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Coupled Electromagnetic-Thermal Model Applicable for Distribution Transformers

Ž. Tašner[1] and B. Ćućić[1]

[1] Končar - Distribution & Special Transformers Inc., Josipa Mokrovića 8, 10090 Zagreb, Croatia

E-mail: zeljko.tasner@koncar-dst.hr

***Abstract*—Distribution transformers, with their specific passive cooling mechanism, are investigated in this research. FEM based approach was used for electromagnetic field distribution and losses calculation, following with the methodology for thermal modelling. Detailed temperature measurements using thermocouples and thermal camera were done on 1600 kVA unit, the results of which are compared against calculated values. The aim of this research is to present a viable approach for adequate thermal modelling of distribution transformers applicable for research and design purposes.**

***Index Terms*— coupled electromagnetic-thermal model, distribution transformers, finite element method, losses calculation.**

I. INTRODUCTION

In order to increase the distribution transformer reliability by making them more robust, in some designs an oil conservator is avoided, and a completely closed tank is used. In such solutions, both oil volumetric change due to its temperature rise and transformer cooling capabilities are resolved using thin cooling fins. Such design imposes a natural oil flow within the transformer and hence careful design practice needs to be taken in order to adequately model the fin number and total cooling area. A number of different approaches exists, ranging from analytical/empirical methods, through static conductive thermal simplifications to detailed models using computational fluid dynamics (CFD) solvers [1]–[4].

Since the heat originates from the overall losses within the transformer, all of the approaches have to be electromagnetically-thermally coupled to some degree; they need to address the loss calculation as a first step, and then obtain the temperature distribution using thermal models [5], [6]. These losses can also be calculated in several ways, depending on the needed accuracy and calculation speed, using either analytical and semi-empirical methods or modern numerical approaches such as finite element method-based (FEM) solvers.

There are two main heat-generating sources within the transformers: the first one are the ohmic losses in current-carrying conductors such as windings and leads, and the second one are additional losses within other metallic parts such as clamping system and transformer tank. The former ones are the main losses and need to be considered when adequately modelling winding oil ducts and transformer cooling system. The latter ones, arising from stray magnetic field within metallic elements, have to be taken into account in order to avoid local temperature hotspots. These can cause either oil, paint or gasket deterioration, depending whether they occur within the transformer or outside on its tank.

This work presents the use of FEM-based approach for both additional losses and thermal calculations, and the results obtained from numerical models will be compared against the measurements on a 1600 kVA distribution unit. In Section II, the overview of the electromagnetic and thermal modelling approach is given. The following section shows the experimental results, obtained using both thermocouple and thermal camera results. Section IV presents the comparison of the results and finally the conclusion of this research is given.

II. FEM-BASED MODEL

A distribution transformer unit rated at 1600 kVA, 22000/420 V, with passive cooling and without oil conservator was used in this research. Loss and thermal calculations were done using Mentor Graphics® MagNet and ThermNet software, respectively. A 3D model is visible in Fig. 1, showing all the parts relevant for loss and thermal calculations modelled. This includes both the low and high voltage windings, iron core, clamping structure, additional supporting elements, low voltage leads and transformer tank with cooling fins. High voltage leads and bushings were not modelled since they carry insignificant amount of current for generating additional losses.

A. Electromagnetic modelling

A non-linear time-harmonic solver with adaptive mesh was used for electromagnetic calculation. The windings and leads were modelled as aluminum, the iron core as electrical steel, and all the other elements as low carbon steel apart from the non-magnetic insert surrounding the low voltage leads which was modelled using stainless steel material. The simulation represents the transformer temperature rise test. Therefore, low voltage windings were shorted, and the currents were set slightly larger than nominal, to account for both short- and open-circuit losses. All the currents correspond to the ones obtained during the temperature rise measurements presented in Section III.

The visualization of the total loss distribution is given in Fig. 2, omitting the irrelevant elements for better visibility of the results. Additional losses are defined as losses in clamping structure, supporting metal elements, transformer tank wall, cover and bottom. Using proprietary factory software, these losses were calculated at 1037.6 W. Presented simulation gives 1062.6 W, which shows the validity of the model used in this research. As can be seen in Fig. 2, the advantage of using detailed FEM-based models is in the possibility of knowing the distribution of these losses which can help in locating the regions where temperature hotspots can occur. On the other hand, these models, being time-consuming and complex, are not applicable in the design phase of the transformer.

