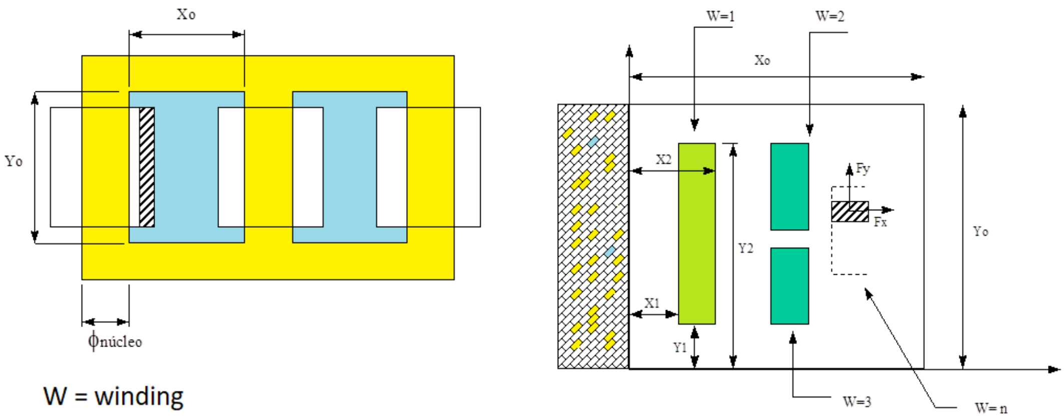
We can use two methods presenting (eventually) two different results. Nobody can prove if one or the other is more correct. This would require complex measurements. Nobody would pay for this. The first method is based on Reference [2], a great book from M. Waters "The Short Circuit Strength of Power Transformers". The forces and stresses are calculated by the equations below. The values of mechanical stresses (forces divided by affected area) are compared with the limit values for the Stress $\sigma_{0.2}$ like, if copper wire, 88N/mm$^2$ (5,6 ton/in$^2$) or, if aluminum wire 70 N/mm2 (4,6 ton/in$^2$) .

The second method (by Sergio Feitoza) suppose that each winding is a single solid helical conductor divided in a certain number of subparts "in series". We calculate the forces considering the influence of a sub-section over all the others and sum the resultants in a vertical and a radial component. It is basically the method used in SwitchgearDesign and based on IEC 60865 (Ref. [3] and [4] ).

## 2.1) Classical method from M. Waters book

The simplified and complete equations are shown in 2.1.1 and 2.1.2 (see Figure 2) . The program employs the full expressions. The expressions for calculating the forces in the radial (Fx) and axial (Fy) directions are the starting point for calculating the minimum number of rods and shims. The rods are vertically arranged having the function of preventing the winding from "closing". The shims are placed between sub-coils and, when necessary, they are assumed to have a radial dimension equal to that of the coil.

Figure 2 - Variables for the equations of the M. Waters method (classical)




The premises are:
- the overall dimensions and reference axes of the transformers are as in Figure 2;
- windings of one phase do not affect, for electromechanical efforts, those of the other phases.
- When calculating the stress distribution, the winding (W) is subdivided into 30 equal sub-windings (SW);
- the ampere-turn values of each winding (NI [W]) are input data specified by the designer based on the expression:

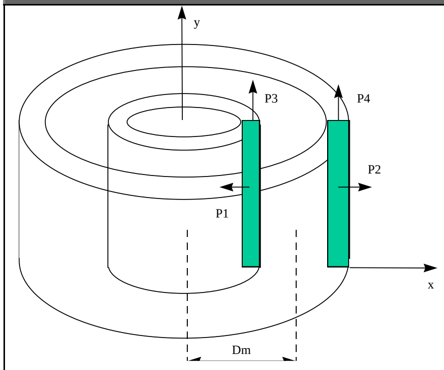
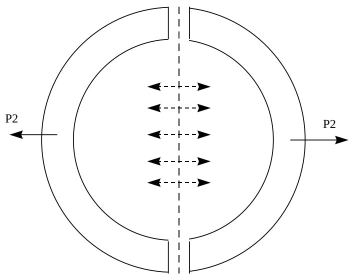
**NI [W] = ( number of turns x rated power $_{(KW)}$ x $\beta$ ) / ( 1,731 x rated voltage phase-phase $_{kV}$ x Z short-circuit$_{(0/1)}$ )**

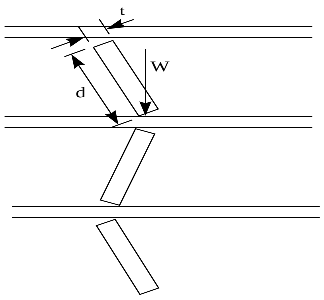
$\beta$ = 1 if Y connection or single-phase and $\beta$ = 1/1,731 if connection in $\Delta$.

