Multiphysics Simulation Analysis of Copper Lead Arrangement in a Very High Power Transformer

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***Abstract*— This paper presents a thorough investigation into the copper lead arrangement within a 191 MVA very high-power transformer through multiphysics simulation. Utilizing electromagnetic, thermal, and Computational Fluid Dynamics (CFD) methodologies, the study scrutinizes lead positioning relative to steel components, with a specific focus on the area between the On-Load Tap Changer (OLTC) and winding. Identified as a critical scenario, lead proximity to steel necessitates protective measures like M5 and Aluminum tank shields. Despite their implementation, potential high-temperature issues stemming from geometric variations and additional leakage losses in steel parts remain concerns, challenging traditional analytical approaches and emphasizing the indispensability of multiphysics simulations throughout the design and manufacturing phases. Validation of simulation results against real test data via 3D electromagnetic and thermal coupled simulations reveals close agreement between simulated and experimental outcomes. Further validation employing 2D electromagnetic and CFD techniques confirms the findings, showcasing minimal disparities compared to test results. Ultimately, the study advocates for a final transformer design integrating both M5 and Aluminum shields, effectively mitigating temperature fluctuations on the tank surface. This research underscores the pivotal role of multiphysics simulation in optimizing transformer design, mitigating operational risks, and providing valuable insights for future transformer development endeavors.**

Keywords—Multiphysics analysis, High power transformer, CFD, Electromagnetic shield

I. INTRODUCTION

The production of power transformers has been increasing in recent years. In this context, its dimensions, cost, and loss are extremely important to compete in the global market. As a result, the efficiency is aspect that must be considered in the design stage.

In power transformers, efficiency is proportional to the losses, including the stray losses. According to [1] and [2], the stray losses problem increases with the power rating of the units. The stray magnetic field strength of transformers with rated capacity from 100 to 150 MVA is proportional to the fourth root of their ratings. Above 150 MVA, it is proportional to the rated power. As a result, a lot of losses would occur in large transformers if solutions were not adopted. They not only reduce the efficiency of transformers but also lead to local overheating, which affects the operational reliability of the transformers and shortens their service life.

Most of these stray losses occur in steel parts with large areas such as those of the transformer tank. Several methods can be used to reduce them. Magnetic and electromagnetic shields are the more usual passive techniques to achieve this goal in transformer tanks. An insufficient or incorrect shielding of these parts can significantly increase loss of the transformer and reduce its efficiency. For this reason, specific studies must be carried out to implement the proper shielding. Thus, in 1992, Holland et al. adapted the surface impedance method to be used in a 3D finite element software to calculate the eddy currents in thick conducting materials such as the tank walls of a power transformer, [3]. Some simplifications were considered such as the use of linearity in the B-H curve of the mild steel and the low number of elements used. They verified this solver by applying it on a 90 MVA, 3-phase, 132/33kV transformer mounting in a straight sided mild steel tank. Also, shunts made of plates of core steel were mounted close to the transformer walls to reduce the stray losses. They compared experimental short-circuit stray losses results with those obtained from the numerical model with/without shield. They concluded the model accuracy was good enough. Additionally, this method avoids the need to mesh deeply from the surface to account for the skin effects, thus reducing the complexity and size of the models. In 1994, Yongbin et al. conducted a study comparing several shielding configurations using a 3D finite-element method, the T-Ω method, [2]