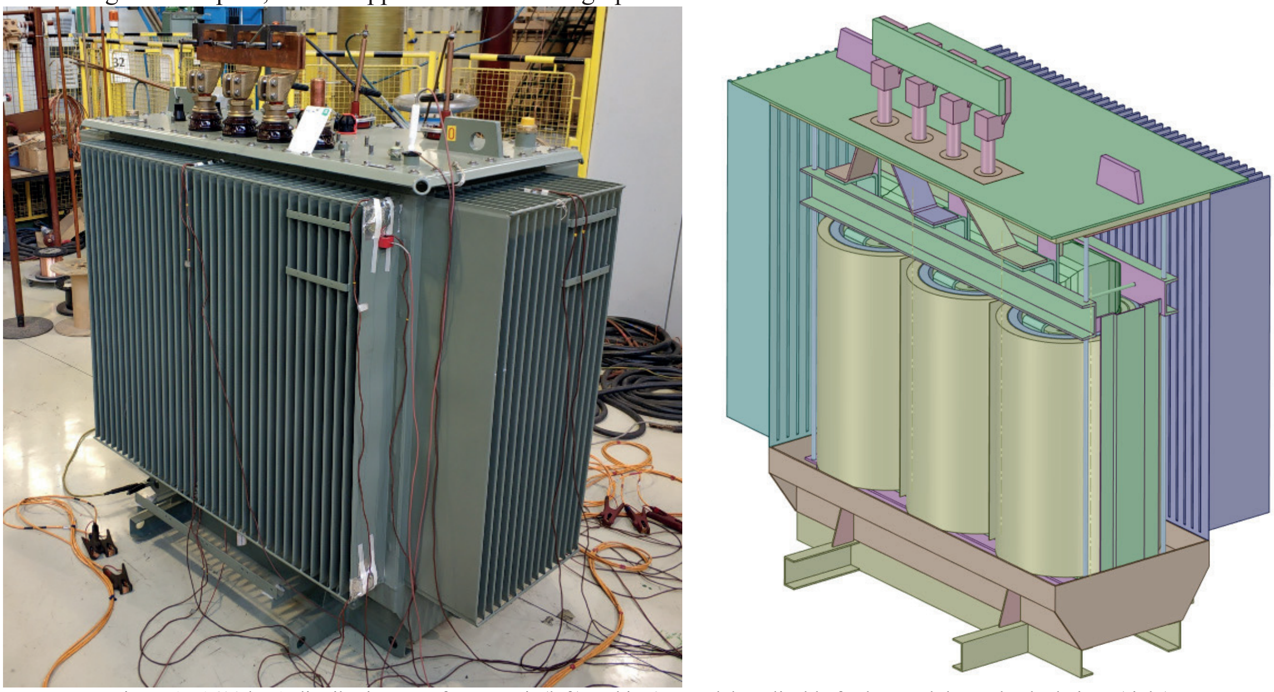

Figure 1: 1600 kVA distribution transformer unit (left) and its 3D model applicable for loss and thermal calculations (right).

B. Thermal modelling

After the electromagnetic calculation was done, it was coupled with thermal solver. Since this work was focused on obtaining the additional losses in metallic parts arising from the stray flux, the increase in oil temperature was calculated using the proprietary factory software . This can be solved using either semi-empirical formulations, thermal network models or CFD solvers, none of which is the scope of this paper.

The cooling of the simulated transformer is only done using natural convection of air [7], [8]. This was modelled as an air boundary with convective heat transfer coefficient of 5 W/(m^2·C). The surrounding air temperature was set to 23.8 °C, so the results can be comparable with the measurements in Section III. The results from the FEM-based solution, shown in Fig. 3., show the computed temperature distribution along the transformer tank and cover. There are no pronounced temperature hotspots and the overall maximum tank temperature is within the expected limits.

