Journal of Energy

VOLUME 73 Number 2 | 2024

journal homepage: http://journalofenergy.com/

Numerical Calculation and Direct Measurement of Local Hot Spot Temperatures in Transformer Clamping Plates

Dino Kovačević, Mladen Marković, Damir Blažina

***Summary* — A verified multiphysics model is developed to simulate local hot spot temperatures in clamping structures. Stray field losses in clamping plates are obtained with the use of nonlinear impedance boundary condition through finite element method (FEM) while hot spot temperatures are simulated with the use of computational fluid dynamics (CFD). This multiphysics coupling is validated through direct measurements of local hot spot temperatures that were carried out with fiber optic temperature probes in real transformer. The local hot spot temperatures obtained with the simulations were in good agreement with the measured values, thus verifying overall approach and indirectly the calculation of local stray field losses.**

***Keywords* —Transformer, Multiphysics, Stray Field Losses, Hot Spot Temperature, Clamping Plates, Fiber Optic Probes**

I. Introduction

Power transformers play a pivotal role in the robust functioning of electric grids, facilitating the efficient transmission of electrical energy across vast distances. As energy demands continue to rise, power transformers have evolved to meet the needs of modern electrical transmission systems. Particularly, transformers designed with high short circuit impedance have garnered attention due to their significance in grid stability and fault management. Their elevated short circuit impedance serves as a safeguard against potential disruptions caused by short circuits or faults in the electrical grid. By limiting fault currents, they mitigate the risk of cascading failures, thereby preserving the integrity of the overall grid infrastructure.

In the design stage of power transformer production, it is crucial to know stray field losses and their effects for optimum design of transformer. This knowledge is even more important for oil immersed transformers with high short circuit impedance which results in higher stray field losses. Local temperature hot spots will appear in structural metallic components that are in direct contact with insulating liquid forming "faulted gasses". The main concern of designing this type of transformers will be prevention of reaching temperature hotspots that could form gasses. With this type of transformers, thermal analysis of components such as clamps or tanks becomes important. Designers must know this information to choose appropriate materials such as non-magnetic steel.

In essence, this calculation requires multiphysics approach using numerical simulations. Stray field losses in clamps are calculated using Finite Element Method (FEM) while induced eddy currents have been modeled with surface impedance boundary condition [1], [2]. Temperatures will be calculated using 3-D steady-state Computational Fluid Dynamics (CFD) analysis. Since two different analyses will be used, effective coupling between them must be assured. Stray field losses calculated in FEM will be used as input losses in CFD analysis.

Calculation of losses and therefore temperatures is validated by experiment on 40 MVA 145 kV power transformer with its short circuit impedance value of 20%. Temperatures were measured with fiber optic temperature probes on multiple locations. Therefore, 5 different hotspots were measured on both internal and external side of clamps, as well as low and high voltage side of clamps.

In Section II, the overview of multiphysics approach combining electromagnetic and thermal modelling is given. Validation of the model with experimental tests is explained in Section III, while Section IV presents the comparison of the results, and finally the conclusion of the research is given in Section V.

II. Multiphysics Coupling (FEM & CFD)

A. Electromagnetic Modeling

Electromagnetic modeling was done in SimCenter Magnet 3D Time Harmonic (TH) Solver. Both linear and nonlinear TH calculation was done with clamping plate material S-235 (industrial magnetic steel) for which B-H characteristic is shown on Fig. 1. This material was also used for tank and cover plate modeling.

(Corresponding author: Dino Kovačević)

Dino Kovačević, Mladen Marković and Damir Blažina are with the Končar – Distribution and Special Transformers Inc., Zagreb, Croatia (e-mail: dino.kovacevic@koncar-dst.hr, mladen.markovic@koncar-dst.hr, damir.blazina@koncar-dst.hr)