In 2004, Saleh et al. presented a very basic 3D numerical model in which overall tank eddy losses were calculated for different dimensions of the tank walls of a 25 MVA, 66/11 KV, D/Y transformer, [6]. Also, the effect of an electromagnetic shield (copper) placed in the long tank walls were analyzing, concluding that this method is very effective to reduce drastically these losses. One year later, Janic et al. performed a simplified numerical study of the shielding of a 300 MVA power transformer tank, [7]. Some simplifications were considered in the model, such as the geometrical design analyzed (3D with symmetries) and the constant value of the material permeability of the core steel used in the shield. The goal was to optimize the shielding efficiency using a parametric study: height and width of the shield and its distance to the windings were analyzed. According to the study, assuming that the distance from the shield to the windings does not vary, increasing the height rather than the width is more important to reduce the losses. Five years later, the same authors, in addition to studying the tank losses caused by eight different leads arrangements of a 220 MVA transformer, presented the influence of the shield height on the values and distribution of these losses. Both studies were performed using a 3D FEM software, [8]. The main conclusion of the second study was that the change of magnetic characteristics around the leads caused the model with higher shields to have higher loss densities on the tank. That is, better shielding does not necessarily imply a more reliable transformer, as is often thought. In 2017, Najafi et al. presented a 3D FEM study where different widthwise magnetic shunts applied to 1 MVA distribution transformer were studied to obtain the optimum, [9]. Then, they compared its performance with the conventional shunts. In the same year, Moghaddami et al. proposed the use of horizontal wall shunts to reduce stray losses, [10]. To justify the proposal, they compared their performance with that of the vertical shunts using a novel hybrid numerical (FEM)/analytical method for the calculation of the stray losses in the magnetic shunts. This method was applied in the vertical and horizontal shunts of a 200 MVA power transformer. The main conclusion was that the proposed horizontal magnetic shunts arrangement were as effective as conventional vertical shunts while reducing the weight of the shields. Two years later, Al-Abadi et al. investigated the effective parameter influencing the magnetic shunts design to reduce not only the stray losses but also the noise in transformers, [11]. The investigation involves FEM simulations and their validation against measurements. Results showed improvements in both aspects, losses and noise, for different power transformers.

Most of the studies presented above are focused on reducing the stray losses. This reduction does not always lead to the reduction of local temperature rises (hot spots) in the constructional parts. For instance, if a transformer has leads arrangement with high currents close to the metal parts, areas with high loss density can be generated. These areas have to be cooled appropriately to avoid the hot spots. Two papers studying this topic have been recently published. The first one in 2012, in which Sitar and Janic developed a 3D numerical model to analyze the electromagnetic-thermal behavior of an electromagnetic shielding, [12]. Several shapes and dimensions of the shielding were analyzed. Two main conclusions were inferred: Shielding most of the area affected by the stray flux is not always the best solution and the properties of the materials surrounding the shield and transformer lead arrangement have to be considered. Three years later, a complementary study of the previous one was carried out by the same authors in which power losses and temperature distributions in the 220 MVA transformer tank were calculated for different lead arrangements of the LV winding connections, [13]. A thermomagnetic 3D numerical model was developed. Following the conclusions of the previous paper, B-H curves of structural steel and the dependence of the heat transfer coefficient on heat flux and temperature were considered in this model. Cooling conditions were determined using an approximated heat transfer coefficient that was calculated with standard empirical formulas for vertical plates at rated conditions (70 ºC). Several lead arrangements of the delta connection used in the LV winding were studied to get tank losses and the corresponding local overheating. Magnetic shield losses hardly varied with the lead arrangement choosen. Also, a complementary study was carried out using the best configuration, i. e. with the lowest overheating. The magnetic shield height was varied to determine its influence on the tank losses and temperatures. The authors concluded that a fully shielding was necessary to reduce these variables since a partial shielding could even increase the magnetic flux in the tank.

As it is mentioned in [13], a more appropriate approach to model the cooling would be to carry out a fluid dynamics calculation, such as computational fluid dynamics (CFD).

II. Description of the Numerical Model

Taking a mono-phase power transformer typed 191MVA/420kV as objective target, the calculation model is established. In this study, it is aimed to examine the effect of different shielding methods on the bottom of the transformer and shown in Fig. 1.

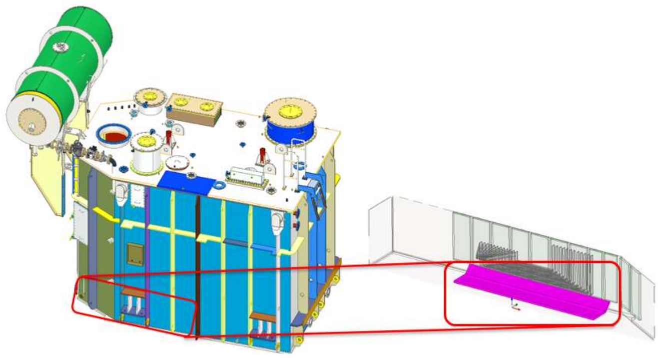

Fig. 1. Mono-Phase 191MVA/420kV Analysis Model

To reduce these losses, shielding should be applied to the tank-wall where copper leads pass. In this study, aluminum and M5 shielding are used to reduce losses and the results are compared.

