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DEVELOPMENT OF A PROGRAM FOR THE DETERMINATION OF THE TEMPERATURE AT TRANSFORMERS COPPER BUS BARS BY CALCULATING THEIR DIMENSIONLESS NUMBERS

SUMMARY

The present technical study aims to demonstrate how to make the determination of the temperature at Transformers Copper Bus Bars by calculating their dimensionless numbers its will explain about the development of a thermal software that represents a viable and cost-effective to dimensioning the transformers Bus Bars due the temperature rise generate by the current. In this environment, the program is basically a virtual lab where is only necessary the cost of specialized engineering analysis and the critical time analysis.

This program allows to be done a large number of tests with different types of Bus Bars and different positions of this Bus Bars with the main objective of loss and temperature reduction, material and final cost of the equipment it can also be used to avoid a possible re-work, non-acceptance or disapproval in heating tests, improving the overall performance of the equipment.

To find the temperature at the Bus Bar was necessary to calculate the losses at the Bus Bars and the dimensionless numbers of Prandtl which is the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity, Grashof which is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid, Rayleigh which is associated with buoyancy driven flow (also known as free convection or natural convection) and is the product of the Grashof number and the Prandtl number also and finally Nusselt which is the ratio of convective to conductive heat transfer across (normal to) the boundary. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid. All dimensionless numbers were considered for natural convection.

To do this calculation an analytical program using Visual Basic at MSExcel was created. To find this temperature some variables are dependent. In that case, this variables need to be fixed after the first temperature found at copper Bus Bars. Some iterations must be done using the program starting from this first temperature to find the correct final temperature.

After this procedure is possible to determinate the temperature considering the paper layer of the copper Bus Bars when it exists.

The measured results show the reliability of the proposed model by calculating the dimensionless numbers for the determination of the temperature at Transformers copper Bus Bars.

Key words: Losses, Prandtl, Nusselt, Rayleigh, Temperature, Program.

1. INTRODUCTION

ABB Brazil Transformer Division is performing a technical study about the temperature at High Current Leads in Power Transformers. This Leads are very common in Generate Step-Up Transformers and Industrial Transformers.

This study was done considering the transformer location, the copper bus bar, the winding type, the current density, the temperature rise and top oil temperature.

The main objective of this report is the technical study to find the temperature at the High Current Leads in Power Transformers.

To find the temperature at the Bus Bar was necessary to calculate the dimensionless numbers of Prandtl, Rayleigh, Grashof and Nusselt when the natural convection is being considered.

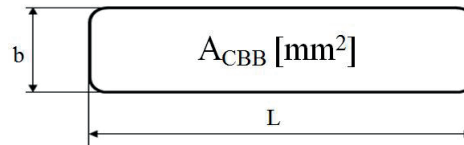The Bus Bar dimensions can be seen at the Fig. 1 below as example:

Figure 1 - Bus Bar Section Example

2. LOSSES CALCULATION

To calculate the losses, the electrical resistance and the current must be known.

The current of busbar lead is established by the winding. The resistance is calculated across of resistivity of copper. To fix the resistance is possible to fix the resistivity. In that case the fixed resistivity was used. To calculate the resistance was input in the calculation the temperature rise and the electrical factors as skin factor, proximity factor and leakage flux factor.

This factors are calculated from electromagnetic 3D software which use numerical method (Finite Element Method).

$$R_{CuCalc} = \frac{\rho_0 \cdot \{1 + [\alpha_{Cu} \cdot (T_{CuCalc} - T_{20^\circ C})]\}}{\left(\frac{L}{1000} \cdot \frac{X}{1000}\right)} \cdot f_s \cdot f_p \cdot f_d \tag{1}$$

where:

- L = characteristic length [m]
- X = busbar thickness [m]
- T_{cucalc} = Calculated Temperature [ºC]
- α_{Cu} = correction resistivity coeficient [ºC^{-1}]
- ρ = copper resistivity at 20ºC DC [Ω/m]
- f_s = skin factor [ ]
- f_p = proximity busbar factor [ ]
- f_d = winding leakage flux factor [ ]