https://doi.org/10.37798/2024732513

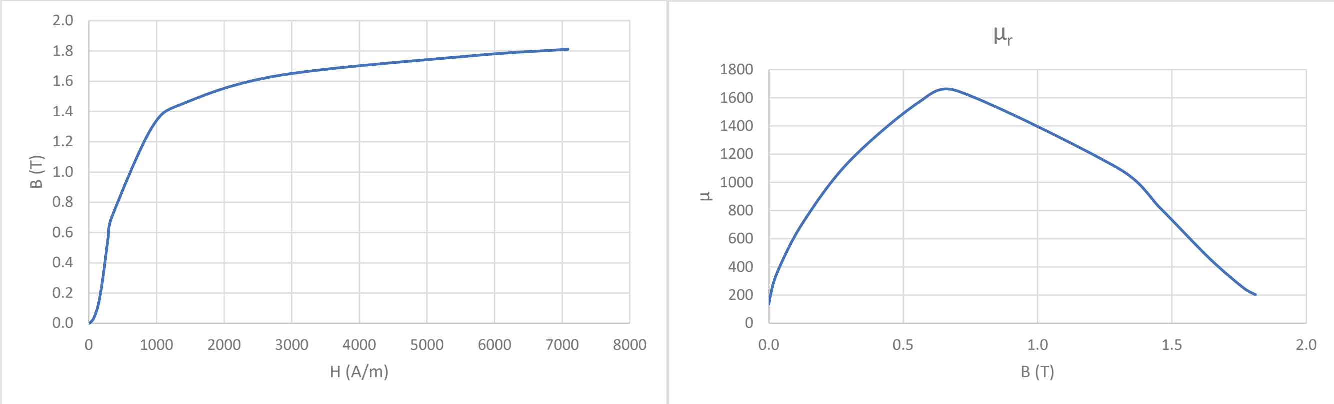

Fig. 1. Magnetic Steel Characteristic for S-235 [3]

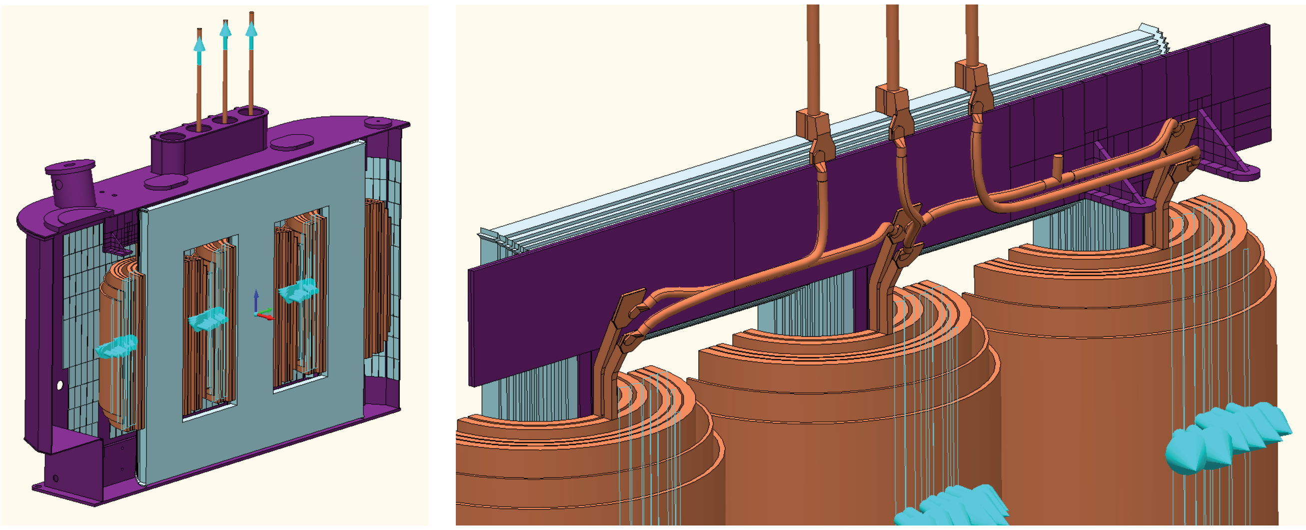

Fig. 2. LV side of modeled transformer (left) with LV star connected leads (right)

To reduce computing resources, 3D model was divided into two halves: one half for HV and the other one for LV side (computed separately), where LV side included detailed geometry of LV leads shown on Fig. 2.

Apart from dividing the transformer in two halves, further reducing of computing resources was done by using Surface Impedance boundary condition for each magnetic steel object (tank, tank plate, clamping system), even though the losses for thermal modeling were only needed to be calculated in the clamping system itself. For further notice, nonlinear solver gave approx. 15% higher loss values than linear solver but took considerably more solving time (counted in days instead of hours), so the majority of preparing calculation was done in linear solver, and the final calculation of the losses that were needed for thermal analysis were obtained by nonlinear solver.