Copper leads are positioned at a distance of 222 mm from the horizontal and 140 mm from the vertical and 1340A current passes through them. (Fig.2)

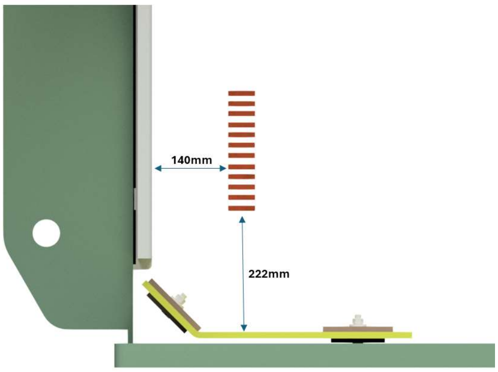

Fig. 2. The position of copper leads

III. Electromagnetic-Thermal Coupled Method

The stray losses calculated by electromagnetic is regarded as the heat source, which would be coupled with thermal field analysis. Finite element (FE) simulations using commercial software should be used to calculate the stray losses generated.

First, 3D electromagnetic and thermal analyzes are performed for the heating caused by stray losses. Then, 2D electromagnetic analysis and CFD fluid analysis are performed and the results are analyzed.

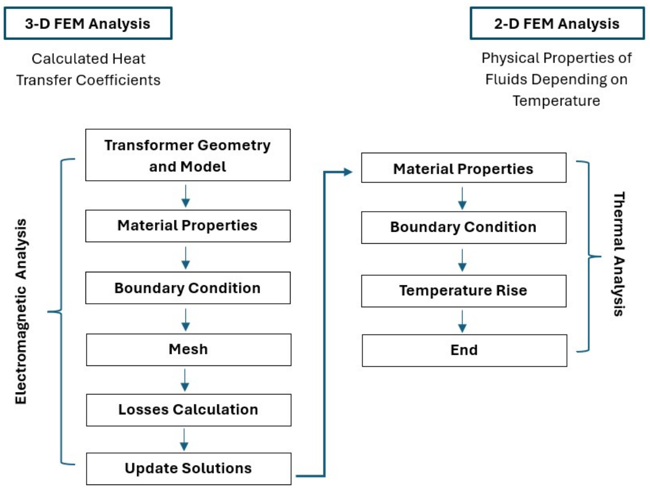

Fig. 3. Electromagnetic -Thermal coupling

A. Material Properties

In this study, there is a total of 2 independent design variables. These variables are material for shielding. The detail of transformer design variables is given in Table 1.

TABLE I. Properties of solid materials which used for E-mag, thermal and CFD analysis.

Component Materials	Properties		
	Density (kg/m^3)	Bulk Conductivity (siemens/m)	Thermal Conductivity(W/(m*K))
Tank Steel	7800	6670000	50,5
Copper Leads	8900	58000000	380
M5 Shield	7800	1960780	16,3
Aluminum	2700	38000000	237

Also, Table 2 presents the physical properties of the oils taken into consideration in the model solved of CFD as mathematical expressions. Since the liquid is commercial oil, these expressions rely on the temperature expressed in Kelvin and are computed using information from public datasheets.

TABLE II. Physical properties of the oil that used in the CFD model

	Mineral oil
ρ (kg/m^3)	1055-0.660*T
C_p (J/(kg·K))	1172.7+3.6097*T
K (W/(m·K))	0.1529-6.95E-5*T
μ (Pa·s)	6.8715-7.6222E-2*T+3.1820E-4*T^2-5.9186E-7*T^3+4.1355E-10*T^4

B. Boundary and Conditions

First, electromagnetic analysis is established in ANSYS Maxwell. Peak ampere values, number of turns are used as input data respectively for all turns in electromagnetic models. Its nominal current in the copper leads is 1340A. The input excitation should be equal to the exit excitation. There are 2 types of winding modeling. One of them is solid and the other is stranded. Solid is used in this analysis because it contains a single conductor, not a bundle of wires. Moreover, conductors are used in conjunction with Impedance Boundaries in the Eddy Current solvers to handle the following conditions:

a. The skin depth in the conductor is less than two orders of magnitude smaller than the dimensions of the structure. In models like this, the mesh maker may not be able to create a fine enough mesh in the conductor to compute eddy currents.

b. The magnetic field decays much more rapidly inside the conductor in the direction that's normal to the surface than it does in directions that are tangential to the surface.

c. The AC current source is relatively far away from the surface where eddy currents occur, compared to the size of the skin depth.