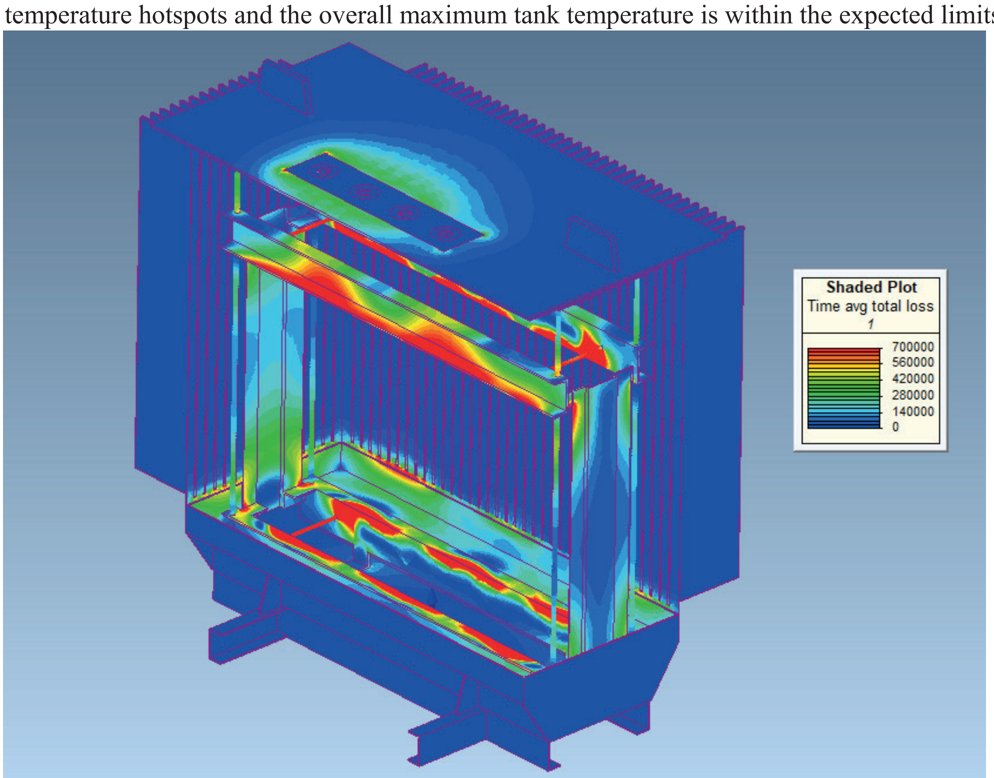

Figure 2: Visualization of the calculated additional losses distribution on relevant elements in the model obtained using Mentor Graphics® MagNet.

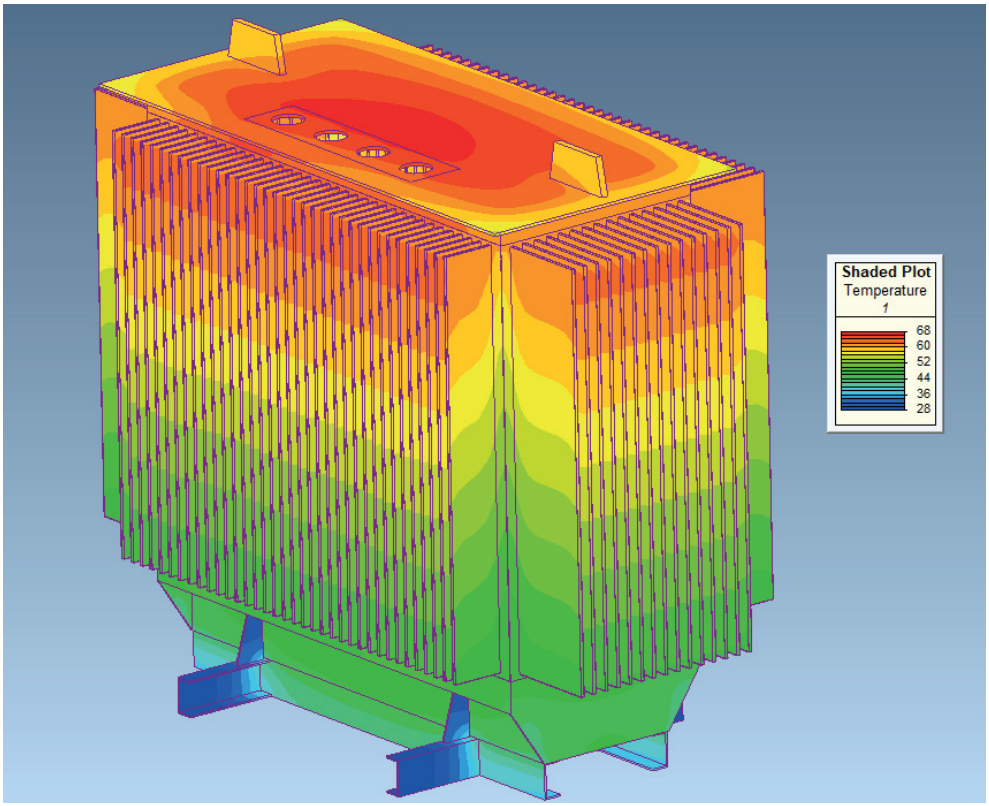

Figure 3: Visualization of the calculated temperature distribution on the transformer tank obtained using Mentor Graphics® ThermNet.

