THERMAL ANALYSIS OF A THREE PHASE TRANSFORMER WITH COUPLED SIMULATION

Mohammadali Salari, Pascal Bayrasy, Klaus Wolf

Fraunhofer institute for scientific computing and algorithms (SCAI)

SUMMARY

Thermal performance of an oil-immersed power transformer is governed by the oil flow, which acts as an electrical insulator as well as a medium for the transfer of heat generated in the windings and core toward the tank and the surrounding air. This paper investigates the thermal performance of a three phase transformer by coupling JMAG and Fluent software through MpCCI. Accurate local representation of oil flow and heat dissipations has been achieved by this approach.

In our approach JMAG calculates the magnetic flux and Joule losses but is not able to analyze the behaviour of fluid flow, temperature distribution or the local interaction of losses with coolant. For these effects use a dedicated CFD code like Fluent. With Fluent we could simulate the fluid flow and temperature distribution in different parts of the transformer. Heat generation is handled in a thermal analysis by a steady state analysis of a transformer with oil coolant. Losses distribution has been used as heat source terms for each part (core and coils).

Losses in a transformer include copper loss in the windings and iron loss (hysteresis and eddy current losses) in the core which are calculated in JMAG and passed to Fluent as the heat source. Then, the Fluent passes the temperature back to JMAG. This is a bidirectional coupling, but in this case we could also use a unidirectional coupling from JMAG to Fluent in which Fluent doesn’t return the temperature back to JMAG.

For our benchmarks we used a step down three phase transformer with a turn ratio of 10-to-1 and the primary voltage of 141.42 V operating at 60 Hz. The connection pattern in the transformer and load sides are Delta-Delta and Y connection respectively. The fluid flow and temperature distribution analysis in different parts of the transformer is handled in a thermal steady state analysis of a transformer with oil coolant. We used heptane-n as the coolant and a steel tank surrounding the transformer.

THERMAL ANALYSIS OF A THREE PHASE TRANSFORMER WITH COUPLED SIMULATION

The temperature distribution in coils is very important because standards require heat resistant design for safety. Thermal limits imposed by the IEEE Standard C57.91-1995(R2002) put a limit on the maximum allowable winding temperature and coil temperature to 120°C and 110°C respectively.

1: Introduction

In modern engineering it is necessary to be more precise in order to reach better designs and better performances, therefore the different physical aspects of a problem have to be taken into account. Today computer aided engineering is an integral part of the design and different simulators are used for different analyses, e.g. there are dedicated software tools for fluid mechanics analysis and others for electromagnetic analysis.

In some cases the different physical phenomena are strongly coupled and correlated, e.g. in a transformer the electromagnetic phenomenon is coupled with fluid flow and heat transfer. When we model this system mathematically we have a system of coupled partial differential equations, which can be solved by numerical methods such as FEM (Finite Element Method). The solution procedure can also be done by providing a connection between two different simulators through third-party software.

In this paper we will present a solution based on MpCCI [1]. MpCCI is an application independent interface for the coupling of different simulation codes, like JMAG [2], Fluent [3], Abaqus, STAR-CCM+, OpenFOAM, etc. The paper is organized as follows: section II describes limitations of standalone models, section III deals with the coupled multi-physical models, section IV explains magnetic frequency response analysis in JMAG. In section V the thermal fluid analysis in Fluent is investigated. Co-simulation setup is described in section V and the results are discussed in section VI.

2: Limitations of standalone models

Design and analysis objectives for transformers can be expressed as follows:

- Transformers are made to be used long-term, design policy to control running costs from losses.
- Losses include copper loss in the coil and iron loss in the core.

- Heat is produced and standards require heat resistant design for safety.
- Losses and heat prediction are a vital component for transformer design
- Use a coupled approach to obtain losses in a transformer and use them to evaluate the temperature distribution in the transformer.