The losses are calculated as below.

$$Q = I_{busbar}{}^2 \cdot R_{AC\theta} \tag{2}$$

where:

- I_{busbar} = BusBar Current [A]
- $R_{AC\theta}$ = Resistance at Calculated Temperature [Ω/m]
- Q = Power Losses [W

3. DEFINITION OF DIMENSIONLESS NUMBERS

3.1. Prandtl Number

The Prandtl number Pr is a dimensionless number; the ratio of momentum diffusivity (kinematic viscosity) to thermal diffusivity.

$$P_r = \frac{\upsilon}{\alpha} = \frac{ViscousDiffusionRate}{ThermalDiffutionRate} = \frac{c_p \cdot \mu}{k} \tag{3}$$

where:

- υ : kinematic viscosity, $\upsilon = \mu / \rho$ [m^2/s]
- α : thermal diffusivity, $\alpha = k / (\rho{*}cp)$ [m^2/s]
- μ : dynamic viscosity [(N*s)/m^2]
- k: thermal conductivity [W/(m*K)]
- cp : specific heat [J/(kg*K)]
- ρ : density [kg/m^3]

3.2. Grashof Number

The Grashof number Gr is a dimensionless number in fluid dynamics and heat transfer which approximates the ratio of the buoyancy to viscous force acting on a fluid. It frequently arises in the study of situations involving natural convection.

$$G_{rL} = \frac{g \cdot \beta \cdot (T_s - T_\infty) \cdot L^3}{\upsilon^2} \tag{4}$$

where:

- g = acceleration due to Earth's gravity [m/s^2]
- β = volumetric thermal expansion coefficient [1/ºC]
- T_s = surface temperature
- T_∞ = bulk temperature
- L = length [m]
- υ = kinematic viscosity [m^2/s]

3.3. Rayleigh Number

In fluid mechanics, the Rayleigh number for a fluid is a dimensionless number associated with buoyancy driven flow (also known as free convection or natural convection).

The Rayleigh number is the product of the Grashof number and the Prandtl number. Hence the Rayleigh number itself may also be viewed as the ratio of buoyancy forces and (the product of) thermal and momentum diffusivities.

For free convection near a vertical wall, this number is:

$$R_a = G_r \cdot P_r = \frac{g \cdot \beta}{\upsilon \cdot \alpha} \cdot (T_s - T_\infty) \cdot L^3 \tag{5}$$

where:

- L = Characteristic length [m]
- Gr = Grashof number
- Pr = Prandtl number

- g = acceleration due to Earth's gravity [m/s^2]
- Ts = Surface temperature
- T∞ = Quiescent temperature
- ν = kinematic viscosity [m^2/s]
- α = Thermal diffusivity
- β = volumetric thermal expansion coefficient [1/ºC]

3.4. Nusselt Number

The Nusselt number is the ratio of convective to conductive heat transfer across (normal to) the boundary. The conductive component is measured under the same conditions as the heat convection but with a (hypothetically) stagnant (or motionless) fluid.

The convection and conduction heat flows are parallel to each other and to the surface normal of the boundary surface, and are all perpendicular to the mean fluid flow in the simple case.

$$N_u = \frac{h \cdot L}{k} = \frac{Convective\, Heat\, Transfer\, Coefficient}{Conductive\, Heat\, Transfer\, Coefficient} \tag{6}$$

And considering $\dfrac{dI}{dt} = 0$, the heat transfer is:

$$h = \frac{Q}{A \cdot \Delta T} \tag{7}$$

where:

- L = characteristic length [m]
- kf = thermal conductivity of the fluid [W/(m*K)]
- h = convective heat transfer coefficient [W/(m^2*K)]
- Q = losses [W]
- ΔT = rise temperature
- A = cooling area, $A_{cool} = 2 \cdot \left(\dfrac{b}{1000} + \dfrac{L}{1000} \right)$ [m^2]

The selection of the characteristic length should be in the direction of growth (or thickness) of the boundary layer.

