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Coupled numerical modelling of power loss generation in busbar system of low-voltage switchgear

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ABSTRACT

This paper presents a coupled mathematical model of the heat transfer processes in an electric switchgear. The considered problem required the computation of the detailed distribution of the power losses and all the heat transfer modes (radiation, convection, and conduction) within a unit. In this complex thermal analysis, different definitions of electric busbar heating were considered and compared. The most advanced model, which couples the thermal and electromagnetic fields in two ways, was also compared with the simplified approaches. First, the direct current loading of the busbar, which neglected the alternating current effects, was considered. Second, models that included only one method of coupling were calculated for different assumed average busbar temperatures. Finally, the model with the two-way coupling, which took the eddy currents and proximity effects into account, was simulated using an iteration loop between the electromagnetic and fluid flow solvers. This study employed a geometrical model of industrial low-voltage switchgear. The presented mathematical model was also validated against temperature measurements carried out by a certified laboratory. The obtained results show that a fully coupled model produces very satisfactory agreement between computed and experimental data.

1. Introduction

Power distribution systems require reliable and trustworthy devices to ensure the continuity of electric energy delivery. These power distribution devices include switches, fuses, breakers, and busbars. A piece of switchgear combines these devices in one unit, which makes it possible to insulate the electric equipment and measure the circuit parameters. Therefore, the importance of switchgear in modern power engineering is continually increasing [1].

Technical progress requires the continuous improvement of devices. The main goal in switchgear development is to increase the ampacity of the components [2] and to reduce the material requirements. As a result of the current flow in busbars, power losses occur, which always turn into heat. Hence, a cooling system is required to protect the equipment. Strict technical restrictions [3,4] define the maximum temperature rises for the elements of the switchgear. Because the regulations are becoming stricter for new products, 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 [5–10]. Although the available mathematical models significantly reduce the calculation time for these power losses, the developed formulae are restricted to simple geometries, e.g., conductors with circular or rectangular cross-sections [11–13]. Alternative methods based on lumped-parameter thermal networks or field numerical solvers are used for more complex geometries such as electrical machines or pieces of switchgear [14].

Nevertheless, a numerical solution requires the accurate calculation of the electromagnetic, fluid flow, and thermal fields inside the switchgear. These physical phenomena are defined by mathematical equations, which include the heat generation due to the current flow and the heat transfer processes. The ohmic losses depend on the current rating, material properties, and shape and size of the conductors. The Joule losses for direct current (DC) can be calculated by multiplying the conductor resistivity by the

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squared current that flows through a conductor. However, for alternating current (AC), additional losses have to be considered [15]. Because of the periodic reversal of the electric charge flowing through the busbar, a magnetic field is formed near the conductor, which leads to the presence of inductance effects [16,17]. These effects, which are called skin and proximity effects, can significantly increase the total power losses in comparison with the DC losses alone [15].

The influence of the eddy current and proximity effects on the busbar power losses has been widely discussed in the literature [15,18–21]. Generally, the skin effect causes the intensity of the current flux to be higher at the boundaries of a conductor, while the middle section of the conductor is mostly neglected [22,23]. 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, which increases the production costs for the switchgear. In addition, because of the phase differences, the proximity effect intensifies the uneven distribution of the current in conductors and locally increases the power losses. Therefore, when considering AC switchgear, the skin and proximity effects should be included in a simulation.

Furthermore, for safety reasons, the switchgear used in industrial applications is usually protected by a steel casing [1] to prevent the devices from interacting with the environment. To ensure the appropriate ingress protection (IP), the area of the inlet/outlet grids is usually reduced, and the duct channels have baffled shapes. As a result, the intensity of natural cooling is limited. For the same safety reasons, forced convection is rarely used because unit reliability is a priority for the designers. On the other hand, insufficient heat dissipation can cause serious switchgear damage.

Taking into account the above-mentioned issues, a thorough thermal analysis should be incorporated into the design process for any switchgear application. Therefore, the aim of the work presented in this paper was to propose a 3-D coupled numerical model of the industrial low-voltage switchgear. Such a model included the most important fundamental phenomena that occur in the unit, i.e. the power losses as a result of the coupled generation, all heat transfer mechanisms and contact resistance.

