Numerical Model of a Three-Phase Busbar Trunking System

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***Abstract*—The thermal behavior of an industrial Low Voltage non-segregated three-phase busduct is analyzed by means of the comparison of a 3D numerical model with experimental results. This model has been carried out using COMSOL Multiphysics, software based on finite element method. The numerical model replicates the short-circuit test, using the same geometry configuration and the boundary conditions of the laboratory in which this assay is carried out. The standard IEC 61439 is applied, both in test and model, in order to obtain the steady state temperatures in several parts of the busbar system. As a result of the data comparison can be concluded that the experimental test is replicated with sufficient accuracy by the numerical model. In fact, the average error of all the temperatures is smaller than 5%. As a general conclusion, the numerical model developed can be considered accurate enough to use it in the first steps of the busbar design.**

Keywords— ***Busbar Trunking System (BTS), 3D Thermal modelling, Numerical Simulation, Experimental validation***

I. Introduction

An electric Busbar Trunking System (BTS) is an enclosed electrical distribution system comprising solid conductors separated by insulating materials. They are used in many applications due to their technical advantages and cost effectiveness. For instance, the most common use is in the power distribution in a predetermined area, thus feeding applications such as light fittings, factories, offices, etc. Even more, they can be also used in the interconnection between switchboards or switchboards and transformers.

Many technical specifications have to be fulfilled in these assemblies. In fact, their design is habitually done according the standard [1], in which many technical requirements are established. Many and very expensive laboratory tests have to be carried out in order to verify that these requirements are fulfilled.

As a consequence of the above, a good theoretical design would be needed. This would allow us to minimize as much as possible the number of verification tests. The numerical modeling, jointly with the great development of the computational resources, both in hardware and software, seems to be a good way to accomplish the aforementioned goal. Many models can be developed. For instance, the temperature-rise test can be replicated by means of a thermal model.

The thermal models of electrical machines and systems are very usual in the literature since their operating conditions and lifetime depend on their heat losses. For instance, in relation to electrical cables, several papers in which thermal models are developed have been made in last years. In 1999, the ampacity derating of electric cables in wrapped trays of nuclear power stations are determined by Figueiredo et al. [2]. Heat losses in underground cables were studied by Kovac et al. in [3], De Lieto et al. in [4] and Chatziathanasiou et al. in [5].

A thermal model of a low-voltage BTS is presented in this article. This model was carried out by using the heat transfer module of COMSOL Multiphysics. The simulation results were validated comparing them with experimental results obtained from a heating test. The model validity allows us to design new low voltage three-phase BTS. In fact, new geometries and materials can be checked or the thermal behavior of the busways can be studied a priori in different operating conditions. This way, more efficient BTSs can be designed, thus reducing their weight and cost.

Section two shows the geometrical description of the BTS studied. Experimental test is presented in the third section. Fourth section introduces the numerical model developed. Simulation results and their comparison with experimental ones are shown in the fifth section. Finally, conclusions are presented in last section.

II. Geometrical description of the BTS studied

As mentioned above, a low voltage non-segregated three-phase BTS is analyzed in this paper. This busway is designed considering an operating voltage smaller than 1 kV (or equal) and a rated current of 1.5 kA. It is made up six copper bars with two different sections: the larger sections belong to the three phases and the ground, while the two smaller ones belong to the protective conductors. Main dimensions of the studied busway are shown in Figure 1.

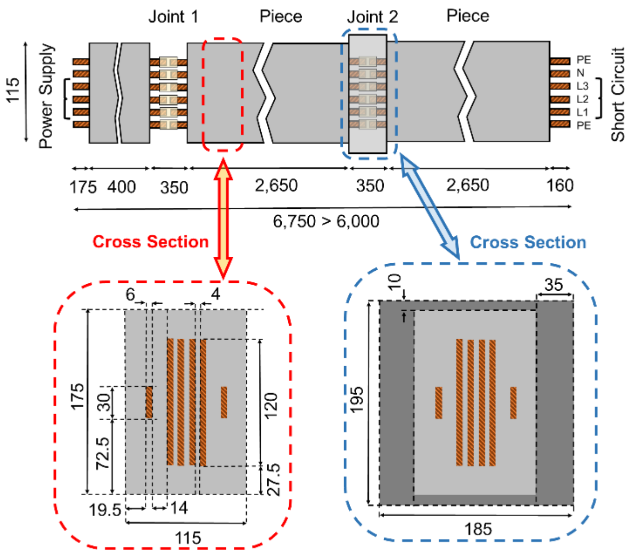

Figure 1. Geometrical description of the tested BST (mm)

