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Coupled Electromagnetic and Thermal Field Modeling of a Laboratory Busbar System

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***Abstract*—**The paper presents coupled electromagnetic and thermal field analysis of busbar system (of rectangular cross-section geometry) submitted to short circuit conditions. The laboratory model was validated against both analytical solution and experimental observations. The considered problem required the computation of the detailed distribution of the power losses and the heat transfer modes. In this electromagnetic and thermal analysis, different definitions of electric busbar heating were considered and compared. The busbar system is a three phase one and consists of aluminum, painted aluminum and copper busbar. The solution to the coupled field problem is obtained using the finite element method and the QuickField™ program. Experiments have been carried out using two different approaches and compared with computed results.

***Keywords*—**Busbar system, coupled problems, finite element method, short-circuit currents.

I. Introduction

A better understanding of the electromagnetic and thermal behavior of the busbars can help in solutions of these problems. However, the electromagnetic and thermal calculations of such regimes are rather involved because of complexity of the structures and the non-uniform current distributions caused mainly by skin and proximity effects [1].

Technical progress requires the continuous improvement of busbars. The main goal in busbar development is to increase the ampacity of the components and to reduce the material requirements. As a result of the current flow in busbars, power losses occur, which always turn into heat. Because of the strict technical restrictions, the heat dissipation has to be intensified, or the power losses in busbars must be reduced to remain within the temperature limits. Many studies that considered magnetic- and thermal-field solutions have already been published [2], [3].

For a proper rating of power conductors and equipment the thermal effects of short-circuit currents have to be considered. In the majority of cases in practice the three-phase short-circuit currents have the highest magnitudes and produce the most pronounced thermal stresses. Therefore, the impacts of such faults are usually considered as relevant for thermal sizing.

A numerical solution is required for the accurate calculation of the electromagnetic and thermal fields. The power losses depend on the conductor material properties (electrical conductivity, thermal emission and convection coefficients), while the temperature increase (in the phase conductors and shields) not only depend on the material properties but are additionally influenced by the ambient conditions.

Skin and proximity effects [4], [5] can significantly increase the total power losses. The influence of these effects on the busbar power losses has been widely discussed in the literature. This results in a reduction in the active cross-section of the conductor and increases the heat generation. This represents a significant practical material loss for the conductor.

The heating of conductors, equipment components and elements of distribution systems in normal mode is determined by the load currents and their temperatures do not exceed normal for continuous operation. In case of short circuit the currents are significantly higher than normal currents. Therefore, their temperatures increase rapidly and can reach higher than the permissible values in normal mode. Regardless of short duration of the short circuit these high temperatures can lead to decreased mechanical strength and deformation of the material the electrical parts and equipment. Taking into account the above-mentioned issues, a thorough thermal analysis should be incorporated into the design process.

In the present paper, coupled field problem for a laboratory busbar system has been solved using the finite element method and compared with experiments carried out using two approaches.

II. Description of the Studied Busbar System

The laboratory busbar system (Fig. 1) consists of three different bars of the same cross section: not painted aluminum Al 30x4 mm, painted aluminum Al 30x4 mm and copper busbar Cu 40x3 mm, all of length of 800 mm. Each bar is supplied by its own transformer, thus allowing for setting different currents in the different bars [6].

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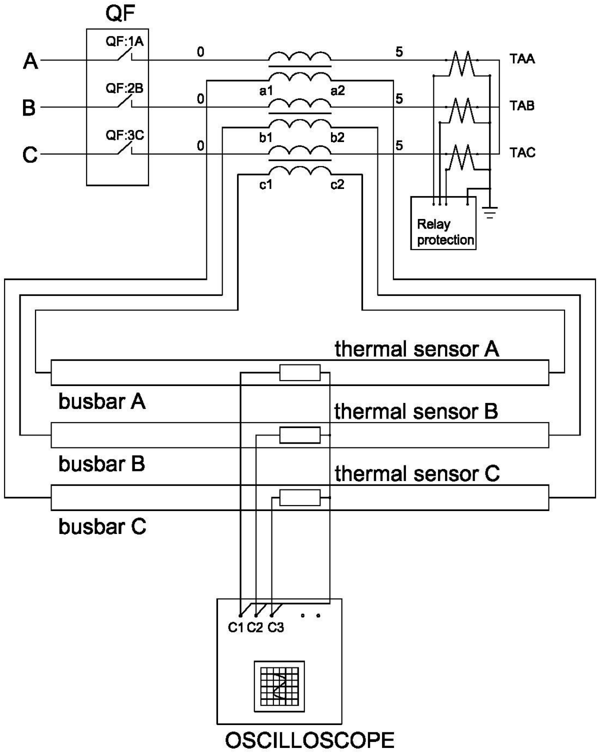

Fig. 1 Experimental setup of laboratory busbar system

III. FINITE ELEMENT MODELLING

The finite element method has been employed for solving the coupled electromagnetic-thermal field problem. The solution process comprises two stages.