III. TEMPERATURE RISE TEST

The transformer unit under consideration underwent the standard temperature rise test in the factory (see Fig. 1). Since the aim of this research is to evaluate the FEM-based approach to thermal modelling, more detailed thermal measurements were done. Two approaches were used: discrete point measurements from thermocouples on the transformer tank, and overall thermal imaging using a thermal camera.

Two sets of 9 thermocouples were placed on 9 different locations on the tank, visible in Fig. 4. Positions P1-P4 had two sets, one at the bottom and one at the top of the cooling fin. Position P5 had only one set at the top of the fin, due to the lack of additional measuring channels. Each set consisted of two thermocouples: one was only taped to the fin, and the other one was glued using the thermal paste and additionally thermally insulated from the surroundings. This was done in order to measure the relevant temperatures as accurately as possible.

The thermocouple measurements were recorded using Fluke 2635A Hydra Series II in time steps of 15 minutes. The results are given in Fig. 5. Slight lowering of the temperatures during the end of the recording period is due to the end of the temperature rise test and lowering of the current to its nominal value for the winding resistance/temperature measurement. Images from the FLIR thermal camera are visible in Fig.6.

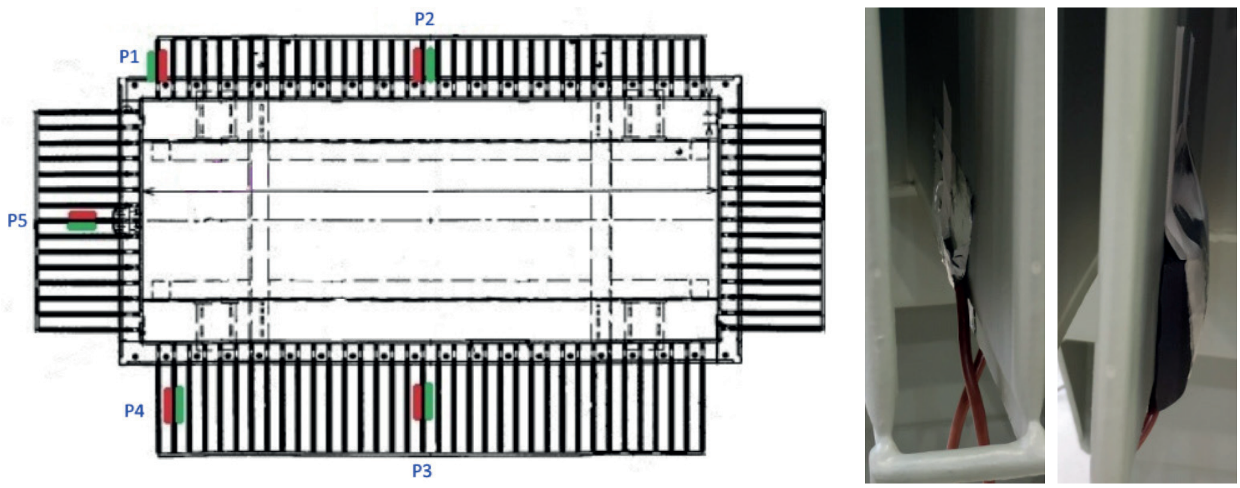

Figure 4: Location of the thermocouples during the temperature rise test (left). At each location, two thermocouples were placed, taped and insulated (right).