B. Thermal modeling

Thermal modeling was conducted using ANSYS CFD software package. The initial step involved preparing the model's geometry using ANSYS SpaceClaim. Clamping plates serve the purpose of pressing the core's steel sheets together horizontally, as well as pressing the windings vertically. They exist on both the upper and lower yokes. However, solely the upper clamps were modeled, given their association with hotter oil on top side of transformer. To simplify the model, certain components of clamps that were not considered important in calculation were removed or slightly changed. In the modeling process, the clamping plates were depicted as solid objects immersed within an oil domain. While components such as the core, windings, and tank were excluded from the model, the focus remained solely on the clamping plates within the oil, Fig. 3.

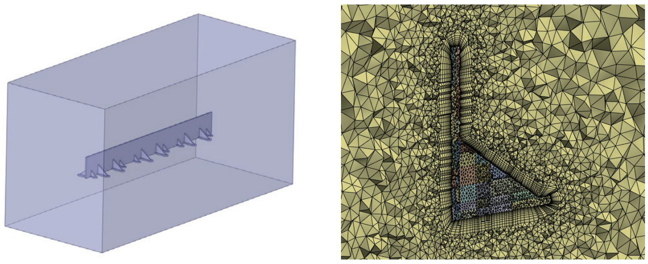

Fig. 3. Clamping plate submerged in oil domain (left) with cross sectional view of the mesh (right)

The subsequent meshing phase was executed using ANSYS Meshing software, utilizing tetrahedral elements for both solid and fluid domain. Acknowledging the significance of the boundary layer in problems involving heat transfer between solids and fluids, an inflation layer was used. With a total cell count of five million, the quality of elements was maintained to guarantee stable simulation and accurate results.

ANSYS Fluent was used to configure and solve the simulation utilizing a steady-state 3D solver. As oil enters the tank from the bottom, it gets heated by the core and windings and accelerates towards the top of the tank. At the top, oil from all sides of the tank is being mixed which makes it a reasonable assumption that flow in top of the tank is turbulent. The turbulence model chosen was

https://doi.org/10.37798/2024732513

k-omega SST, which yielded satisfactory results. Material used for the clamps was steel, while the fluid domain was represented by mineral oil with thermal properties supplied by the manufacturer. Fluid's specific heat, viscosity and thermal conductivity were modelled with respect to temperature. Due to the natural convection problem, buoyancy was accounted for using the Boussinesq density model. This model assumes constant density for all equations except the gravitational term in the momentum equation. Thermal expansion coefficient was used together with constant density to ensure proper density modeling and natural driving force of oil.

Loss density data, imported from Simcenter Magnet software, were assigned to solid part of the domain. The losses from FEM analysis were applied as heat sources within the CFD analysis. Pressure boundary condition was applied to the outer boundaries of the oil domain with temperature equal to the measured top-oil results.

Residuals were considered converged under 10^{-3}. To ensure simulation stability, heat imbalance, mass imbalance and y+ were monitored as well as temperature of the probes.

III. Model Validation

Computational model was validated by direct measurement of local hot spot temperatures using fiber optic temperature probes. 40 MVA 145 kV power transformer was chosen, having relatively high short circuit impedance of 20% for medium power transformer. Sensors were installed during the assembly phase and transformers underwent temperature testing. The recorded temperatures were then compared and used for validation.

Fiber optic temperature probes were affixed to various points on the clamping plates, chosen based on temperature results from the multiphysical model. Positioning of the probes covered both core clamps and winding clamps on low voltage and high voltage side of the transformer. Probes were placed on core clamps on both internal and external side. Eddy losses FEM analysis showed that clamps closer to tap changer will be induced by higher losses, therefore probes were placed on that side of clamping plates which is shown on Fig. 4.

