# Numerical Analysis of Heat Transfer Processes within Selected Electrical Transformers

## ABSTRACT

The thesis presents a numerical analysis of coupled processes within three phase dry-type electrical transformers. The developed model employed a multi-disciplinary approach involving heat and fluid flow, electromagnetic and mechanical phenomena. The main CFD analysis was coupled with the electromagnetic model to examine the specific power losses within coils and a core. The mechanical model determined the thermal stresses within the encapsulated device based on the final temperature field obtained from the CFD-electromagnetic coupling. The thermal boundary conditions, *i.e.* local and temperature-dependent heat fluxes, were computed by considering a numerical model of the surrounding air. Moreover, separate numerical and analytical models were considered to obtain the anisotropic thermal conductivities for different types of the coils and also for the laminated cores. To validate the numerical model, experimental transformer temperature tests in the short-circuit, open-circuit, and under rated parameters according to the current European Standards for dry-type transformers were performed. During the tests, temperatures were measured at selected points on transformer elements using thermocouples, while on the external tank walls an infrared thermography was employed. The obtained numerical results showed that the prediction of the temperature distribution within the analyzed transformers and their surroundings was very accurate.

The considered transformers dissipate heat from the external walls by natural convection to the environment and by radiation to the internal walls of the large room. Therefore, the model including fluid flows *i.e.* the internal air surrounding the transformer itself and the external air outside the transformer tank, was developed to determine local and temperature-dependent heat fluxes (both convective and radiative) on external walls of the transformer and its tank. In order to perform such calculations, the continuity of the temperature and heat flux on the interface between the transformer and the surrounding air was enforced through an iterative procedure. It is also worth mentioning that the idea of the local heat fluxes can be successfully applied to any transformer working in an arbitrary surrounding.

In the electromagnetic analysis, both the coil and the core transformer losses were taken into account. The local core losses were calculated using a Steinmetz-based equation approach. Therefore, the core losses were a function of the amplitude of the magnetic flux field. The coil losses known as Joule heat were determined on the basis of a local current flux and a local electrical resistivity defined as temperature-dependent quantity. To obtain the temperature-dependent power loss distribution for the coils, the CFD analysis was coupled with the analysis of the electromagnetic field in the iterative procedure. When all the specific power losses were determined locally in the current iterative loop, their values were transferred to the CFD model. Then, using the solution of the CFD model, a new set of electrical material properties were calculated and updated into the electromagnetic model.

Due to the complicated, heterogeneous construction of the transformer coil, thermal properties for these elements were considered as anisotropic. For instance, the thermal conductivity was much higher along wires than in the cross-sectional plane of the wires. Similarly for the core, it consisted of laminates and its thermal conductivity across laminates was not the same as along them. Therefore, for the core in each direction and for coils along the wires, analytical models were used to determine the effective values of the properties. However, for both directions in the cross-sectional plane to the wires, these values were obtained numerically.

Apart from the CFD-electromagnetic coupling, the CFD and the mechanical fields were also coupled. Such an approach enabled to analyze thermal stress within the device, especially on the interface between dissimilar materials. For the considered case, the most sensitive regions were between transformer elements and resin, and also between resin and a tank. Moreover, an estimation of the stresses level and their location was required for safety reasons. Additionally, an analysis of the cracks impact on the maximum temperature in the windings was determined. In these computations, both real and hypothetic, but possible cracks were simulated.

Mathematical models and procedures presented within the thesis may be applied both during design process and also during a transformer operation. Especially, this analysis can be useful in situations, where the device works in rigorous conditions in terms of heat removal. Such a broad application of the results of this project could be reached because of the following industrial transformers used for numerical simulations: the water-cooled low power encapsulated transformer, the water-cooled medium power dry-type transformer with ventilated coils positioned horizontally and working within the transformer chamber of the heading machine, and the air-cooled medium power dry-type transformer with ventilated coils as main part of the transformer station.

The above examples were selected and analyzed since they were good representatives among other dry-type transformers. Due to the different internal construction, position in the tank, configuration of cooling system, a simulation model enabled to answer the question of the most effective heat transfer mode for the heat removal for this group of devices. To achieve this, the analyses of the heat pipes application and crack influence on the winding temperature were also carried out. Moreover, the procedures developed for dry-type transformers can be easily extended to the most common oil-cooled devices. It requires a redefinition of material properties for the different type of a coolant only.

It should be also stressed that results of the thesis can be used in a different type of scientific works. For instance, the effective anisotropic thermal conductivities were developed for many types of coils and these values are usually crucial for circuit analyses. Moreover, in the thesis, the average values of heat transfer coefficients were calculated on the basis of local distribution of wall heat fluxes. This information was obtained for all important transformer elements in terms of the heat transfer. For this reason, the average heat transfer coefficients can be used in simplified analyses, in which the coolant flows around the transformer is not considered.