III. Laboratory Test

A. Test requirements

The performance of a BTS is fixed by means of the compliance of the international standard IEC 61439-6 [1]. Many electrical, mechanical and fire-safety requirements are established by this standard. The Temperature rises of the different components of the BTSs with respect to ambient temperature is one of these requirements. The limits of these temperature rises are prescribed in other part of the standard, IEC 61439-1, [6]. The verification of these limits can be carried out using a laboratory test.

In this laboratory test, the climatic chamber has to fulfill several requirements. For instance, its ambient temperature must be among 10ºC and 40ºC, and its average value referred to a 24-hour period shall not exceed 35ºC during this test. Also, this chamber must not have forced airflow.

After satisfying the temperature conditions of the laboratory, the previously mentioned temperature limits in the different components of busway must not be exceeded during the temperature-rise test. In our case, the maximum temperature rise is 40ºC for the accessible external enclosure and 105ºC for bare copper busbars.

Regarding the tested BTS, this must be installed as in-service position, with straight lengths and two joints. All of these parts have to be connected, thus obtaining at least a total length of the tested assembly of 6 m. The first joint has to be left open air while the second has to be filled with cast resin, as it shown in Figure 2.

The connection terminals to the power supply have to be on the side of the open joint and the other terminals have to be short-circuited. The three phase busbars are powered with current sources, with the ground and the protective conductors without power supply. The BTS has to be tested using rated current and the temperatures in the assembly have to be measured when the stationary regime of these temperatures is reached.

B. Test description

The heating test was carried using an assembly of 6.75 m. placed horizontally (edgewise) on supports approx. 1 m. from the floor, in a climatic chamber, according the standard, [6].

This assembly consists: a flange; a first uncovered joint that was left open air; a first straight length; a second joint covered with cast resin; a second straight length; a shorting piece directly connected on the end of the second straight length (See Figure 2).

A 50 Hz, 415 V, three-phase current source (three single phase transformers) was connected to the assembly. This connection was made by means of two copper bars of 100x5 mm cross-section per phase. The rated current (1,500 A) was loaded per phase and was kept constant until thermal equilibrium was reached.

The temperature rises of various points were measured by means of 24 thermocouples, and one sensor for the ambient temperature. The location of the thermocouples is indicated in Figure 2.

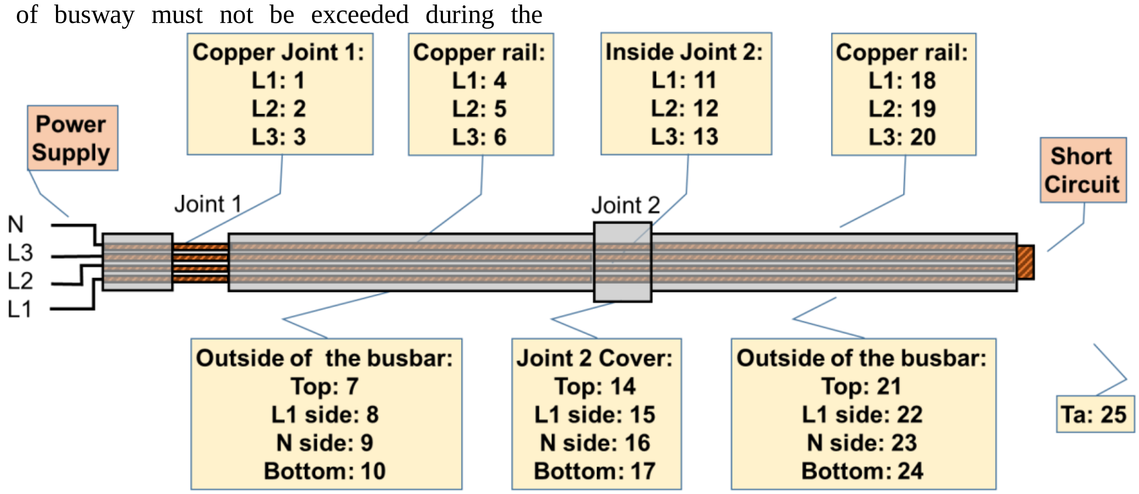

Figure 2. Location of the thermocouples in the assembly

IV. NUMERICAL MODEL

A. Governing equations

This study is based on the numerical solution of the heat transfer equations by conduction, convection and radiation, Eqs. (1), (2) and (3).