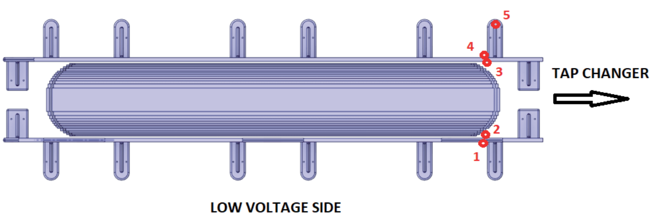

Fig. 4. Top view of clamping plates and position of the probes

Fiber optic sensors were attached to the clamping plates with a conductive adhesive as recommended by the manufacturer, shown on Fig. 5. The probes were still surrounded by the oil, however the glue ensured efficient heat transfer via thermal conduction.

Transformer was loaded up to full capacity in ONAF mode until stationary temperature was achieved, Fig. 6. Initially, it was loaded at position 15, representing the lowest voltage level (-). In that tap position, regulation windings remain unloaded, leading to a reduced short circuit impedance and lower generated losses in the clamping plates. However, overall losses in the transformer's windings and core are higher, resulting in elevated top oil temperature. Following the recording of top oil and probe temperatures, the voltage was adjusted to tap position 1, which corresponds to

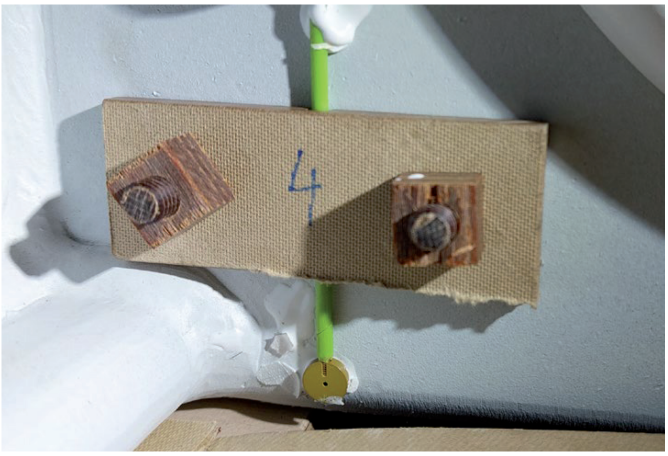

Fig. 5. Detailed view of fiber optic probes mounted on clamps

the highest voltage level (+). In this configuration, the short circuit impedance is maximized, leading to elevated losses in the clamping system, however top oil temperature will be lower. Resulting temperatures and analysis of both tap positions will be presented in subsequent chapter.

Fig. 6. Power transformer during experiment

IV. Results

Simulation results show stray field losses from FEM calculation on the left, alongside with corresponding temperature distribution obtained through CFD analysis on the right, Fig. 7. The connection point between the steel clamp and winding clamp experienced higher stray field losses, aligning with the local temperature hotspot at that location. Many factors effect where stray field losses will be induced, but in this case, that connection turned out to have the most significant impact. Due to the steel being a good thermal conductor, temperature difference between hot and cold spots is not as large as stray field loss plot could indicate. Higher induced losses in smaller parts of the plate are being thermally conducted through the rest of the plate.

Dino Kovačević, Mladen Marković, Damir Blažina, Numerical Calculation and Direct Measurement of Local Hot Spot Temperatures in Transformer Clamping Plates, Journal of Energy, vol. 73 Number 2 (2024), 8–12
https://doi.org/10.37798/2024732513