At the first stage, coupled problem for steady-state electromagnetic and thermal field is solved. The solution of this problem gives the initial conditions for the solution of the transient problem at the second stage.

At the second stage, coupled steady state electromagnetic (time harmonic) and transient thermal field problem is solved using the initial conditions for the temperature obtained at the first stage, thus taking into account the dependence of different properties on the temperature.

At both stages, the heat source is obtained from the solution of the electromagnetic field problem.

Having in mind the geometry of the system, the field is modeled as two-dimensional. The QuickField$^{\text{TM}}$ program [7], which is suitable for solution of coupled problems of this type, is used for solving the problem.

The currents set to the three busbars at the second stage are as follows: Al – 1300 A, Al painted – 1350 A, Cu – 1400 A. The busbars are subject to these current during time interval of 6 seconds.

The magnetic flux lines distribution and the magnitude of the total flux density for three phase angles (0, 120 and 240 degrees) are shown in Fig. 2. The left bar is copper, the middle painted aluminum and the right one is non-painted aluminum.

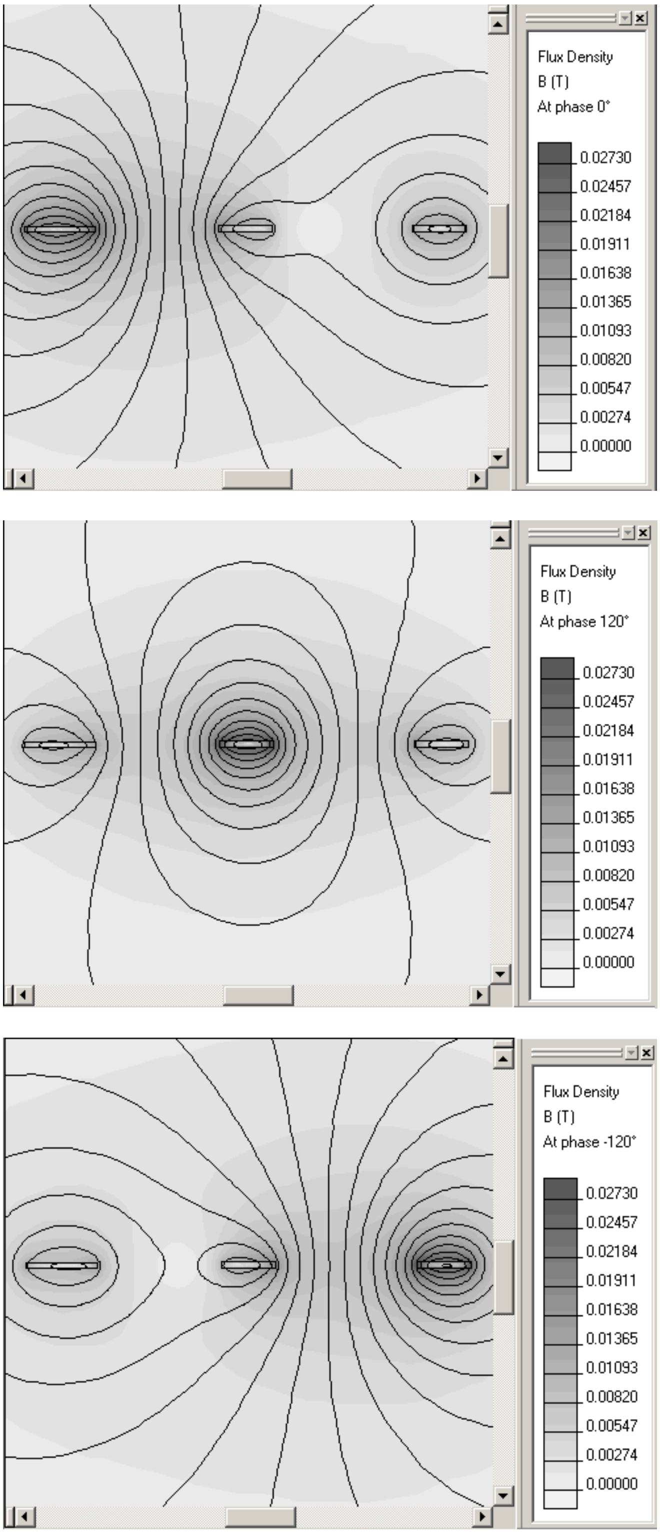

Fig. 2 Map of magnetic field lines and total flux density at three phase angles

The distribution of the total current density (r.m.s. value) and the Joule heat (average value) obtained from the electromagnetic field analysis are shown in Figs. 3 and 4, respectively.

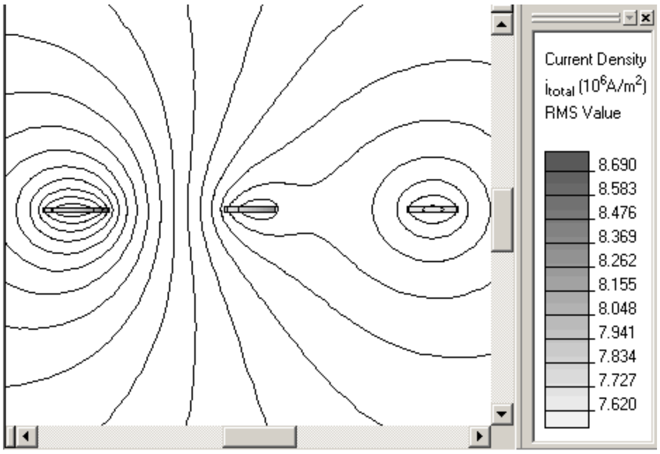

Fig. 3 Distribution of the total current density

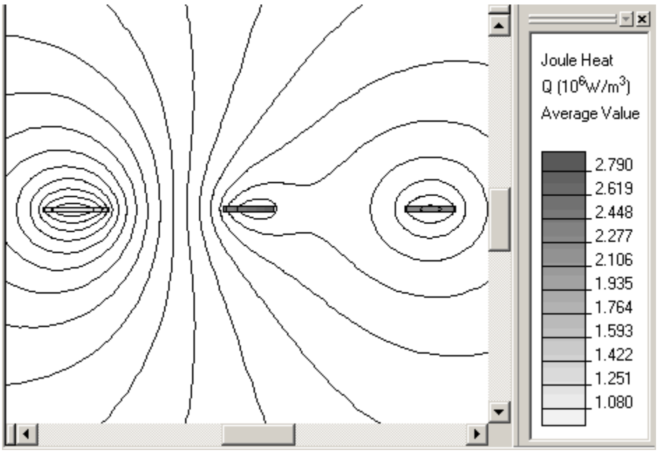

Fig. 4 Distribution of the Joule heat

The temperature distribution obtained at 6th second (at the end of the heating period) is shown in Fig. 5. Due to the high thermal conductivity of the bars, the temperature distribution within the bars is practically uniform.

Fig. 5 Temperature distribution at the end of the heating

The time evolution of the temperature of the middle points of each busbar during the heating period is shown in Fig. 6. The dependencies are practically linear.