Typically, for free convection, the average Nusselt number is expressed as a function of the Rayleigh number and the Prandtl number, written as: Nu = f(Ra, Pr).

$$N_u = 0.68 + \frac{0.67 \cdot R_a^{\frac{1}{4}}}{\left[1 + \left(\dfrac{0.492}{P_r} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}} \tag{8}$$

$$R_a \leq 10^9$$

where:

- Ra = Rayleigh number
- Pr = Prandtl number

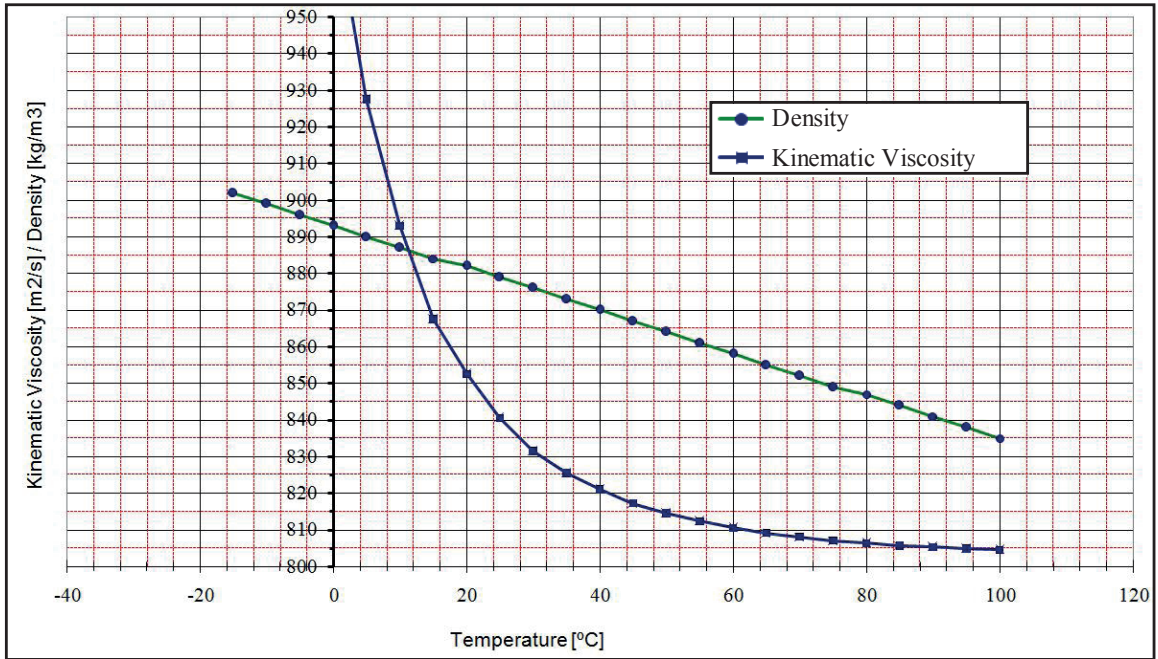## 4.   TEMPERATURE FUCTIONS VARIABLES

Figure 2 - Density and Kinematic Viscosity Variation
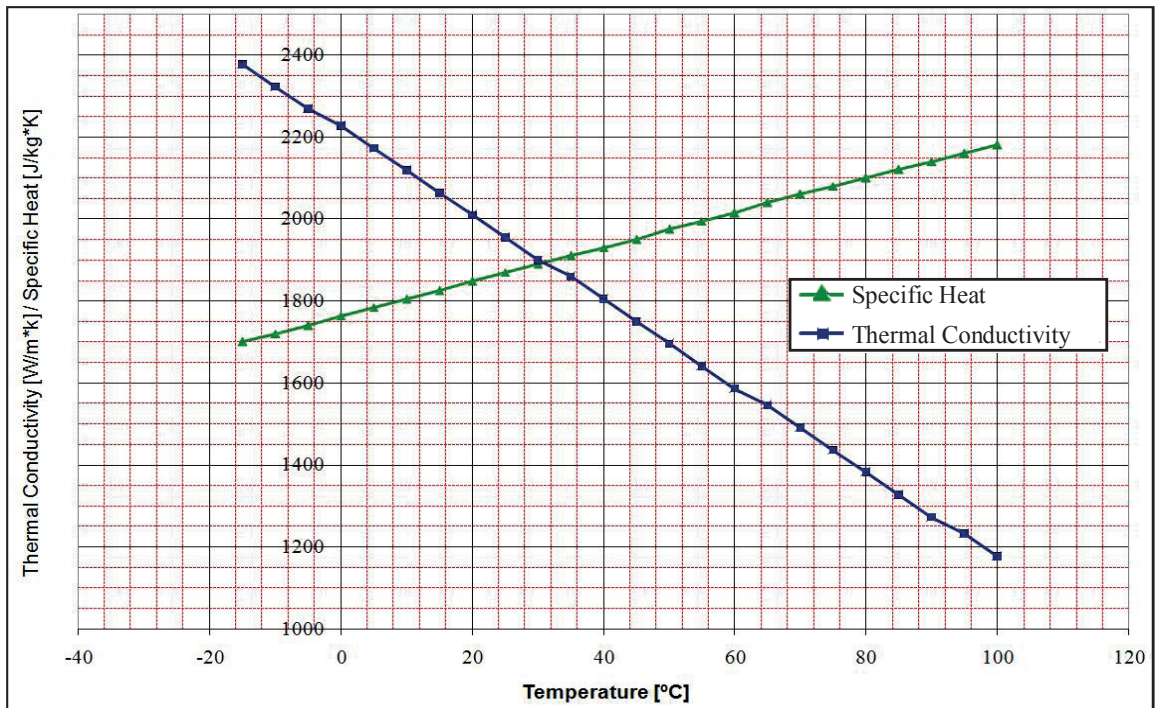

Figure 3 - Thermal Conductivity and Specific Heat Variation

5. TEMPERATURE RISE DUE TO PAPER COVERED

To calculate the temperature at the paper layer of the copper bus bar, the following expression must be used:

$$\Delta T_{paper} = \frac{Q}{A} \cdot \left(\frac{1}{h} + \frac{e}{kp} \right) \tag{9}$$

where:

- Q = losses [W]
- k_p = Paper Thermal Conductivity [W/(m*K)]
- h = convective heat transfer coefficient [W/(m^2*K)]
- e = Paper thickness
- ΔT_{paper} = rise temperature at the layer of paper
- A = cooling area, $A_{cool} = 2 \cdot \left(\frac{b}{1000} + \frac{L}{1000} \right)$ [m^2]