Finally, the stray losses caused by the current flowing conductor on the tank surface is calculated.

Secondly stray losses are transferred to the thermal model with making connection between ANSYS Maxwell and ANSYS Mechanical thermal model using ANSYS Workbench analysis platform. Calculated heat transfer coefficient in Fig-4 is applied in the FEM thermal analysis to the inside of tank wall where insulation oil touching. Moreover, thermal conductivity properties of other materials in Table-1 are applied in mechanical thermal module.

In the thermal model, convection between oil and inside of the tank surface have carried out using convection coefficient depending on oil temperature. At outside of tank, between air and tank surface, convection and radiation were defined as a boundary conditions. Convection coefficient of air depending on temperature as a nonlinear BC, and emissivity value was defined as 0.95.

In CFD analysis steps are same as mechanical thermal, but main differences are that is not defined heat transfer coefficients since fluid domain modelling and detailed fluid properties define in this technique.

The numerical method, based on finite volume principles, resolves the Navier–Stokes equations, which express the conservation principles of mass, momentum, and energy in fluid dynamics.

$$\nabla \cdot (\rho\, u) = 0 \qquad (1)$$
$$(u \cdot \nabla)\rho u = -\nabla p + \mu(\nabla^2 u) + g\rho \qquad (2)$$
$$\nabla \cdot \left(\rho\, c_p\, u\, T\right) = \nabla \cdot (k\, \nabla T) + q \qquad (3)$$
$$0 = \nabla \cdot (k\, \nabla T) + q_s \qquad (4)$$

In equations (1-4), the variables ρ, ρref, u, p, μ, g, Cp, T, k, and qs represent density, reference density, velocity vector, pressure, dynamic viscosity, gravity, specific heat capacity, temperature, thermal conductivity, and heat source, respectively, as cited in references [20-21].

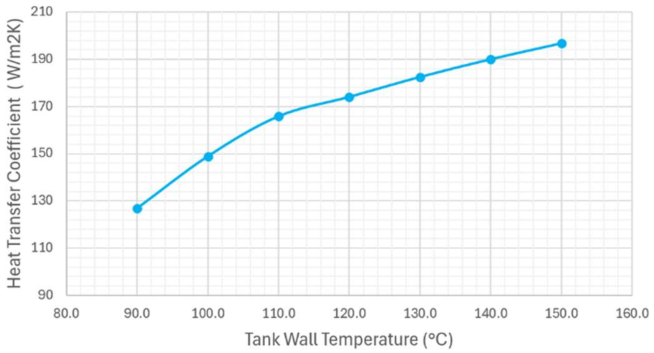

Fig. 4. Convection coefficient / temperature chart

In both thermal analysis bottom oil temperature is considered as 45 °C which obtained from analytic calculation and validated thermographic photo after test.

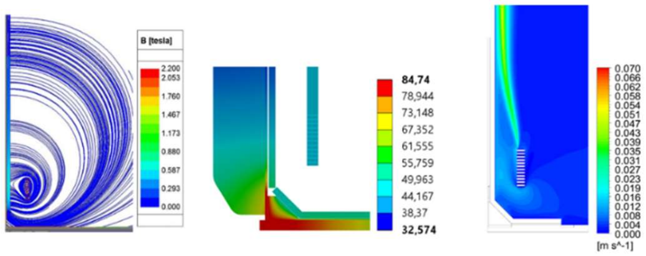

Fig. 5. Comparison of different screen types

C. Computational domain and mesh

Adaptive mesh optimization provides such a dynamic programming environment to adapt the precision of numerical computation based on the needs of a computational problem in specific areas of multidimensional graphs that require precision, while leaving other regions of multidimensional graphs at lower levels for precision and resolution.

Adaptive mesh was used in the electromagnetic analysis. The analysis was completed when 0.41% energy error was reached and passed 9 steps. A total of 108755 tetrahedral meshes were used 30% mesh improvement was achieved at each step.

268891 quadrahedral and tetrahedral meshes were employed in the steady state thermal analysis, with a simulation duration of six minutes. A heat transfer flow convergence value of less than %2 was observed. The 77827 quad mesh's quality of max skewness value in the CFD analysis was 0.75. After 11,000 iterations, the simulation reached convergence, and the entire solution time was roughly 7 hours.