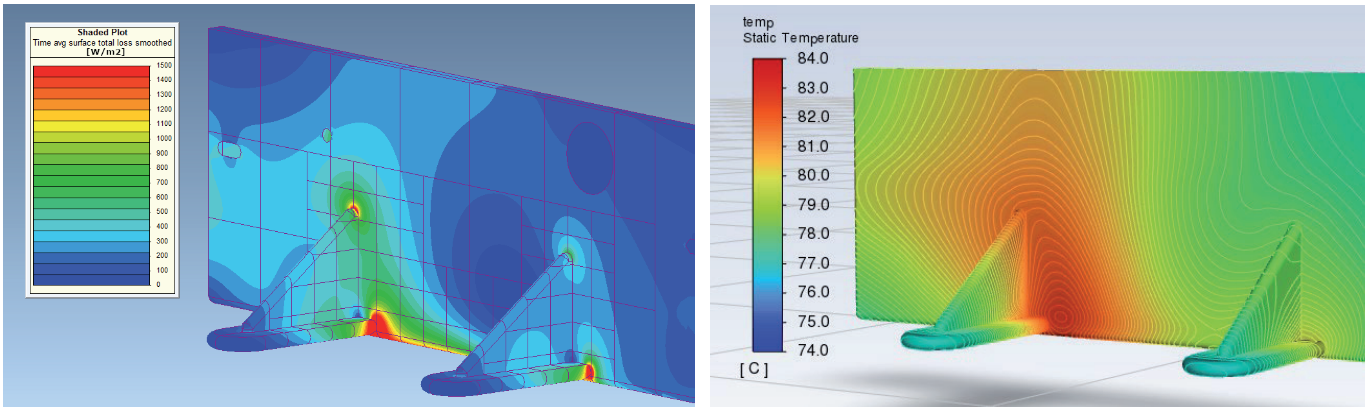

Fig. 7. Eddy losses plot (left) with corresponding temperature field (right)

Results from both simulations and experimental tests were collected and analyzed. A total of 5 probes were positioned on various places in the clamping plates as described before. Resulting comparison between measured and simulated hotspot temperatures for various positions were presented in Fig. 8. This corresponds to tap position 15.

In this scenario, the temperature rise captured by both measurements and simulations remains under 9K. Moreover, the temperature variance between measurement and simulation is not exceeding 1,6K at the worst. The least accurate positions were 1 and 2 on the low-voltage side of the clamping plates.

Moving to tap position 1 where losses induced in the clamps are highest, hotspot temperature rise will increase. Probe positions 1 and 2 that showed max. error of 1,6K were analyzed in tap position 1. Interestingly, the temperature difference between simulation and experiment remained consistent and even decreased. This realization is important, as it emphasizes that increasing the loss density in clamping plates didn't increase the error margin. Considering all the circumstances, this error is considered sufficient.

Probe position 5 shows hotspot temperature within the winding clamps. It is obvious that winding clamps pose minimal concerns for this power transformer. However, it's worth noting that in a different transformer setup, where the primary canal is located beneath the winding clamps, the risk of overheating might be more relevant.

Top oil temperature was measured 74,8°C in tap position 15 (-)

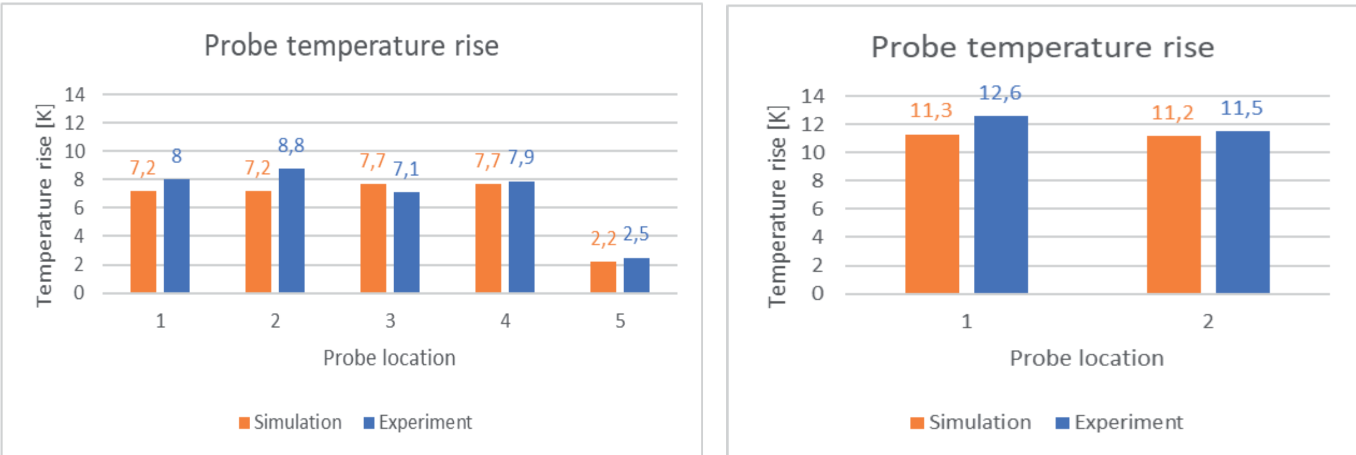

Fig. 8. Probe temperature rise in tap position 15 (left) and 1 (right)