6. PROGRAM FLUXOGRAM

Some variables are temperature dependent. In that case, this variable need to be fixed after the first temperature found at copper busbar. Some iterations must be done starting from this temperature to fix the new temperature found across the formulas written before. See figure below:
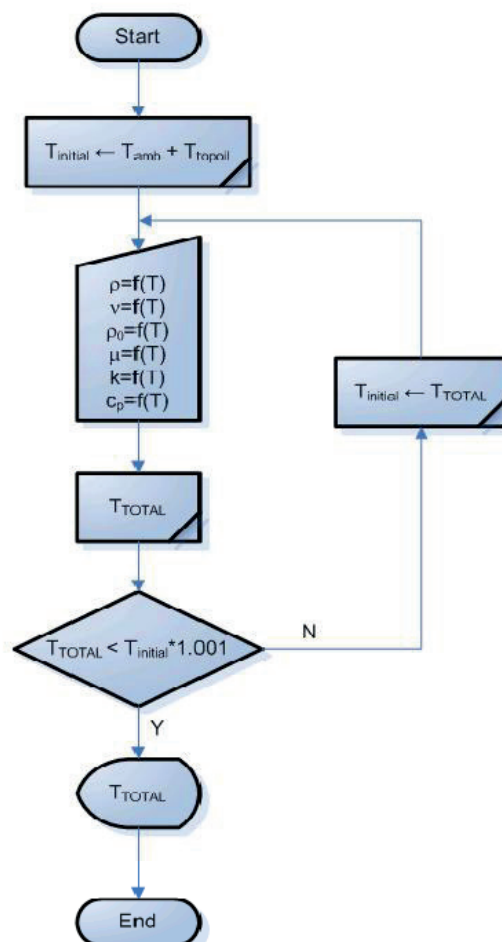