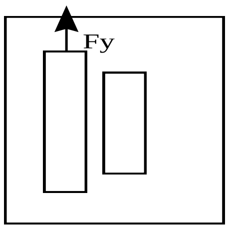
The values of amperes-turns and number of turns of each sub-winding ( NI [ W,SW ] ) are calculated automatically assuming that the ampere-turns of a winding are distributed in the sub-windings in proportion to their cross-section (S) : NI [ W,SW ] = NI [ W ] x ( S [ W,SW ] / S [ W ] );

There are no considerations about resonance and elastic structures. In the Sergio's method this is (more or less) considered. No problem because you don't even know what the real value is.

### 2.1.1) Simplified equations for classical method from M. Waters book

| CONFIGURATION | | |
|---|---|---|
|  | **Radial Force**<br>P2 (in tons)<br>=<br>$\frac{2 X \pi^2 X NI^2 X D_w}{h X 10^{11}}$<br>Eq. 2.1 - page. 19 - Ref [2] | **Axial Force**<br>If equal heights<br>P3 + P4 (in tons)<br>=<br>$\frac{2 X \pi^2 X NI^2 X D_m x( D_0+0,33 x (t1+t2))}{h^2 X 10^{11}}$<br>Eq. 2.2 - page. 19 - Ref [2] |
| **Supportability of external windings** to traction<br>(if Fx>0)<br> | **Radial Force**<br>**Supportability condition**<br>**Mean hoop stress is lower than $\sigma_{0.2}$**<br>$\frac{P_2 / \pi}{2 \text{ x turns x cross section}_{conductor}} < \sigma_{0.2}$ | |

| | |
|---|---|
| **Supportability to compression and minimum number of rods**<br><br>(Calculation done if Fx>0) | **Radial Force**<br><br>**Critical load** W (in tons) =<br>=<br>$\dfrac{Z^2 \times E_{Young} \times t^2}{12 \times D_w^2}$<br><br>**t = conductor radial dimension and Z = number of rods**<br><br>**Stress =** $\dfrac{P_2 / \pi}{2 \times turns \times cross\ section_{conductor}}$<br><br>Eq. 7.1 - Ref [1] |
| **Supportability to collapse of the windings considering only the effect of conductor and the value of Fy**<br><br> | **Axial Force**<br><br>**Critical Load W (in tons) =**<br>=<br>$\dfrac{\pi \times E_{Young} \times turns \times a_c \times t}{6 \times radius\ of\ turn}$<br><br>**t = conductor radial dimension**<br><br>**W = axial force Fy per length of turn** $2\pi r$<br><br>Eq. 7.4 - Ref [2] |

| | |
|---|---|
| Force Fy<br><br> | **Axial Force**<br><br>Values in Table of Ref. [2] |
| **Supportability for not having damages to spacers** | **Axial Force**<br><br>$\dfrac{P3\ or\ P4}{Useful\ cross\ section\ for\ each\ spacer \times number\ of\ spacers} < Stress_{mat..esp}$ |

| Bending of conductor between spacers (minimum number of spacers by page. 152 da Ref. [2]) | Axial Force<br><br>( (P3 or P4) / $2\pi R$ ) x ( $l^2$ /12 )<br>--------------------------------------------------------------- < $\sigma_{0.2}$<br>Resistant moment of sub winding |
|---|---|

## 2.1.2) Complete equations for classical method from M. Waters book

The expressions for the forces Fx and Fy in each sub-winding or winding due to all other windings is calculated based on the following expressions from Ref [2] - pages. 57 and 58

$$F_x = -\sum_M \sum_N \frac{\pi}{X_o} \cdot \frac{(NI)_p}{\left(\frac{\pi \cdot X_{2p}}{X_o} - \frac{\pi \cdot X_{1p}}{X_o}\right) \cdot \left(\frac{\pi \cdot Y_{2p}}{Y_o} - \frac{\pi \cdot Y_{1p}}{Y_o}\right)} \cdot P_{MN} \cdot \left[\cos M \frac{\pi \cdot X_{2p}}{X_o} - \cos M \frac{\pi \cdot X_{1p}}{X_o}\right] \cdot \left[\frac{\sin N \frac{\pi \cdot Y_{2p}}{Y_o} - \sin N \frac{\pi \cdot Y_{1p}}{Y_o}}{N}\right]$$