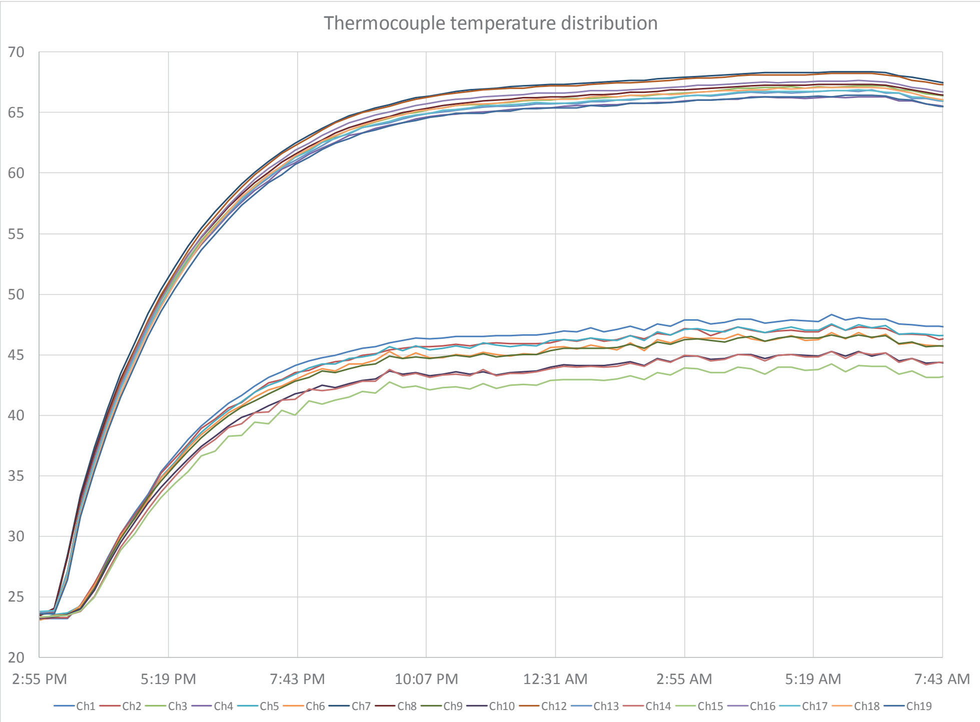

Figure 5: Thermocouple temperature measurements during the test.

The thermal images show the temperature distribution along the transformer tank and its cooling fins. As can be seen, there are no significant temperature hotspots on either the tank cover or the tank sides.