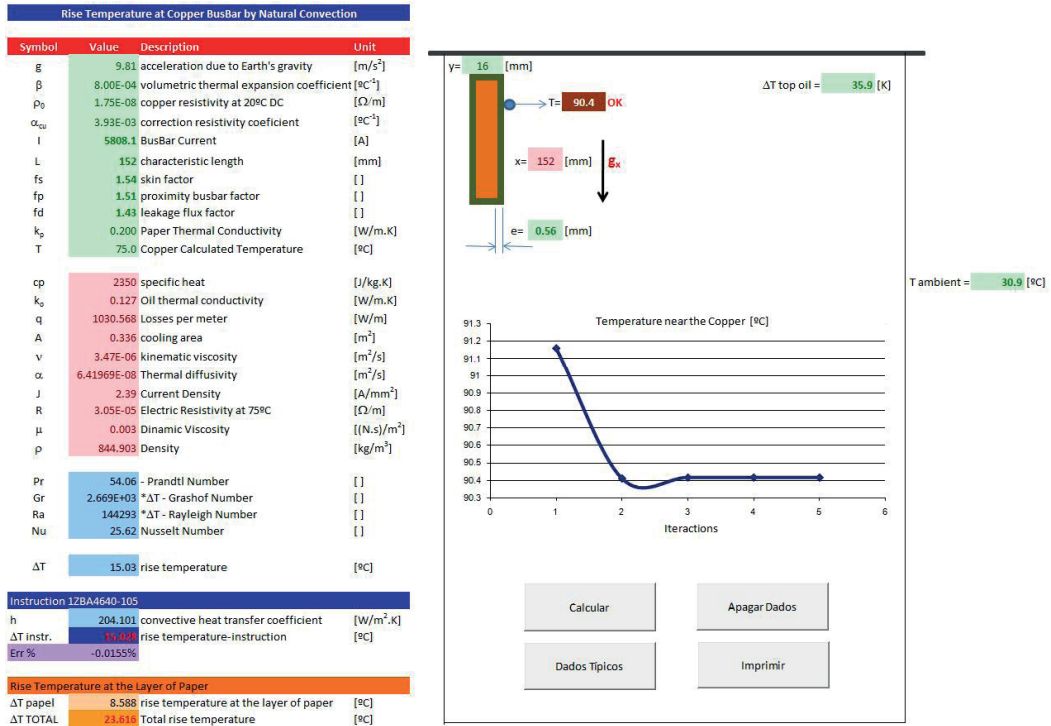Figure 4 - Program Fluxogram

7.   PROGRAM LAYOUT

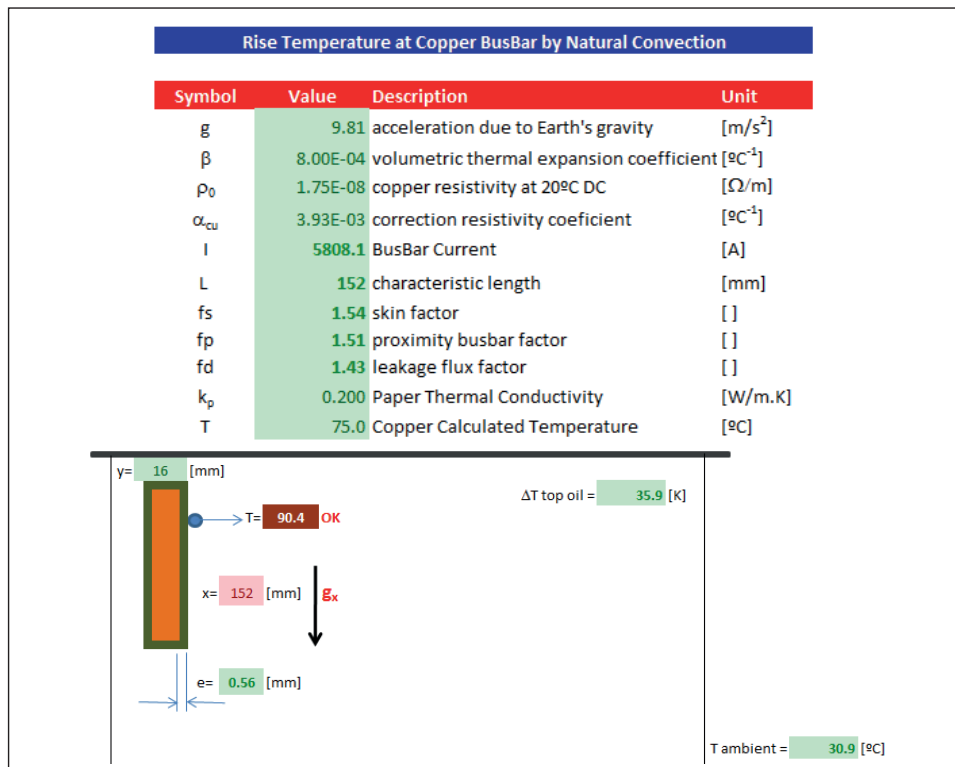Figure 5 - Software BBT - BusBar Temperature - Visual Basic Application