$$F_x = \sum_M \sum_N \frac{\pi}{Y_o} \cdot \frac{(NI)_p}{\left(\frac{\pi \cdot X_{2p}}{X_o} - \frac{\pi \cdot X_{1p}}{X_o}\right) \cdot \left(\frac{\pi \cdot Y_{2p}}{Y_o} - \frac{\pi \cdot Y_{1p}}{Y_o}\right)} \cdot P_{MN} \cdot \left[\frac{\sin M \frac{\pi \cdot X_{2p}}{X_o} - \sin M \frac{\pi \cdot X_{1p}}{X_o}}{M}\right] \cdot \left[\cos N \frac{\pi \cdot Y_{2p}}{Y_o} - \cos N \frac{\pi \cdot Y_{1p}}{Y_o}\right]$$

$$P_{MN} = \frac{4}{\pi} \cdot \frac{X_o}{Y_o} \cdot \frac{H_{MN}}{M^2 + N^2 \cdot \left(\frac{X_o}{Y_o}\right)^2} \cdot \sum_{n=1}^{n=k} [A_{MN}]_n$$

$$(A_{MN})_n = \frac{(NI)_n}{\left[\frac{\pi \cdot X_{2n}}{X_o} - \frac{\pi \cdot X_{1n}}{X_o}\right] \cdot \left[\frac{\pi \cdot Y_{2n}}{Y_o} - \frac{\pi \cdot Y_{1n}}{Y_o}\right]} \cdot \left[\frac{\sin \frac{M \cdot \pi \cdot X_{2n}}{X_o} - \sin \frac{M \cdot \pi \cdot X_{1n}}{X_o}}{M}\right] \cdot \left[\frac{\sin \frac{N \cdot \pi \cdot Y_{2n}}{Y_o} - \sin \frac{N \cdot \pi \cdot Y_{1n}}{Y_o}}{N}\right]$$

Values are multiplied by the factor $1.02.10^{-8}.\pi$.Dm, where Dm is the average transformer diameter in the same unit of window width (Xo).

## 2.1.3) Calculation sequence for classical method from M. Waters book

The input data is:

- Window dimensions (X0 and Y0) and core diameter based on the Figure 1 and adjusting the values for Figure 2
- geometrical dimensions of the windings according to Figures 1 and 2 (max 50 windings)
- number of turns of each winding.
- the ampere-turns of each winding
- axial and radial dimension of each winding.
- the number of conductors in parallel for each winding

At first calculate the total force applied at the center of the winding. For the distribution of stresses, the program subdivides the winding chosen for analysis into 30 sub-coils of the same length, number of turns and ampere-turns. Each sub-winding is considered to have a straight section of height h and thickness b and forming a cylinder. The forces Fx and Fy are calculated on each sub-winding and thereafter the following are made:

### 2.1.3.1) Stresses due to forces Fx.for classical method from M. Waters book

If Fx <0 (trend to open windings) it must be checked if this stress does not exceed $\sigma$0.2.
If it is higher do a review in the design, especially the cross section of each conductor. In this case the rods are not necessary.

If Fx> 0 (trend to close windings) the minimum number of rods is calculated based on the expression shown before. The minimum number of rods to be used by the designer is the largest number that occurs in any of the sub-windings.

### 2.1.3.2) Stresses due to forces Fy for classical method from M. Waters book.

The force Fy must always be smaller than that indicated in Equation 7.4 of Reference [2] to avoid collapse of the windings. If this value does not turn out less, an alert message shall be done.

The stress due to Fy at any point between two adjacent spacers shall not be greater than $\sigma$0.2. to avoid permanent deformation of the windings at unacceptable levels. Calculation of the minimum number of spacers ($n_{esp}$) is done from the maximum value of $l = 2\pi R / n_{esp}$ that meets this condition.

The stress on each spacer is equal to Fy divided by the product of the useful cross section of each spacer by the number of spacers. This stress should not be greater than the supportability of the material of the spacer.