Magnetic field analysis handles the phenomena that produce magnetic flux and eddy currents in transformer's core, when current flows through the coil. Loss evaluation for a single excitation frequency at 60 Hz is done by magnetic frequency response analysis in typical EMAG simulation tools; also transient response magnetic field analysis can be adopted. On the other hand the fluid flow and heat transfer analysis can be done by CFD software like Fluent. The point is that the electromagnetic and thermal phenomena are coupled and each of the softwares mentioned before are just able to do either an electromagnetic analysis or a thermal and fluid flow analysis. Thus standalone models and simulators are not able to model the whole physics of the problem efficiently. This means we need to couple both models in order to achieve more accurate results that can later be used to improve the design. As an example for a coupled simulation with JMAG and ANSYS the coupled thermal solution of a high current bus bar exit in GSU (Generator Step-up) transformers can be mentioned [4]. Another example for coupled simulation of a three phase transformer could be found in reference [5].

3: Coupled Multiphysical Models

As mentioned before JMAG calculates the magnetic flux and Joule losses but is not able to analyze the behavior of fluid flow, temperature distribution or the local interaction of losses with coolant, so we need to use a CFD code like Fluent. With Fluent we could simulate the fluid flow and temperature distribution in different parts of the transformer. Heat generation is handled in a thermal analysis by a steady state analysis of a transformer with oil coolant. Distribution of losses is used as heat source terms for each part (core and coils)

Losses in a transformer include copper loss in the windings and iron loss (hysteresis and eddy current losses) in the core which are calculated in JMAG and passed to Fluent as the heat source. Then, Fluent passes the temperature back to JMAG. The JMAG electrical property for the copper material is temperature dependent. This results in a new distribution of Joule losses.

4: Magnetic frequency response analysis in JMAG

For our benchmarks we used a step down three phase transformer with a turn ratio of 10-to-1 and the primary voltage of 141.42 V operating at 60 Hz. The connection pattern in the transformer and load sides are Delta-Delta and Y connection respectively. The coil resistance for primary winding is 0.031 Ohm/phase and 0.00156 Ohm/phase for secondary winding. External load resistance is 0.06 Ohm/phase. The core material is 50JN270 (manufacturer JFE steel) with laminating factor of 98%. The dimensions of the tank are 0.6m*0.6m*0.3m. The condition for windings is set to FEM coil which assumes a uniform current distribution in the cross section of the wires. Because of existing symmetry in the structure we construct a half model and analyze this model which has a lower computational cost. This can be done by setting the symmetry boundary condition in JMAG. To check the standalone models in JMAG we have run some standard test cases.

The magnetic flux density of a standalone JMAG calculation is shown in Fig.1. In Fig. 2 the Joule loss density distribution of a standalone JMAG calculation is shown. In this case the maximum Joule loss density is 1.28e8 W/m^3.

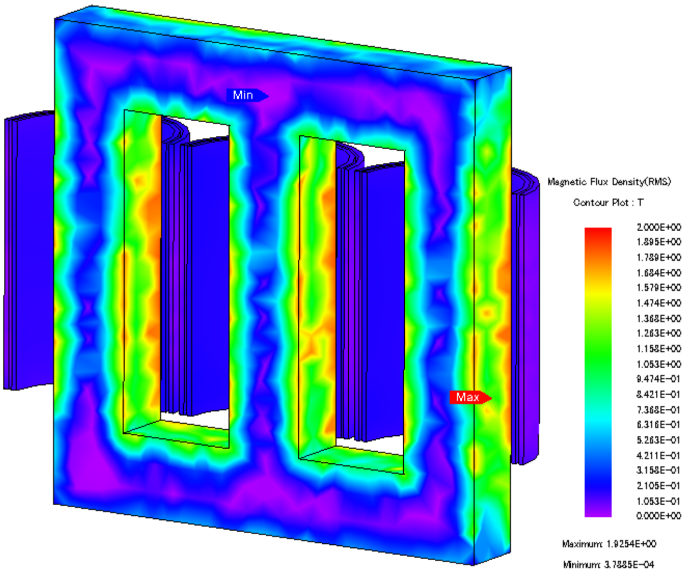


Figure 1: Magnetic flux density (RMS view). Maximum magnetic flux density is 1.92 T.