7.1.   Input data

Figure 6 - Input Data - Only Green Square

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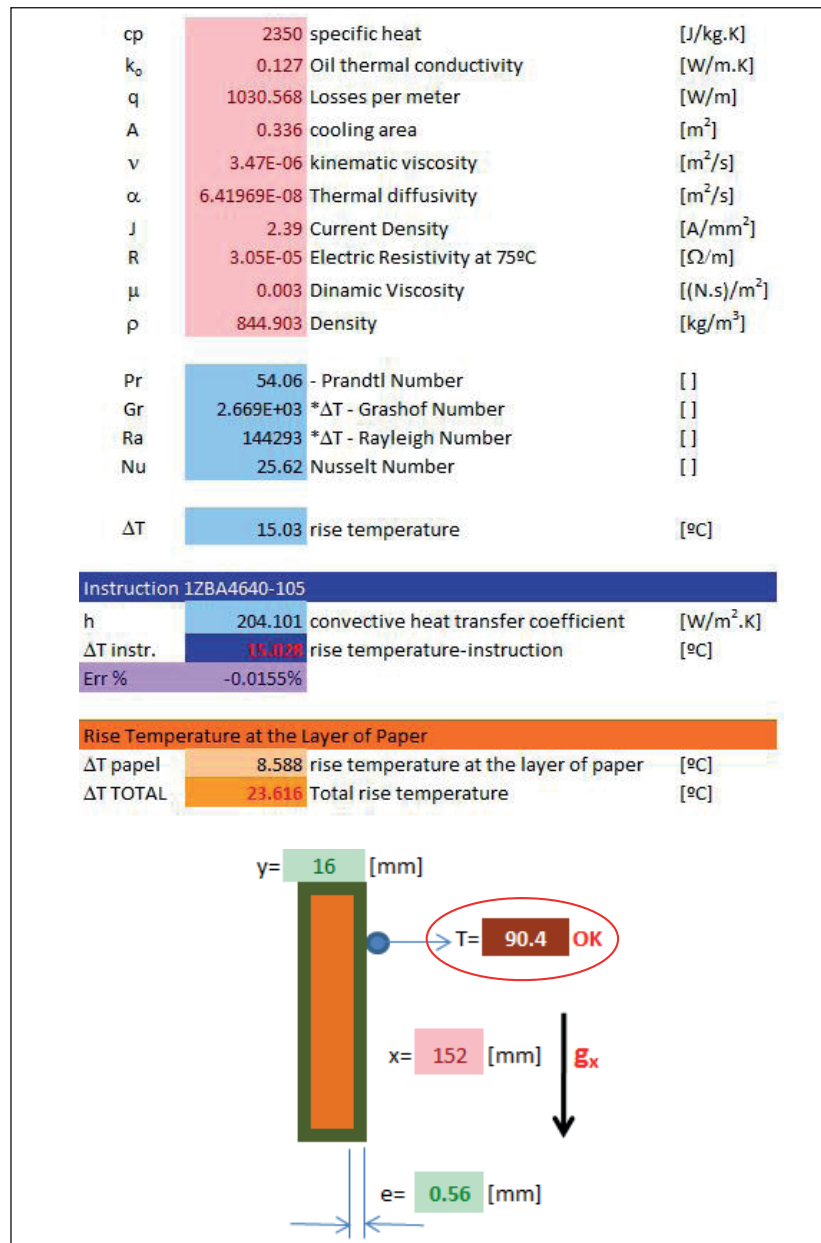
7.2. Output data

Figure 7 - Output Data - Absolute Temperature at BusBar

7.   RESULTS FROM REAL CASE

The real case tested was a transformer 460MVA Nominal Power, 13.2kV Low Voltage Busbar , 60Hz frequency, Cooling System ODAF. The heating hest was 100% load during 72 hours and with internal measurements using optical fibers.

The used sensor was the model T2™ Fiber Optic Temperature Sensor from NEOPTIX. The Fig. 8 shows the optical fibers positioning for the measurement of temperature on the busbars.
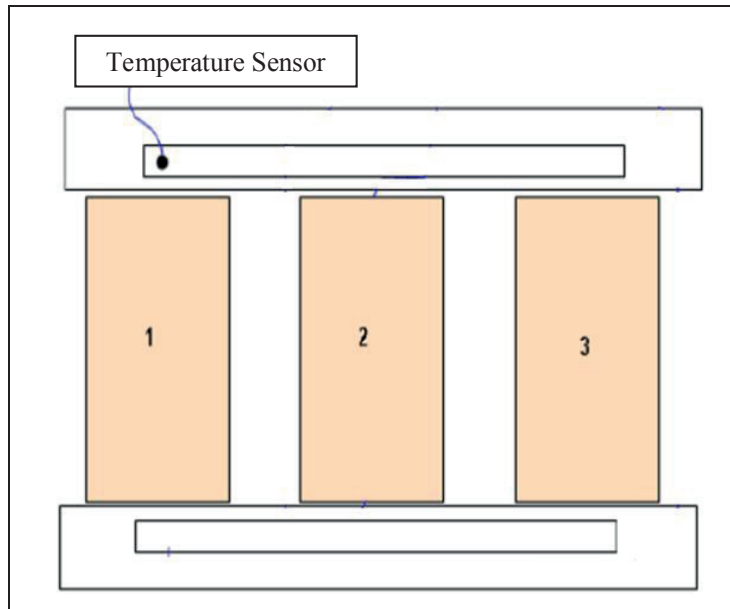