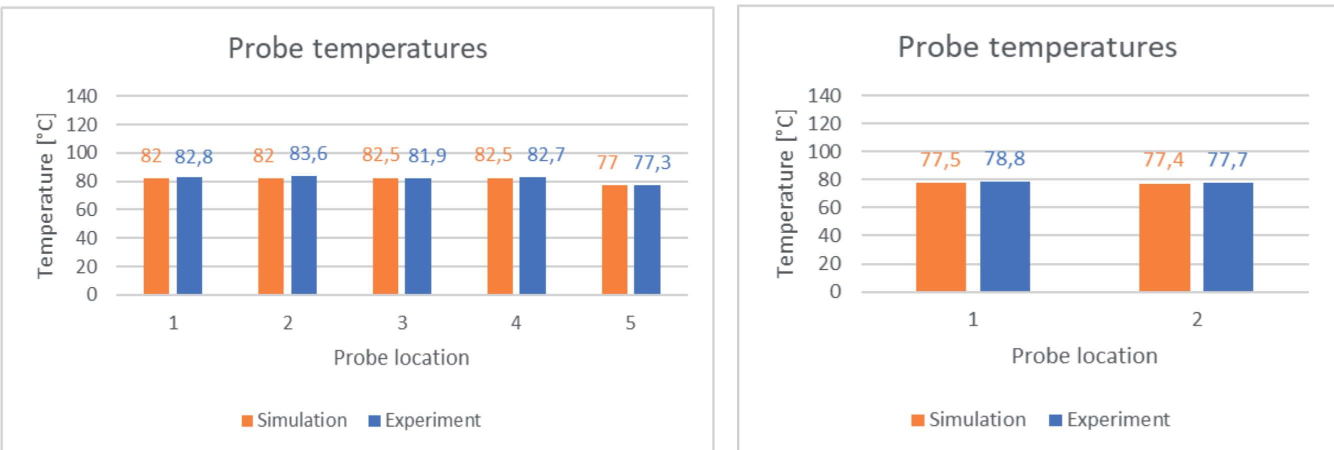

Fig. 9. Probe temperatures in tap position 15 (left) and 1 (right)

and 66,2°C in tap position 1 (+). Graph with probe temperatures that take top oil temperatures into account is shown on Fig. 9. For this specific power transformer, it was found that probe 2 on LV side of the internal steel clamp in tap position 15 (-) registered the highest temperature. Additionally, tap position 15 (-) consistently exhibited higher temperatures due to its elevated top-oil temperature. It's important to point out that this was the case specific for this power transformer. In other transformers with higher short circuit impedances, tap position 1 could potentially lead to higher hotspots.

For this particular power transformer, probe temperatures remain well below 140°C, a threshold at which the formation of gases could occur for most mineral oils.

V. Conclusion

The paper presented multiphysics approach combining electromagnetic and thermal modeling. It has been shown that this methodology can be effective for analyzing local hot spot temperatures in transformer clamping plates. The validation process, which involved direct measurement of local hot spot temperatures using fiber optic temperature probes, demonstrated the accuracy and reliability of the computational model. The results from simulations aligned closely with the experimental measurements, highlighting the model's capability to predict temperature behavior with a sufficient level of precision. With an emphasis on the specific power transformer investigated in this study, it's important to recognize that results may vary for transformers with different short circuit impedances. Upcoming studies might examine power transformers with higher short circuit impedances, potentially revealing tap position 1 as less favorable.

References

[1] D. Žarko, Z. Maljković, and S. Štefan, "Calculation of Losses in Core Clamps of Transformer Using 3-D Finite-Element Method" *Macedonian - Polish Symposium On Applied Electromagnetics*, Ohrid, Macedonia, 2006.

[2] L. Šušnjić, Z. Haznadar, and Z. Valković, "Electromagnetic Analysis Applied to the Prediction of Stray Losses in Power Transformer" *ICEM 2004 Conference Proceeding*, Krakov, Poland, 2004.

[3] F. Paolucci, A. Rousseau, "Passive Magnetic Shield – Steel Material", PPT presentation, ITER, 20.7.2021.

Dino Kovačević, Mladen Marković, Damir Blažina, Numerical Calculation and Direct Measurement of Local Hot Spot Temperatures in Transformer Clamping Plates, Journal of Energy, vol. 73 Number 2 (2024), 8–12
https://doi.org/10.37798/2024732513