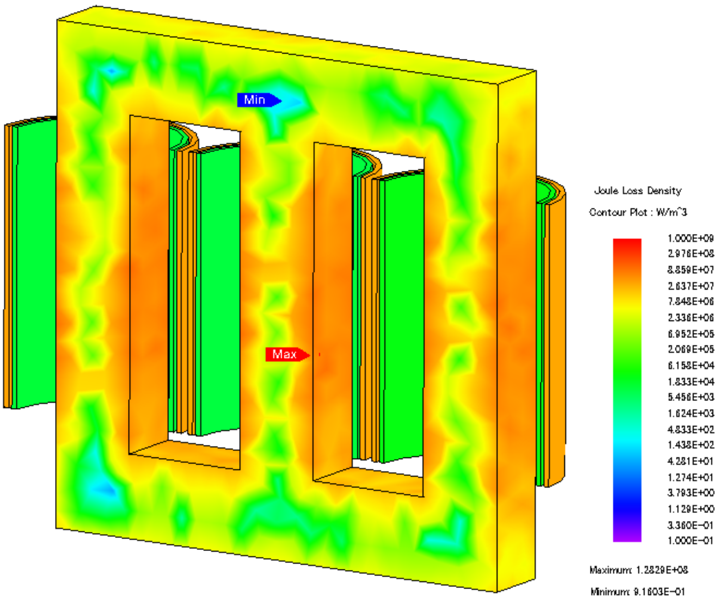


Figure 2: Joule loss density (logarithmic view). Max Joule loss density of 1.28e8 W/m^3.

5: Thermal fluid analysis in Fluent

The fluid flow and temperature distribution analysis in different parts of the transformer are handled in a thermal steady state analysis of a transformer with oil coolant. We used heptane-n as the coolant and a steel tank surrounding the transformer. As said before the coils are made of copper and the core is made of steel. Fig. 3 shows the transformer model with tank and oil coolant.

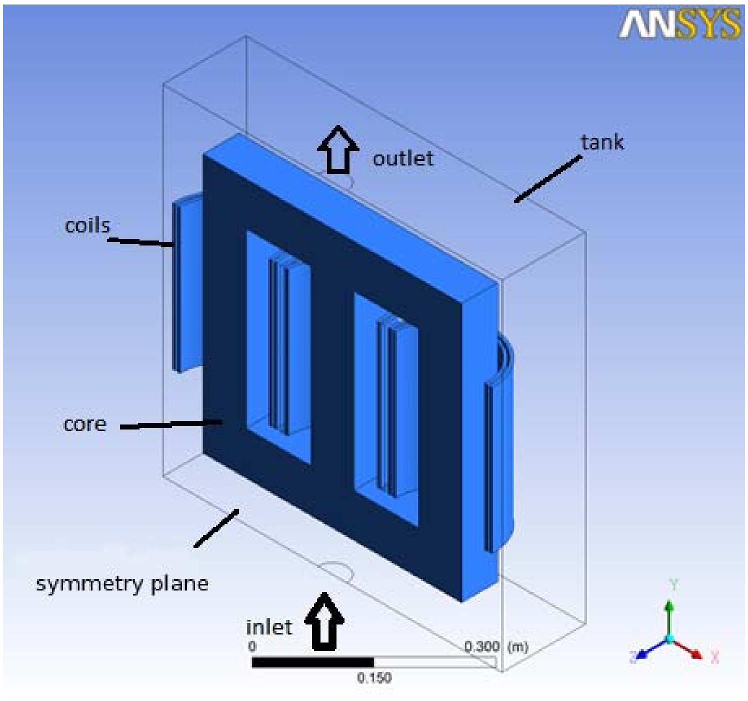


Figure 3: **Transformer with tank half-model in Fluent.**

The 3D thermal transformer analysis is governed by the following form of the Poisson equation [6]:

$$K_x \frac{\partial^2 T}{\partial x^2} + K_y \frac{\partial^2 T}{\partial y^2} + K_z \frac{\partial^2 T}{\partial z^2} = q \qquad (1)$$

where T is the temperature (in Kelvins) at each point of the considered domain, Kx, Ky and Kz are the materials thermal conductivities in the x-, y- and z-direction, respectively (W/(m°K)) and q is the heat source in the transformer. The calculated losses distribution in JMAG is used as heat source term q for core and coils in Fluent. Then Fluent calculates the temperature distribution in the transformer and the heat transfer to coolant and from coolant to tank and at last from tank to the surrounding air. Moreover the flow of coolant around the transformer can be calculated by Fluent.

Now we know how to solve equation (1) numerically with the aid of JMAG and Fluent software separately. A coupled simulation through MpCCI provides the framework for exchanging the q term, the generated heat in the core and coils and the temperature T.