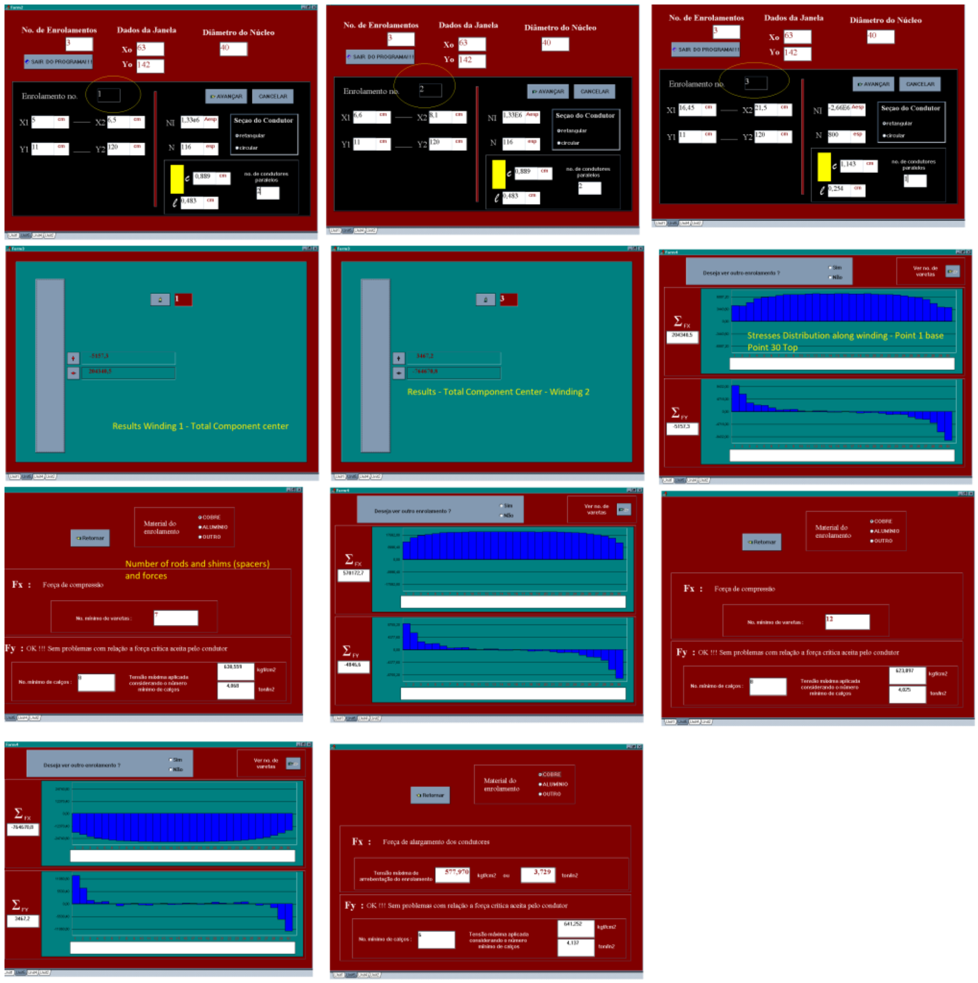
### 2.1.3.2) Test case to check the results of the program for classical method from M. Waters book.

This test case corresponds to a simulation published in Reference [2]. Calculations are made using the simplified expressions and the program with the complete expressions. The variables correspond to those in Figures 1 and 2.

| Dimensions of the core (cm) | | |
|---|---|---|
| Xo | Yo | Diameter |
| 63 | 142 | 40 |

| Winding | Positioning (cm) | | | | NI | N | Dimensions of the conductor (cm) Number of conductors in parallel | | | Fx | Fy | No. de Number of rods | Number of shims (spacers ) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| no. | x1 | x2 | y1 | y2 | $A_{esp}$ | esp | radial | axial | np | (kgf) | (kgf) | | |
| 1 | 5 | 6,5 | 11 | 120 | 1,33E6 | 116 | 0,483 | 0,889 | 2 | 204340 | 5157 | 7 | 8 |
| 2 | 6,6 | 8,1 | 11 | 120 | 1,33E6 | 116 | 0,483 | 0,889 | 2 | 570172 | -4847 | 12 | 8 |
| 3 | 16,45 | 21,5 | 11 | 120 | -2,66E6 | 800 | 1,143 | 0,254 | 1 | -764670 | 3467 | - | 6 |

The number of shims (spacers) was calculated considering a withstand of the sub windings equal to 5.8 ton / in2. For different values or for higher safety factor it is possible to use a higher value.




## 3) CALCULATION OF TEMPERATURE RISE

The method of SwitchgearDesign is explained in References [5] and [6]. The focus is getting an estimate of the temperature rise along windings (including in the hot spot) and temperature of the oil along the tank from bottom to top oil). The input data is the geometry in Figure 1 plus the winding losses and core losses. Also, the cooling effects of forced ventilation can be adjusted by considering the values of rated power for ONAN and ONAF conditions.