To accurately predict the power losses, an electromagnetic (EMAG) solver was used. The EMAG computations were performed using the commercial code ANSYS Maxwell [24] to determine the skin and proximity effects. Because of the complex nature of the heat transfer problems, a solution for conduction, natural convection, and radiation was also required. Therefore, the fluid flow and heat transfer problems were solved using a computational fluid dynamic (CFD) solver, ANSYS Fluent [25]. Moreover, the analysis included different approaches for defining the power losses. A simplified uncoupled approach, in which losses were directly determined in the CFD solver, was compared with one-way and two-way coupled models. For the purpose of the comparison, the one-way coupling included two different assumed busbar temperatures, which showed the influence of the copper resistivity on the power loss generation.

Hence, the impact of the initial busbar temperature on the final solution for one-way coupled models was studied. As a result, the approaches discussed in this paper considered the influence of the inductance effects and initial temperature definition on the power losses generation within the busbar system. The model was then validated against the results of the experimental tests that were performed in a certified laboratory to obtain the spatial temperature field within the considered unit. The data were captured from numerous locations on the busbar surfaces and within the casing space.

The results showed the effects of the considered approaches for determining the heat loss in industrial switchgear. Moreover, they confirmed the high accuracy of the proposed two-way coupled model that should be considered when the hot spot temperatures are to be determined. In the case when the busbar temperature is known from the laboratory tests and the average temperature is introduced in the computational model, the one-way coupling can be applied successfully.

2. Geometry and mesh

The geometrical model used in the analysis was based on industrial low-voltage switchgear with one neutral (L0) and three phase conductors (L1 to L3). The conductors were located inside a steel casing, as schematically shown in Fig. 1(a). Because the power losses were generated in the system of conducting busbars, a realistic representation of the busbar geometry was required. The majority of the busbars had cross-sections of 50 mm $\times$ 10 mm or 100 mm $\times$ 10 mm, whereas the dimensions of the switchgear model were 1200 mm (width) $\times$ 1200 mm (depth) $\times$ 2000 mm (height).

As already mentioned, the EMAG and CFD solvers were used in the performed analysis. Because different physical phenomena were considered, the model geometry had to fulfil the limitations and requirements of both the EMAG and CFD solvers, and valid data transfer had to be ensured between these two solvers. Despite the geometrical similarities and presence of a geometrical symmetry plane, the switchgear had to be considered as a full model. Preliminary calculations showed that the obtained power-loss distributions were different for each current path.

Moreover, geometrical parts that were of less importance to the EMAG formulation turned out to be crucial in the CFD model. For example, the insulators for attaching the conductors, which could be neglected in the EMAG solution, significantly influenced the flow field and thus the solution obtained in the CFD solver.

The substantial differences in the model scales (i.e., busbars, switchgear, and casing) required additional attention during the discretisation. The mesh used in the EMAG solution was based on the adaptive discretisation algorithm [24], utilizing the principle of energy conservation. In this method, the iteration process increases the number of numerical elements until the energy imbalance is negligible. Hence, the numerical mesh created during the solution process is guaranteed to fulfil the convergence criteria. The use of this adaptive algorithm resulted in 0.5 million tetrahedrons.

Although the CFD solver allowed the use of tetrahedral elements, hexahedral elements were used to ensure the required accuracy and, at the same time, to reduce the mesh size. In addition, because of the significant differences in the model scales, a non-conformal mesh was generated using the cut-cell method [25]. Based on previous studies [26–28], the mesh density was increased in the vicinity of the busbars, switchgear walls, inlets, and outlets. The results of these efforts are presented in Fig. 1(b).

To calculate the heat transfer process from the solids parts to the flowing air, the numerical mesh had to ensure the accurate prediction of the velocity and temperature fields in the boundary layer. Hence, the mesh in the vicinity of the busbars was refined, and an appropriate wall function was chosen to satisfy the rules for the y^+ parameter near the boundaries of the numerical domain [25].

Furthermore, the inlets and outlets required additional attention during the grid generation. The use of a non-conformal mesh made it possible to locally increase the number of numerical elements near the inlets/outlets, while the total number of elements in the air domain was still under control.

To avoid the need to generate 2-mm discrete elements in the switchgear wireframe, the shell conduction model was applied in these parts [25]. Nevertheless, the mesh size for the CFD analysis included 5.5 million hexahedrons.