6: Coupling with MPCCI

In our case the coupling between Fluent and JMAG is done by MpCCI. The variables, that are exchanged between JMAG and Fluent through MpCCI are shown in Fig. 4. As can be seen in Fig. 4 the Joule losses calculated by JMAG are passed to Fluent as the heat source and then Fluent returns the calculated temperature back to JMAG.

One of the important issues in the coupling of two codes is that the number and structure of meshes are not the same in JMAG and Fluent (Fig. 5). This issue can be solved by MpCCI. The number of nodes and elements are shown in Table I. It is apparent that the number of elements in Fluent is much more than of JMAG and it is the task of MpCCI to interpolate the data from the different meshes in a way that the whole coupled system can be solved.

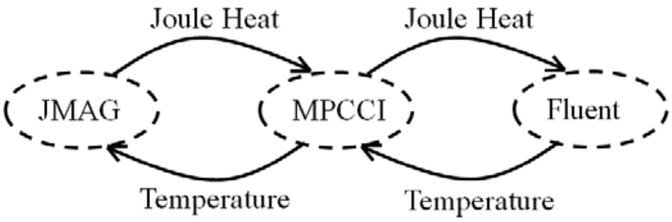
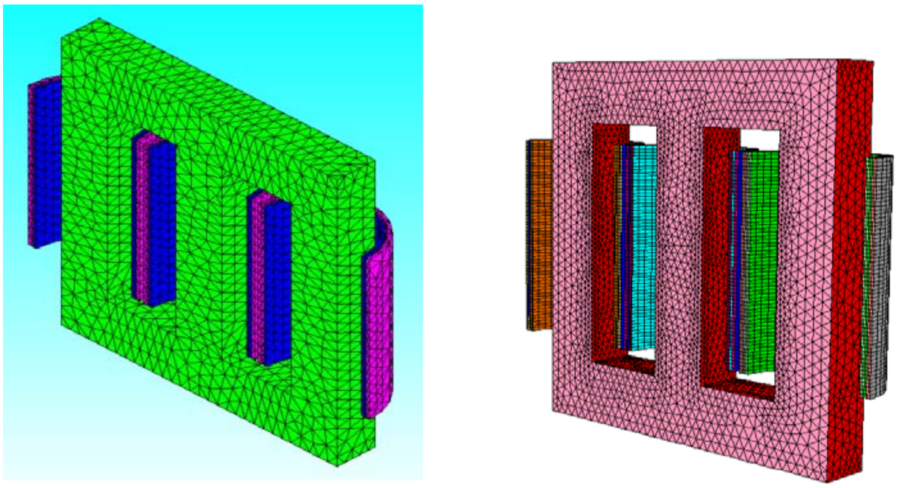


Figure 4: The exchanged variables between JMAG and Fluent through MpCCI.

TABLE I. Number of nodes and elements created in JMAG and Fluent as well as simulation time.

Software	Number of nodes	Number of elements
JMAG	16344	87434
Fluent	165747	768176



(a) (b)

Figure 5: Meshes with incompatible local discretizations (a) JMAG (b) Fluent.

The coupling process is based on a Gauss-Seidel schema: Fluent initializes the JMAG solver with an initial temperature distribution, and then JMAG calculates the Joule losses according to the temperature. The new losses are sent back to Fluent which calculates a new temperature distribution for 20 iterations. This process is repeated until the calculation is finished. The total number of coupled data exchanged for this case has arbitrarily been set to 20.

7: Results

In this section the achieved results are discussed and some numbers are given in order to be able to judge the results of the coupled solution. Fig. 6 shows the Joule loss density distribution in the core and the coils after coupling. The maximum Joule loss density has been reduced to 2.22e4 W/m^3. Fig. 7 shows the temperature distribution in the coils.