Figure 8 - Optical Fibers Positioning

The calculated value of the temperature on the Copper Bus Bars was 90.4°C, while the average value measured through optical fibers was 89.7°C, resulting in a percentage error of 0.78%.
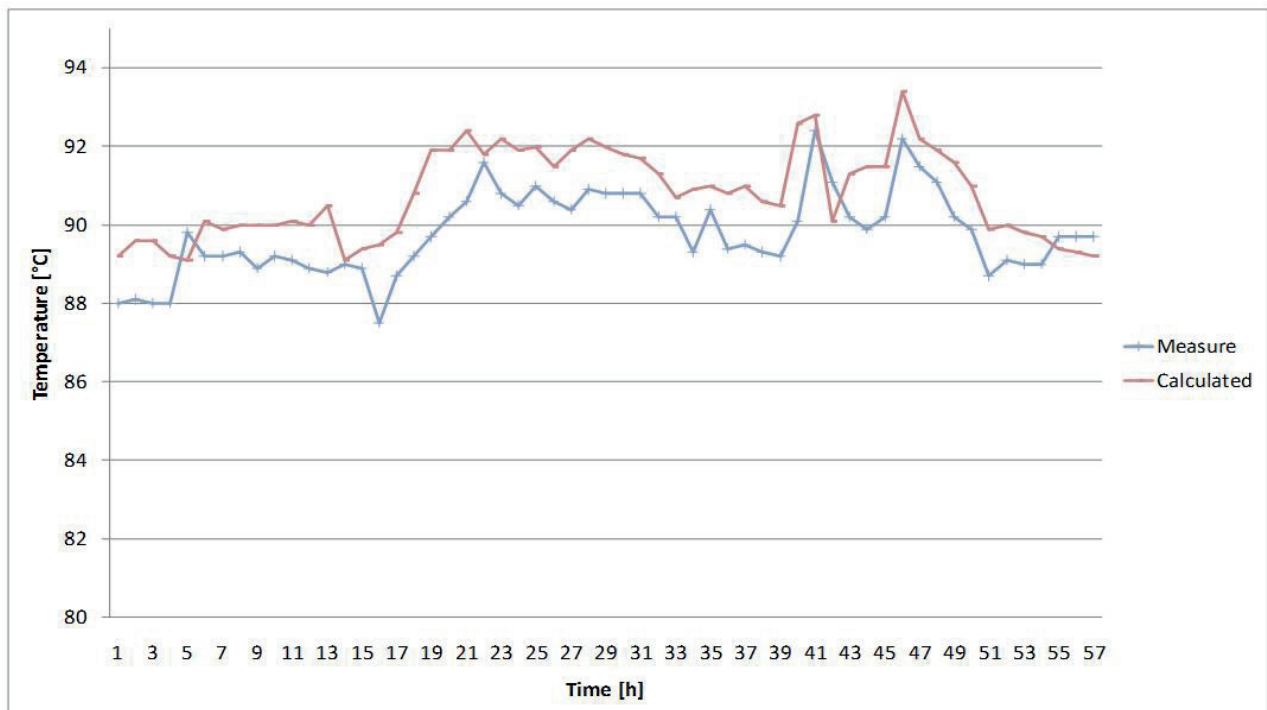

Figure 9 - Measure (test lab) and Calculated Values

The Fig. 9 shows in detail all the measured values and compares the proximity of the calculated value during the heating test.

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8. ACKNOWLEDGMENTS

9. CONCLUSION

Comparing the results from the presented software with the results measured at this real case (test laboratory), it is possible to observe a close proximity of the values.

This analysis validates the developed program and allows a better dimensioning of copper Bus Bars with a great save of material.

Then, it is possible to conclude that the program allows to be done a large number of tests with different types of Bus Bars and different positions of this Bus Bars with the main objective of loss and temperature reduction, material and final cost of the equipment, this calculation can also be used to avoid a possible re-work, non-acceptance or disapproval in heating tests, improving the overall performance of the equipment, as said before.

5. REFERENCES

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