After having the values of winding losses and core losses we sum these values and “create” a helical conductor with proper dimensions for, at the rated currents of the windings to produce the same total losses along the tank. There are several possibilities of doing this or using proper values of conductor’s cross section or even adapting the value of conductor resistivity.

## 4) CALCULATION OF OVERPRESSURES OF AN INTERNAL ARC (AND ACTUATION OF HIGH-SPEED PRESSURE RELIEF DEVICES)

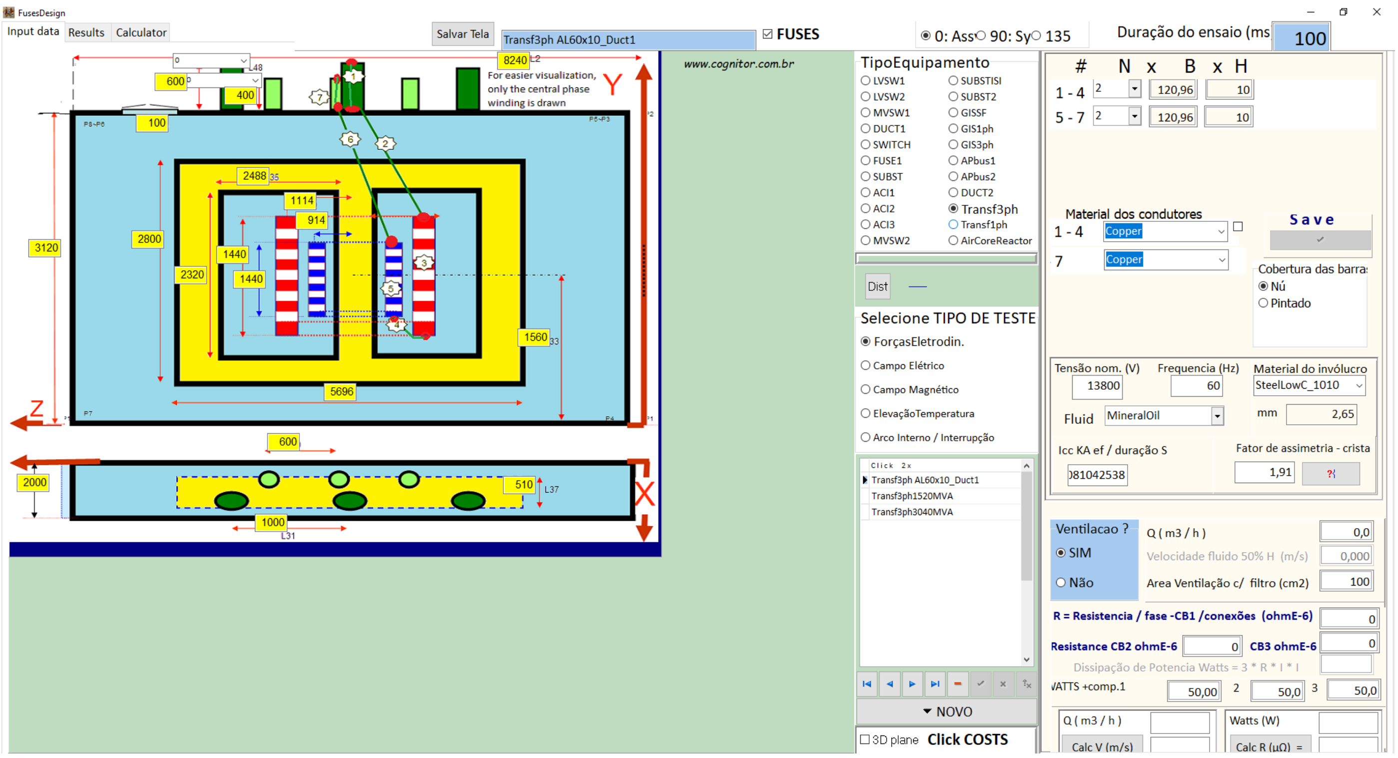
The methodology is explained in Ref [5] and [6]. The focus is getting the overpressure curve considering the existence of an internal pressure relief device with a known opening speed.

The process is similar to the one used for overpressures in panels / cubicles with the difference that the fluid is oil or others.

The input data is the geometry in the Figure (geometry, currents, etc …).