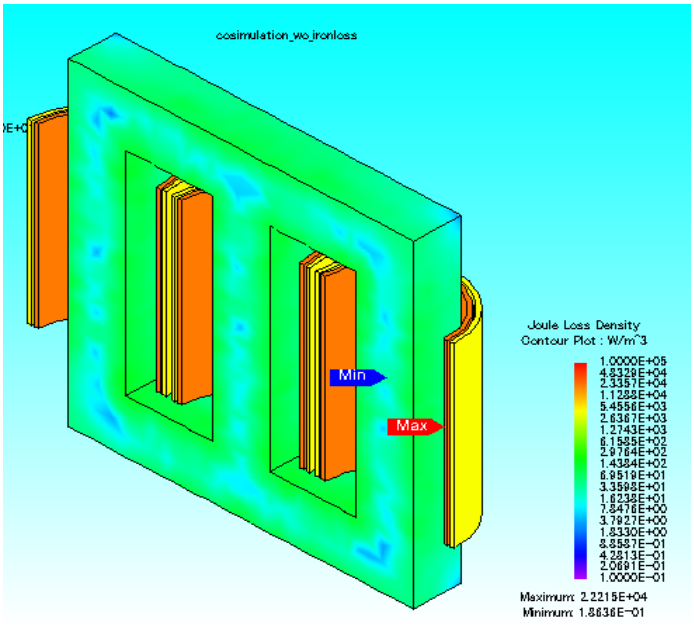


Figure 6: After coupling (Logarithmic view). Maximum Joule loss density is equal to 2.22e4 W/m^3.

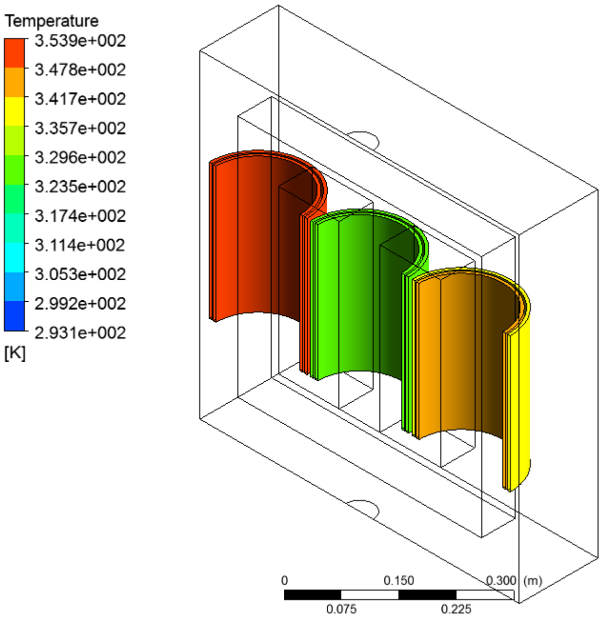


Figure 7: Temperature distribution in the coils.

The temperature distribution in coils is very important because standards require heat resistant design for safety. The IEEE Standard C57.91-1995(R2002) puts a limit on the maximum allowable winding temperature and coil temperature to 120°C and 110°C respectively. This simulation predicts a maximal temperature of 80°C.

Acknowledgment

The authors gratefully acknowledge the contributions of Thiebaud Pfister from POWERSYS, Frankfurt am Main, Germany for his supports.

REFERENCES

[1] Fraunhofer SCAI (2013) *MpCCI software version 4.3.0.*

[2] JSOL (2013) *JMAG software version 13.*

[3] ANSYS Inc. (2013) Fluent software version 15.

[4] Costin Ruja (2012) *Using JMAG and ANSYS for coupled thermal solution of a high current bus bar exit in GSU Transformers*, JMAG UGM, Frankfurt.

[5] Nelu- Cristian Chereches (7 Feb. 2006) *Contribution à l'optimisation de circuits thermoconvectifs*, PhD Thesis, Université de Reims Champagne-Ardenne.

[6] Marina A. Tsili , Eleftherios I. Amoiralis , Antonios G. Kladas , Athanassios T. Souflaris (2012) *Power transformer thermal analysis by using an advanced coupled 3D heat transfer and fluid flow FEM model*, International Journal of Thermal Sciences, Elsevier, 53.

[7] Jon Gastelurrutia, Juan Carlos Ramos, Gorka S. Larraona, Alejandro Rivas, Josu Izagirre, Luis del Rio (2011) *Numerical modelling of natural convection of oil inside distribution transformers*, Applied thermal engineering, Volume 31, Issue 4, Pages 493-505.

[8] J. Driesen, G. Deliége, R. Belmans and K. Hameyer (July 2000) *Coupled thermo-magnetic simulation of a foil-winding transformer connected to a non-linear load*, IEEE Trans. On Magnetics, Vol. 36, NO. 4.