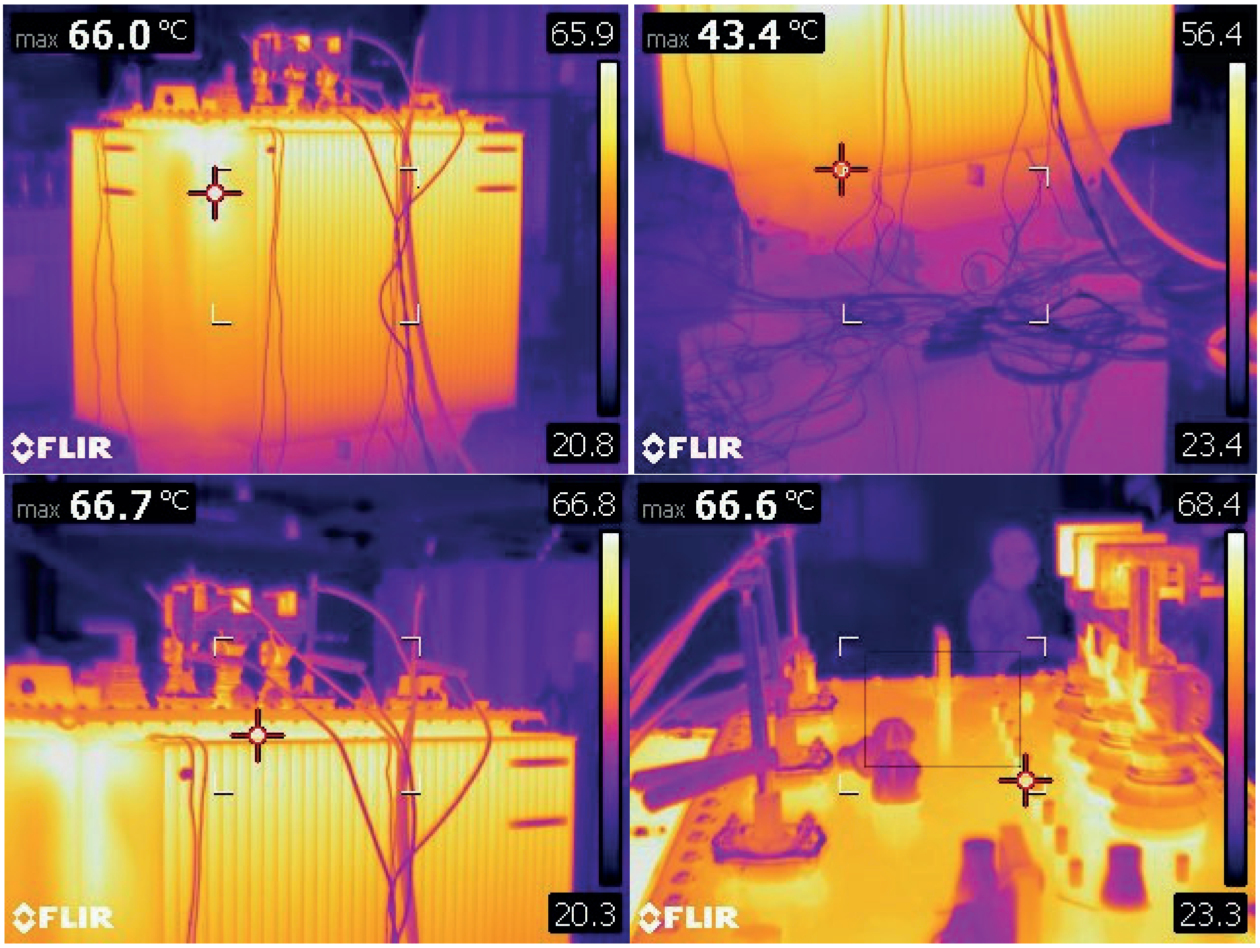

Figure 6: Thermal images obtained using the FLIR thermal camera.

IV. RESULTS

Table I shows the comparison of the thermocouple temperature difference between the two different thermocouple fixation methods on the cooling fin. As can be seen, there is an overall average difference of 1 °C, where glued and insulated readings were always higher.

Qualitatively comparing the images from the thermal camera (Fig. 6) and the temperature distribution visualization obtained using the presented FEM-based approach (Fig. 3), the results are in a good agreement. Table I shows the quantitative comparison of the results at the positions of the thermocouples. In average, there is less than 3 °C difference between measurements and calculations, which is satisfactory. Table II shows quantitive comparison of the calculation results and standard factory heat run test.

TABLE I COMPARISON OF THE TEMPERATURES OBTAINED USING THERMOCOUPLE MEASUREMENTS AND FEM-BASED SIMULATION

	P1 bottom	P1 top	P2 bottom	P2 top	P3 bottom	P3 top	P4 bottom	P4 top	P5 top
Taped [°C]	47.5	66.3	46.8	67.4	45.3	66.8	44.2	66.8	66.3
Glued + Insulated [°C]	48.3	67.1	47.5	68.4	46.6	68.2	45.3	67.6	67.1
FEM [°C]	48.9	63.2	48.7	64	47.7	63.8	47.5	63.5	63.6
Diff. (Glued-Taped)	0.8 °C	0.8 °C	0.7 °C	1.0 °C	1.4 °C	1.4 °C	1.1 °C	0.8 °C	0.8 °C
Diff. (FEM-Taped)	1.4 °C	-3.1 °C	1.9 °C	-3.4 °C	2.4 °C	-3.0 °C	3.3 °C	-3.3 °C	-2.7 °C

TABLE II COMPARISON OF THE TEMPERATURE RISES OBTAINED FROM TEMPERATURE RISE TEST-SHORT CIRCUIT METHO, SEMIEMPIRICAL CALCULATION AND FEM BASED SIMULATION

	Top oil	Average oil	HV windng	LV winding
Semi-empirical calculation [K]	39,6	31,7	67.4	45.3
Temp. rise test [K]	42,66	32,95	68.4	46.6
FEM [K]	40,1	32,3		
Diff. (SE-TEST)	-3.06 K	-1.25 K	-1.0 K	-1.3 K
Diff. (SE-FEM)	-2.56 K	-0.65 K		

V. CONCLUSION

This paper presented the results of the coupled electromagnetic-thermal model based on FEM solvers. Both the obtained loss and the temperature distribution results are in a good agreement with measurements. Detailed thermal measurements were done, using both thermocouples and thermal camera. Different thermocouple fixation methods were investigated, and the results are comparable.

This work shows the applicability of FEM-based models in electromagnetic and thermal calculations. The presented approach, adapted from model for power transformers, can be useful in the research and development purposes for estimating the temperature hotspots when designing the transformer tank. Limitation of used model are coupled with possibility to simulate heat exchange on both fluid side.

VI. REFERENCES

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