## 5) CONCLUSION

This article shows calculation methods used in the software SwitchgearDesign, for power transformers. The input parameters are like in this figure.




////////////////////////////////////////////////////////////////////////////////////////////////////////////

### REFERENCES – PUBLICATIONS LIST:

[1] A "GUIDE" FOR THE USE OF CALCULATIONS AND SIMULATION OF LABORATORY TESTS FOR INCREASING THE COMPETITIVENESS OF THE ELECTRIC INDUSTRY http://www.cognitor.com.br/Article_Competitivity_Eng_04102011.pdf

[2]: M. Waters, "The Short Circuit Strength of Power Transformers"- 1966 - MacDonald & CO Ltd (Gulf House,2 , Portman Street, London, W.1)

[3] IEC TC73, "IEC 60865-1:2011 Short-circuit currents - Calculation of effects - Part 1: Definitions and calculation methods," IEC, Geneva, 2011.

[4] IEC TC73, "IEC TR 60865-2:2015 Short-circuit currents - Calculation of effects - Part 2: Examples of calculation," IEC, Geneva, 2015.

[5] Report 074/2014 VALIDATION OF MAGNETIC & ELECTRIC FIELDS MAPPING & TEMPERATURE RISE TESTS SIMULATIONS.

http://www.cognitor.com.br/TR074ENGValidationTempRise.pdf

[6] 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)

http://www.cognitor.com.br/TR_071_ENG_ValidationSwitchgear.pdf

[7 ] Book "Reference text for the courses SWITCHGEAR, BUSWAYS & ISOLATORS and SUBSTATIONS AND LINES EQUIPMENT" (available also in Spanish and Portuguese in the site)

http://www.cognitor.com.br/Book_SE_SW_2013_ENG.pdf

[ 8 ] "VALIDATION OF SIMULATIONS OF ELECTRODYNAMICAL FORCES, TEMPERATURE-RISE AND INTERNAL ARC TESTS IN SWITCHGEAR (& main parts of a code) (2010) . Presented at the CIGRE Technical Seminar "Modeling and Testing of Transmission and Distribution Switchgear" March 24, 2010 Brisbane – Australia

Download: http://www.cognitor.com.br/Validation_Simulations_English.pdf

[ 9 ] "SIMULATION, IEC STANDARDS AND TESTING LABORATORIES: JOINING THE PIECES FOR HIGHER QUALITY HV EQUIPMENT".Paper published PS1-06 in the CIGRÈ International Technical Colloquium - Rio de Janeiro - September 2007 http://www.cognitor.com.br/Artigo_Cigre_SergioFeitozaCosta_Cognitor.pdf

Published also in in Energy Pulse weekly, September, 28 , 2010 http://www.energypulse.net/centers/article/article_display.cfm?a_id=2338

[ 10 ] "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 Congress Cigre - Paris 2008

http://www.cognitor.com.br/Cigre_Paris_A3_210_2008.pdf

[11 ] SIGNIFICANT PARAMETERS IN INTERNAL ARC SIMULATION AND TESTING,

CIGRE WG A3.24, CIGRE A3 SESSION, 2009 -Co-authors: M. Kriegel, R. Smeets, N. Uzelac, R. Pater, M. Glinkowski, P. Vinson, S. Feitoza Costa, G. Pietsch, E. Dullni, Th. Reiher, L. van der Sluis, D. Yoshida, H.K. Kim, K. Y. Kweon, E. Fjeld,

[ 12] Paper FINDING THE OPTIMAL SWITCHGEAR DESIGN: A comparison between aluminum and copper and an idea of new concept. Coautor: Sergio Feitoza Costa & Marlon Campos

http://www.cognitor.com.br/DesignOptimization.pdf

[13] IEC STANDARDS for developing countries http://www.cognitor.com.br/ProposalToIEC.pdf

LEGEND & UNITS

Power, Voltage: kVA – $kV_{rms}$
Electric Currents (i) : Arms – A cr
Dimensions: (l, h, Dm, Dw, t1, t2, do) mm
Forces (P1, P2, Fx, Fy) N (1kgf = 9,806N)
Stresses N/mm2

Stress $\sigma_{0.2}$
Copper wire 88 N/mm2 or 5,6 ton/in$^2$
Aluminum wire 70 N/mm2 or 4,6 ton/in$^2$

Young Modulus
Copper 110000 N/mm$^2$ or 16. $10^6$ ton/in$^2$
Aluminum 60000 N/mm$^2$ or 8,7. $10^6$ ton/in$^2$ Cross Section cm$^2$