$$\rho \cdot C_p \cdot \mathbf{u} \cdot \nabla \mathrm{T} = \nabla \cdot (\mathrm{k} \cdot \nabla T) + Q \quad (1)$$

$$-\boldsymbol{n} \cdot (-k \cdot \nabla T) = h \cdot (T_{ext} - T_s) \quad (2)$$

$$-\boldsymbol{n} \cdot (-k \cdot \nabla T) = \varepsilon \cdot (G - \sigma \cdot T_s^4) \quad (3)$$

where ρ is the material density, C_p is the specific heat capacity, k is thermal conductivity, h is the heat transfer coefficient, ε is the emissivity, G is the total radiation incident on surface per unit time and per unit area and σ is the Stefan–Boltzmann constant. Also, ***u, n*** are the velocity vector and normal vector to boundary surface, respectively. Moreover, Q is the unitary heat transfer. Finally, T_{ext} and T_s are the ambient temperature and surface temperature, respectively.

B. Physical model and boundary conditions

Two uniform volumetric heat sources (Q) are considered: one of them is applied on the straight lengths and the other on the joints. This disparity is due to the different electrical resistance (R_{Cu}) of both parts as a consequence of the contact resistance ($R_{contact}$) that only appears in the aforementioned joints. This $R_{contact}$ is due to the tightening torque applied to the screws.

In order to obtain the two Q, the Joule losses (P_{Joule}) are determined in both parts of the assembly, by using the rated current (I, 1.5 kA) and the R_{Cu}s. Finally, Q are calculated using eq. (4), where V is the volume of the parts.

$$\mathrm{Q} = \frac{\mathrm{P_{Joule}}}{\mathrm{V}} \quad (4)$$

The surfaces of the electrical connection flange are considered as adiabatic areas in order to replicate the heating test in which this flange is covered by a thermal coating.

Heat transfer by natural convection between the hot surfaces of the assembly (insulating and copper surfaces) and the air is supposed. It is used the eq. (2), in which h is calculated depending on the orientation of the surface: vertical wall (range: 3.7÷5.1 $W/m^2 \cdot K$), horizontal plate upside (range: 5.5÷7.1 $W/m^2 \cdot K$) and horizontal plate downside (range: 2.8÷3.6 $W/m^2 \cdot K$), [7]. In this equation, T_{ext} is the air temperature in the climatic chamber, 33.9 ºC.

Surface-to-ambient radiation is also considered. The radiative surfaces are the same than those used in convective heat transfer. The insulating surfaces have much higher emissivity than that of the copper (See Table 1 in subsection C). Also, surface-to-surface radiation is also considered between copper surfaces

The above physical model has been solved via the "Heat Transfer in solids" interface of the commercial finite elements-based software Comsol Multiphysics v5.0.

C. Material properties

The physical properties (ρ, k, Cp ε, ρ_e and α), shown in Table 1, of the busway solid materials are assumed constant with temperature, except the resistivity, ρ_e. The enclosure is an insulating material that is made with a mixture of polymeric resins and aggregates.

Table 1. Physical properties of solid materials

	ρ [kg·m^{-3}]	k [W·(m·K)$^{-1}$]	C_p [J·(kg·K)$^{-1}$]	ε	$\rho_{e,20\,°C}$ (Ω·m)	α (1/K)
Copper	8,700	400	385	0.19	$1.71 \cdot 10^{-8}$	$3.93 \cdot 10^{-3}$
Encl	1,930	1.05	1,900	0.89		

V. RESULTS

The temperatures distribution of the assembly in stationary régime is shown in Figure 3. The comparison of the temperatures values of the test and the simulation can be seen in Table 2.

The use of cast resin insulation in copper bars produces a temperature gradient of 15º C between its inner and outer surfaces. In case of joint 2, with a thicker layer of this insulation, the value of this gradient is 30º C.

The measured maximum temperature (96.4° C) is situated in the inner bar of the joint that is left on air, both in the test and the simulation (sensor 2). On the other hand, the measured minimum temperature (57.8° C) is located in the upper horizontal surface of the joint that is covered with cast resin (sensor 16).