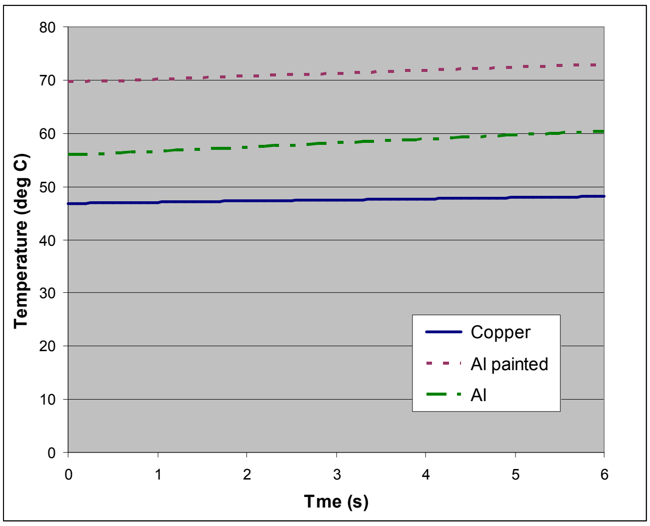

Fig. 6 Temperature vs time for the three bars

IV. Experimental Study

A. Approach Using Thermal Sensors

Measurement of the heat of the busbars is performed by a thermo sensors mounted on the middle of the busbars (Fig. 1) [6]. The sensors for measuring the temperature of the busbars are diagram type SMT 160-30-18. The sensor itself is a rectangular pulse generator. The duty cycle κ_3 of rectangular pulses is proportional to the temperature. The temperature of the corresponding duty cycle κ_3 is calculated by formula, supplied by the manufacturer of the sensor. A probe is mounted in the special holes on the busbars of each phase. Holes around each sensor are filled with silicone sealant for a better heat transfer. Probe terminals are soldered to the secondary circuit board mounted on the busbar. Secondary circuit board is connected with cable to the respective channel of the oscilloscope, and displays the output signal of the sensor. Sensor is powered by a stabilized rectifier output voltage 5 ÷ 15V. The results for the final values of the temperature obtained from the three sensors are given in Table I.

TABLE I
Experimental Results

aluminum not painted	aluminum painted	copper
60°C	71°C	46°C

B. Approach Using Thermovision Camera

The heating process during the transient mode is filmed with thermo camera FLIR P640. Infrared thermal camera has a visual field at least 24°/18°, with a minimum range of temperature measurement of -20°C to +500°C, temperature sensitivity 0.05-0.1°C at 30°C precision, a detector array with a minimum 640/480 pixels, image settings, integrated digital color camera, the metering mode different lenses, 1 GB memory and software.

Experimental results obtained for the temperature of the three bars during the heating are shown in Fig. 7.

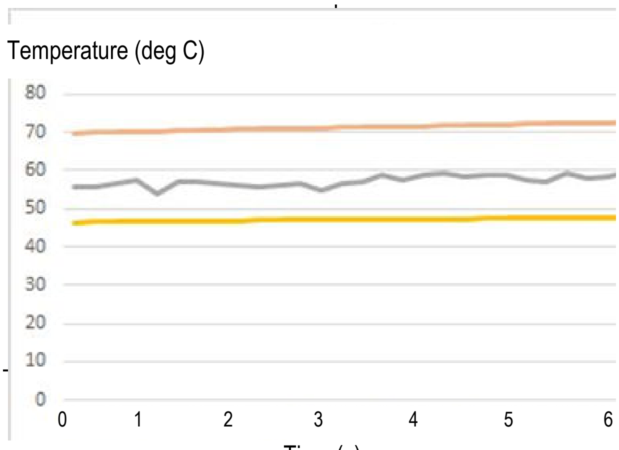

Fig. 7 Temperature vs time for the three bars (measured)

The image obtained from the camera at the end of the heating is shown in Fig. 8.

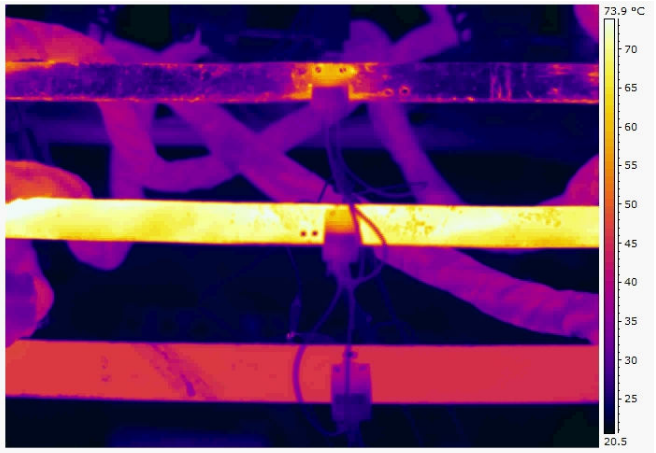

Fig. 8 Temperature distribution at the end of the heating

The computed results are closer to the experimental ones obtained using thermovision camera, where the difference does not exceed 0.5°C, while larger differences (about 2°C) are observed with respect to the experiment using thermosensors. Having in mind that the computed values are greater than the experimental ones, the employed modelling approach could be used for design purposes.

V. CONCLUSION

The presented modelling two-stage approach for solving coupled electromagnetic-thermal field problem for a laboratory busbar system has shown good agreement with the experiment and fast computation, as only 2D problem has to be solved. This approach can be used also for initial assessment of more complex busbar systems.

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