IV. Results

In this study Multiphysics (E-mag, Thermal, Fluid) analysis has been carried out to get accurate results. The study examines a final transformer design that incorporates both M5 and Aluminum shields to reduce tank surface temperatures.

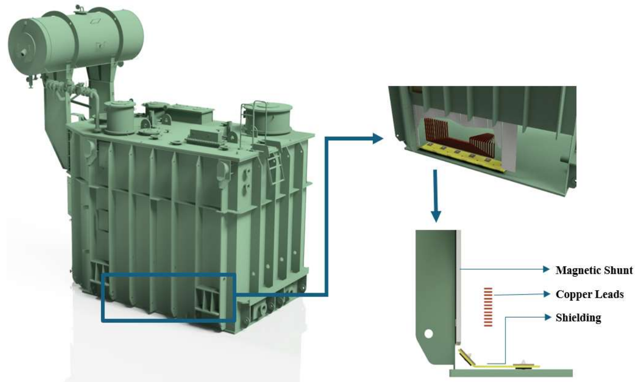

Fig. 6. Geometrical description of the shielding

In the thermal model, convection between oil and inside of the tank surface have carried out using convection coefficient depending on oil temperature. At outside of tank, between air and tank surface, convection and radiation were defined as a boundary conditions. Convection coefficient of air depending on temperature as a nonlinear BC, and emissivity value was defined as 0.95.

TABLE III. COMPARISON OF DIFFERENT SHIELDING TYPES

Screen Type	Tank Wall Loss	Tank Wall Temperature
Aluminum	2968 W	135 °C
M5	1478 W	84 °C

In the case of using an aluminum shielding, the loss density has increased in the bottom part of the shielding on the tank wall due to the aluminum screen directing the leakage flux towards the tank wall. Hence, higher loss and temperature values are obtained on the tank.

When the results obtained are examined, it has been seen that the proper determination of the position and material of the tank shield is quite effective on the tank loss and temperature values.

The heat run test has done for described 191MVA power transformer according to IEC60076-2, then this test results were used to fem model validation. As can be seen at figure-7 between fem result and experimental result difference is less than 4 °C.

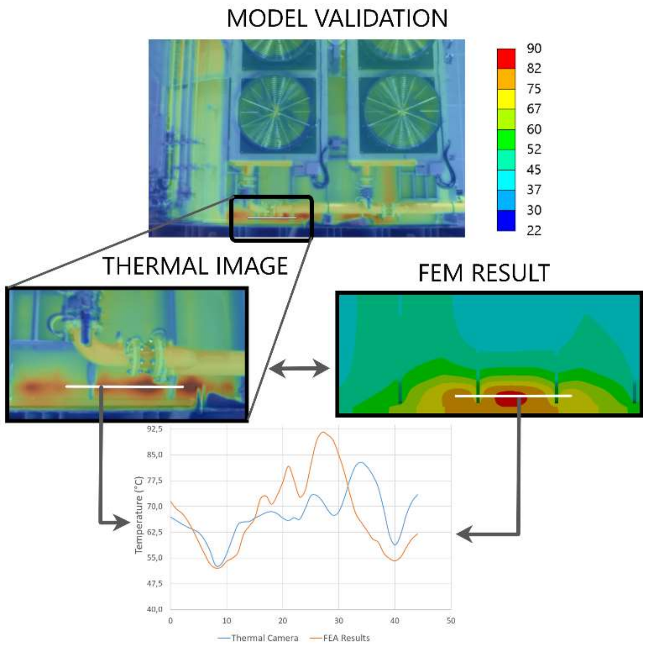

Fig. 7. Model validation between thermography view and FEM and Test results

V. CONCLUSION

In conclusion, this study demonstrates the efficacy of multiphysics analysis in optimizing leakage flux losses within complex geometries. Through comprehensive examination, the impact of various shield materials, including aluminum and M5, on tank temperature and total loss value has been studied. According to the boundary conditions of this problem, CFD analysis results and FEM thermal results were very close to each other. While both methodologies seem suitable to use for the problem, the FEM thermal analysis approach emerges as more advantageous, particularly due to its shorter solution time. These findings underscore the potential of multiphysics simulations in refining transformer design, with implications for enhancing efficiency and mitigating operational risks in high-power systems.

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