These values are close to those obtained in the simulation. The discrepancy appreciated between experimental and simulation temperatures are in the range 3.7 and -2.4 K.

Apart from the compliance with the electrical requirements, the use of the cast resin allows to improve the cooling of the busbar, as can be seen in the temperatures comparison of both type of joints. These improvement is mainly due to the increase of the heat transfer surface between air and the BTS.

In relation to the convective coefficients, the highest ones appear in the upper horizontal surfaces while the lowest values are obtained in the bottom horizontal surfaces.

VI. CONCLUSIONS

A thermal model of a low voltage non-segregated three-phase assembly is developed in this article using COMSOL Multiphysics with the intention to obtain a computational prototype which eases us the design of this type of BTS.

The model results are validated by means of the comparison with the results of a heating test. This test has been performed according IEC standard. The relative errors obtained from this comparison have been smaller than ±5%.

As a general conclusion, the validity of the computational model developed allows us to use it in the first steps of the design of this type of BTS. In these first steps, the model can be modified by using new materials or geometries, thus improving the BTS design from the thermal standpoint without any additional economic costs.

Acknowledgements

The authors of this research wish to acknowledge to the Spanish Ministry of Science for the financial support to the National Research Project: Performance of the insulating systems in transformers: alternative dielectrics, thermal-fluid modelling and post-mortem analysis (DPI2013-43897-P).

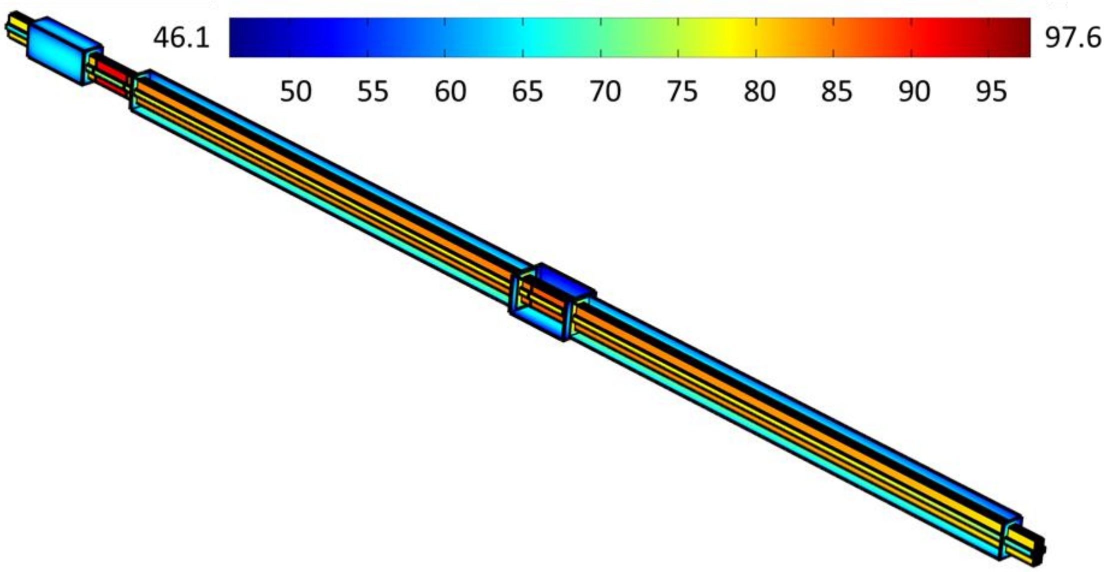

Figure 3. Temperatures distribution of the assembly

Table 2. Comparison of the test and simulation temperatures

	Temperature (º C)	
Sensor Nº	**Experimental**	**Simulation**
S1	92.2	92.1
S2	96.4	97.4
S3	91.8	91.6
S4	80.6	84.2
S5	82.4	85.3
S6	80.2	83.9
S7	68.9	68.0
S8	68.7	70.2
S9	65.2	67.3
S10	68.8	70.3
S11	86.5	89.4
S12	89.3	92.8
S13	86.2	88.8
S14	62.2	63.4
S15	61.9	59.5
S16	57.8	57.6
S17	64.7	65.9
S18	81.0	83.2
S19	83.2	84.2
S20	81.3	82.9
S21	67.2	67.9
S22	67.1	70.2
S23	66.9	67.3
S24	70.8	70.2
S25 (T_{ext})	33.9	

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